CHAPTER III (OTHER ELECTRONIC DEVICES)

Electro Optic Effect

Electro optic effect can be observed when light propagates through a crystal in the presence of an Electric Field. The electric field applied to the crystal can alter or induce birefringence by changing the refractive index of the medium. This effect is known as electro optic effect.

Pockel's Effect (or) Linear Electro Optic Effect

Pockels effect is observed only in non-centrosymmetric materials. The change in the refractive index ($\Delta\mu$) is proportional to the applied electric field (E)
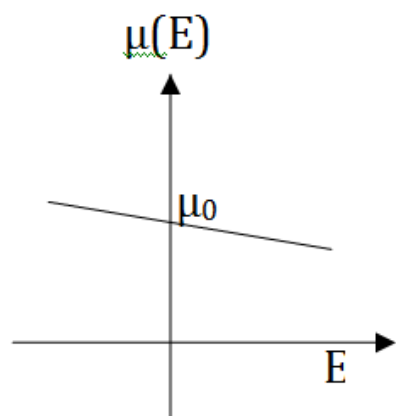
$\mu = f(E)$

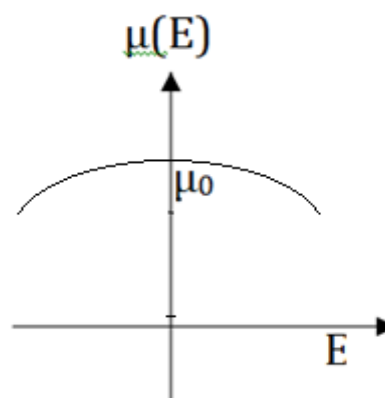Since the change is very small, by using tailor's series, it can be written as

$\mu(E) = \mu_0 - \frac{1}{2} r \mu^3 E$

The change $\Delta\mu = \frac{1}{2} r \mu^3 E$

Where r is a constant for a crystal and it varies from 10^{-12} to 10^{-10} m/V

Pockels Effect   Kerr Effect

Kerr Effect or Non Linear EOE

In Kerr effect, the change in the refractive index is proportional to the square of the applied electric field.

$\mu = f(E^2)$

Since the change is very small, by using tailor's series, it can be written as

$\mu(E) = \mu_0 - \frac{1}{2} s \mu^3 E^2$

The change, $\Delta\mu = \frac{1}{2} s \mu^3 E^2$ (s varies from 10^{-18} to 10^{-14} m^2/V^2)

The Kerr effect is very weak compared with pockel. Some highly transparent crystals show Kerr effect but with smaller Kerr constant. Some polar liquids such as Nitro toluene and nitro benzene show appreciable Kerr value.

The change in the refractive index induces or alters the birefringence of the crystal and therefore the beam suffers a phase shift. Even though the change in the refractive index is very small, the corresponding phase change in the beam propagating along the direction of applied field could be significant.

Example

In the case of KDP crystal, with μ_0 = 1.512, E =v/d = 10^6 V/m and

r_{63}= 10.5x 10-12 m/V, the change by Pockel's effect

$\Delta\mu = 2 \times 10^{-5}$ (very small)

If a plane polarised light (along x direction) with wavelength λ = 0.5μm is propagating along the z axis in the crystal then the phase change in the beam after traversing a path length of 1cm due to the applied electric field is $\Delta\phi = 2\pi/\lambda$

= 0.8π (appreciable phase shift)

Electro Optic Materials – (Pockels)

Frequently used nonlinear crystal materials for EOMs are

Potassium di-deuterium phosphate (KD*P = DKDP),

Ammonium dihydrogen phosphate (NH4H2PO4, ADP).

Potassium titanyl phosphate (KTP),

Beta-barium borate (BBO)

Lithium niobate (LiNbO3), Lithium tantalate (LiTaO3)

Applications

A beam of light propagating through the crystal subjected to an electric filed suffers a phase shift due to Pockels effect and it is useful for Phase Modulation.

Under certain configurations or geometrical conditions the applied electric field acts differently on two linearly polarized light waves passing through the crystal. Therefore it can be used to introduce an electric field dependent retardation between two polarizations and this effect can be used control the amplitude of light beam in accordance with the applied electric filed – Amplitude Modulation.

Thus Electro Optic effect is useful for imposing information on a light beam (called electro optic modulation) - very useful in optical communications.

EOE is used in modulating the power of a laser beam for laser printing and high-speed digital data recording.

Also this principle is used in Electro Optic Sensors.

Types of Electro-optic Modulators

Phase Modulators

The simplest type of electro-optic modulator is a phase modulator containing only a Pockels cell, where an electric field (applied to the crystal via electrodes) changes the phase delay of a laser beam sent through the crystal. The polarization of the input beam often has to be aligned with one of the optical axes of the crystal, so that the polarization state is not changed.
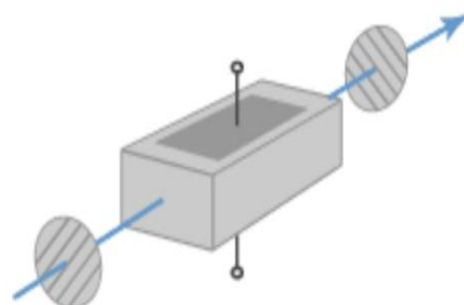
Polarization Modulators

Depending on the type and orientation of the nonlinear crystal, and on the direction of the applied electric field, the phase delay can depend on the polarization direction. A Pockels cell can thus be seen as a voltage-

controlled waveplate, and it can be used for modulating the polarization state. For a linear input polarization (often oriented at 45° to the crystal axes), the output polarization will in general be elliptical, rather than simply a linear polarization state with a rotated direction.

Amplitude Modulators

Combined with other optical elements, in particular with polarizers and anlyzers, Pockel's cells can be used for other kinds of modulation. In particular, an amplitude modulator is based on a Pockels cell for modifying the polarization state and an analyzer for subsequently converting this into a change in transmitted optical amplitude and power.

Electro optic amplitude modulator, containing
a Pockels cell between two polarisers.   →

The input polarizer is used polarize the input beam at 45^0 to the crystal principal axis. The crystal acts as a varying waveplate changing the exit polarization from linearly polarized (0° rotated from the input) to circularly polarized, to linearly polarized (90° rotated from the input), etc., depending on the applied voltage. The analyzer transmits only the component of exit polarization that has been rotated, thereby producing a total transmission of 0,0.5,1 etc.

Magneto Optic Effect (MOE)

It is the result of the interaction between Light and magnetic field within the Magneto Optic Medium.

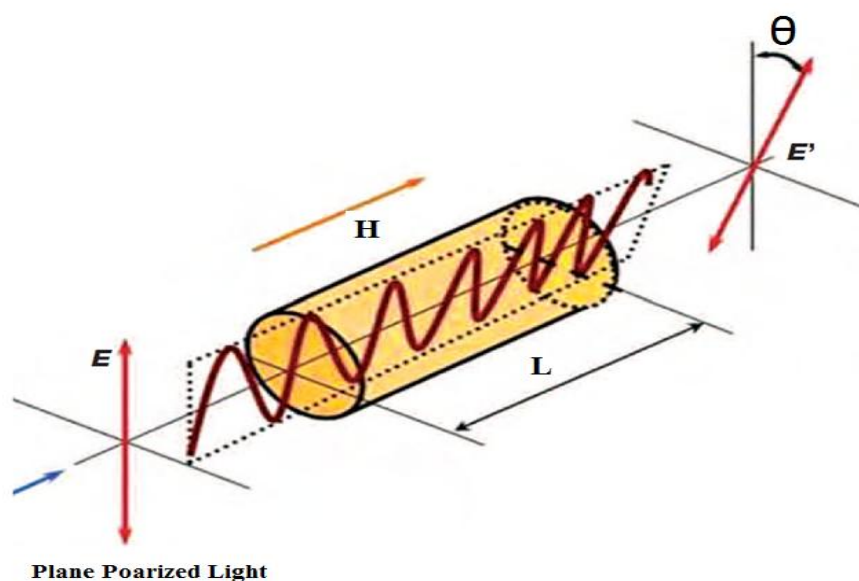MOE are divided in to three main categories related to

1. Transmission   2. Reflection   and   3. Absorption of light

Transmission Mode

Faraday Effect

The rotation of a polarization plane of a linearly polarized light during its propagation through a layer of magneto-optic material, which is placed in a magnetic field is known as Faraday Effect. The rotation is proportional to the intensity of the component of the magnetic field in the direction of propagation of light.

When a magnetic field is applied, a double dispersion effect is generated. Left circularly polarized light is dispersed at V_1 and right circularly polarized light is dispersed at V_2. This causes, the left and right circularly polarized light components to have different indices of refraction. Thus a retardation of one component relative to other gives rise to a a phase difference between them.

Plane Poarized Light

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.

When emerging, these components will combine to give an elliptic polarization whose major axis is rotated relative to the original direction of polarization. This angle is called Faraday angle (Θ_F).

$$\Theta_F = K_V.H.L$$

K_v is a proportionality constant called Verdet Constant describe the strength of Faraday effect. (Kv : 0.001 to 0.1 minute/A).

The birefringence ($\Delta\mu$) related to the angle of rotation by the equation

$$\Theta_F = \Delta\mu. \pi\ L\ /\lambda$$

and the intensity of variation associated with the birefringence is given by

$$I = I_0 \sin^2 \Theta_F$$

Voight Effect

The magnetic field is directed perpendicular to the optical path of the linearly polarized light (normally in gases). This effect is very small in para and dia magnetic materials. The birefringence ($\Delta\mu$) related to the angle of rotation Θ_V by the equation

$$\Theta_V = \Delta\mu. \pi\ L\ /\lambda$$

Similar effect observed in Liquids is known as Cotton-Moulton effect.

Reflection Mode

Kerr Effect

It deals with the reflected light from the surface of a magnetised material. There are three different configurations of light w.r.t magnetization in the sample.

1. Polar Kerr effect
2. Longitudinal Kerr effect
3. Transverse Kerr effect

Polar Kerr Effect

The direction of magnetization is perpendicular to the reflection surface and parallel to the plane of incidence.

In this configuration, the linear polarization becomes elliptic and the change of direction of polarization is $< 1^0$
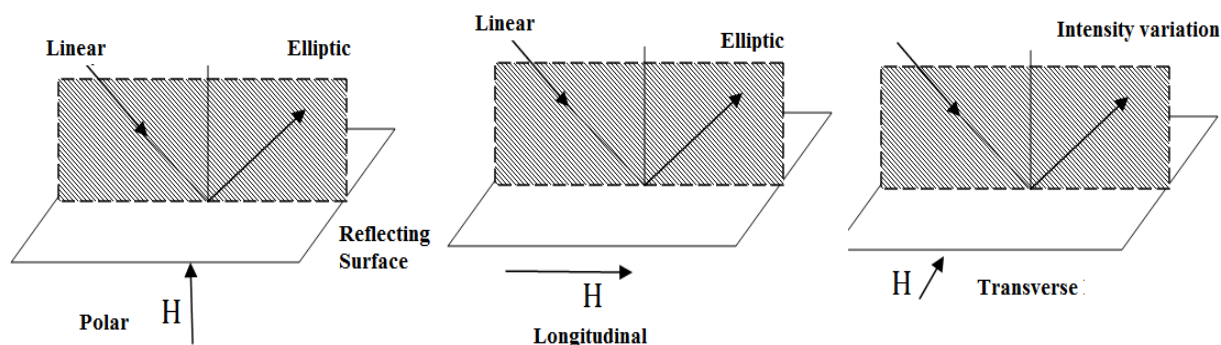
Longitudinal Kerr Effect

Magnetization vector is parallel to the reflection surface and plane of incidence. The incident light is parallel or perpendicular to the plane of incidence. The polarization of reflected light is elliptic and the change in the direction of polarization is $<1^0$

Transverse Kerr Effect

Magnetization vector is perpendicular to the incident plane and parallel to the reflecting surface. In this configuration,

- no change in direction of polarization is observed but
- a variation in the intensity of reflected light is observed.

Absorption Mode

Circular Magnetic Dichroim

This effect is the difference in the absorption coefficient for the right and left circularly polarized light. This difference changes slightly the spectrum of absorption of a sample magnetized in the direction of light propagation.

Linear Magnetic Dichroim

In LMD, magnetic field is perpendicular to the beam direction.

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.

(Dichroim - Light rays having different polarizations are absorbed by different amount. (i.e.) the absorption coefficient (α) depends on the type and direction of polarization)
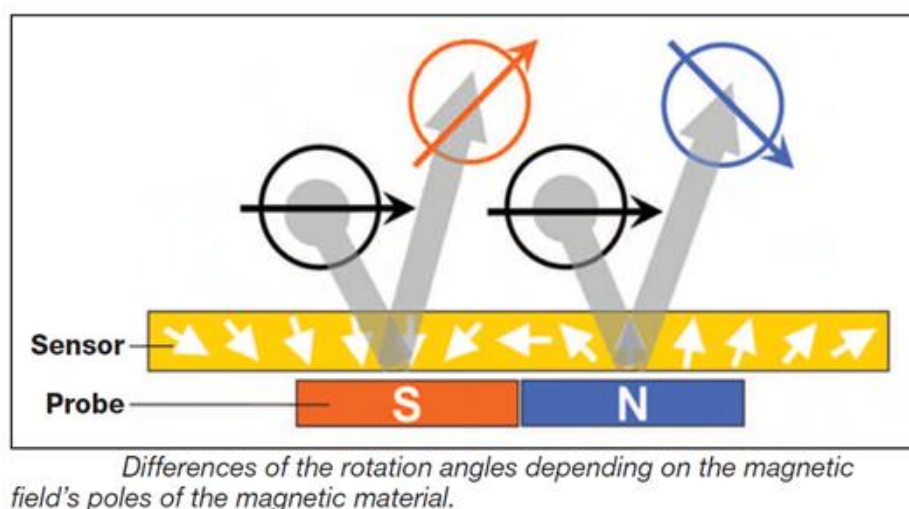
MO Materials

A magneto-optical photonic crystal comprises magneto-optical material such that the optical response of the device depends on the magnetization of the magneto-optical material. The magneto-optical effect can be enhanced by means of optical resonances.

Cadmium Manganese Telluride CdMnTe

Cadmium Manganese Mercury Telluride CdMnHgTe and TdGdG

Applications

MO sensors

Differences of the rotation angles depending on the magnetic field's poles of the magnetic material.
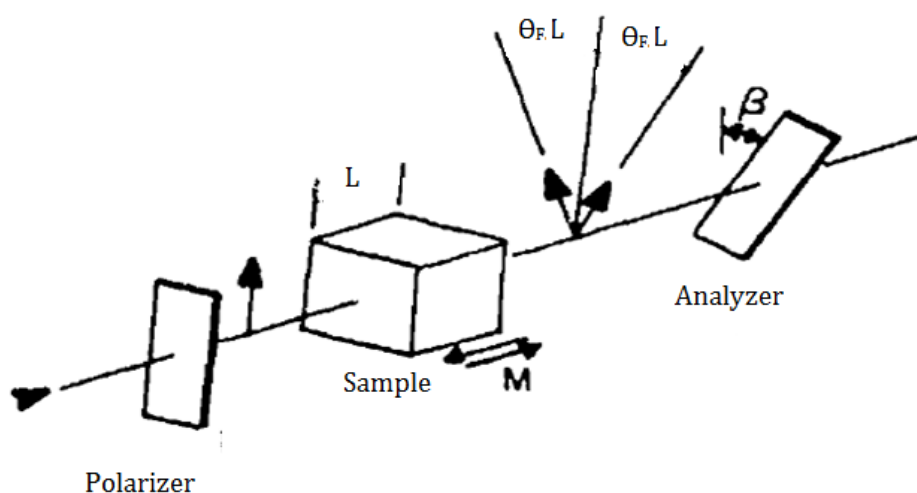
Magneto-optical sensors are based on the Faraday-effect. Light passing through a MO medium under the influence of an external parallel magnetic field splits into two contra-rotating circular partial waves having different phase velocities. This results in a phase shift for both waves, while their frequency remains the same. The phase shift of the contra-rotating circular waves causes the polarization plane to rotate. The different intense

absorption processes for both waves forms an elliptically polarized wave when the light exits the MO medium.

A MO sensor arrangement is shown in figure. The resulting wave carries the magnetic-field information, which is analyzed to determine the specific magnetic properties. The resulting Faraday-rotation changes depending on the strength of the external applied magnetic field. Evaluation of the rotation angle helps to accurately determine the properties of magnetic fields.

Optical Switches (using MO effect)

The straight forward application in the transmission MO mode is an optical switch. The analyzer's angle 'β' relative to initial poliarizatin can be made equal to the Faraday rotation $\theta_F.L$, so that for one magnetization direction $(+\theta_F.L)$ the transmitted light will be extinct and for the other direction the transmitted intensity will be

$$I_t = I_0 e^{-\alpha L} Sin^2 (\beta \pm \theta_F L)$$

An optimum thickness L can be computed from the above equation. It is dependent on the figure of merit of the switch material:

$$L_{opt} = \frac{1}{2\theta_F} tan^{-1} \frac{4\theta_F}{\alpha}$$

Light Modulators

Magneto Optic Deflectors

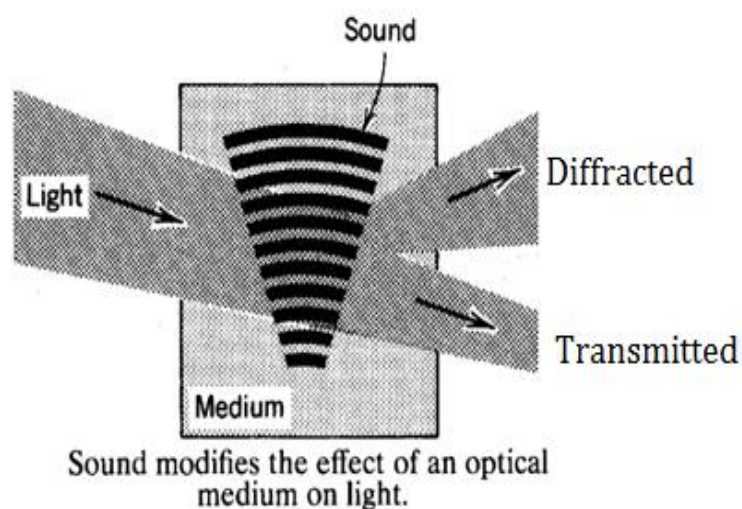LMD and CMD can give insight on Band Structure of Crystals.
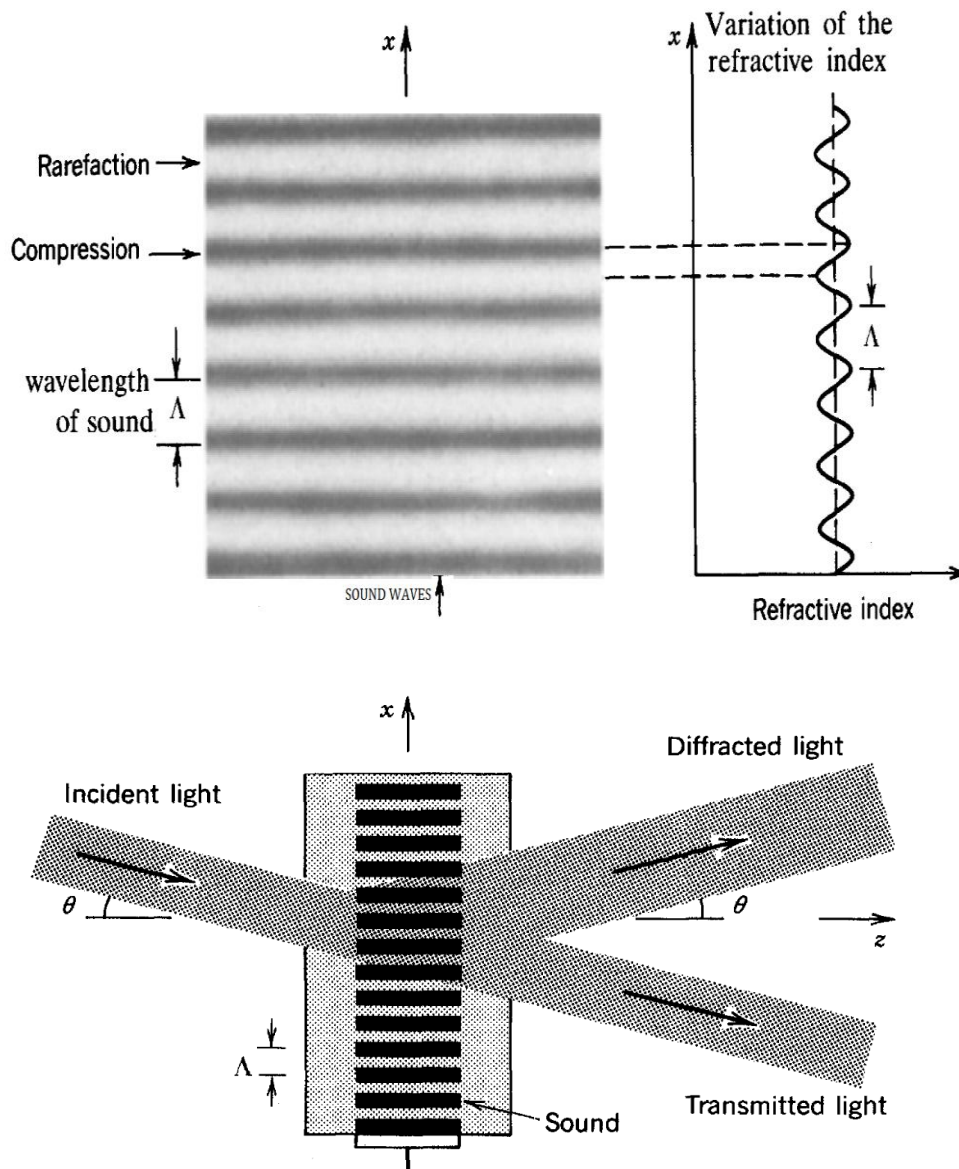
Acousto-Optic Effect (AOE)

It is the interaction between sound waves and light waves in an acousto-optic medium. Essentially it is the diffraction of Laser by Ultrasound.

AOE are based on the change of the refractive index of an optical medium due to the presence of sound waves in that medium. Thus sound alters the refractive index of the medium and therefore modifies the effect of medium on the light. (i.e.) Sound can control light.

Sound is a dynamic strain involving molecular vibrations that takes the form of waves which travel at a velocity determined by the medium. When it is passed through fluid, compressions and rarefactions are produced. In those regions where the medium is compressed the density is higher and refractive index is larger. Where the medium is rarefied, its density is smaller and refractive index is also small. In solids, sound involves vibrations of molecules about their mean position, which alter the polarizability and consequently refractive index.

Thus an acoustic wave creates perturbation of the refractive index in the form of a wave. Therefore, the medium becomes a dynamic graded index medium.

Sound modifies the effect of an optical
medium on light.

Braggs Diffraction

A set of parallel reflectors separated by the wavelength of sound Λ will reflect light if the angle of incidence θ satisfies the Bragg condition for constructive interference,

Sin θ = λ/2Λ

λ - wavelength of incident light , Λ - wave length of sound

This form of light-sound interaction is known as Bragg diffraction, Bragg reflection, or Bragg scattering. The device that produces this effect is known as a Bragg reflector, a Bragg deflector, or a Bragg cell.

Acousto-Optic Materials

> Fused Silica
>
> Lithium Niobate
>
> Arsenic Trisulfide
>
> Tellurium dioxide
>
> Telluride glasses
>
> Gallium Phosphide

The selection of acousto optic material depends upon the specific application. An AO material suitable for one application may not applicable to another. For example, GaP is useful to make modulators and deflectors but it is not suitable for filter purposes since it is optically isotropic.

Various Acousto Optic effects and Applications

Effect	Meaning	Devices
Deflection	The angular deviation in the diffracted light beam is proportional to the acoustic frequency	Acousto Deflectors, Routers, Switches, Optical Scanners
Intensity Variation	Diffracted beam intensity is a function of acoustic power	Amplitude Modulators, Q-Switches
Frequency Shift	A frequency shift is introduced by the acoustic interaction ($\pm\Delta f$ acoustic frequency)	Fixed or Variable Frequency shifter
Filtering	Wave length selection can be carried out with large spectral band sources since only one wavelength will match the condition (for ex. Bragg)	Tunnable Wavelength Filter, Isolators

Examples

Acoustic Spectrum Analyzer

A sound wave containing spectrum of different frequencies disperses the light in different directions with the intensity of deflected light in a given direction proportional to the sound component at the corresponding frequency.
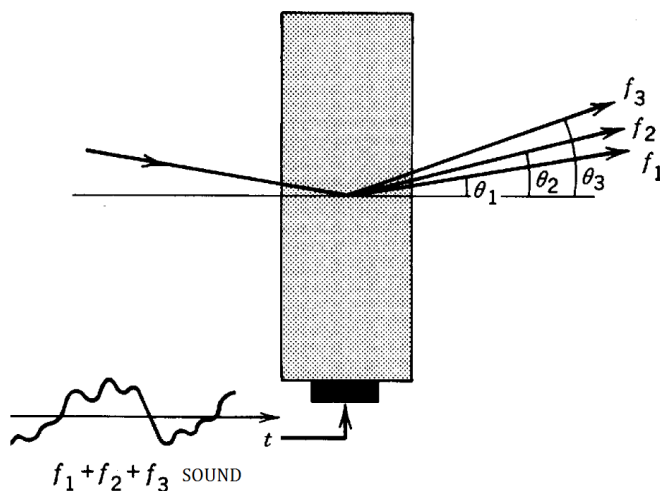

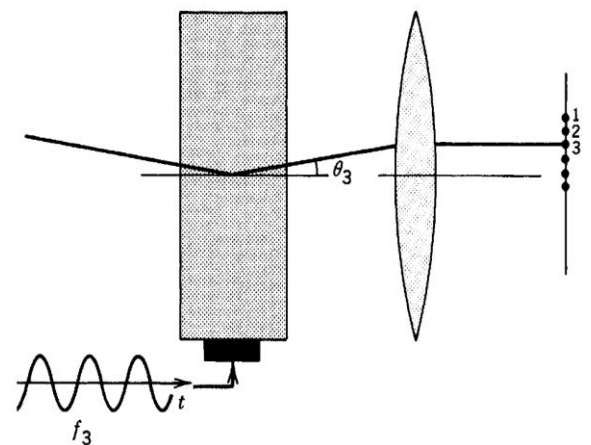Fig. The acousto-optic cell serves as an acoustic spectrum analyzer

Fig. Routing an optical beam to one of N directions

Optical Router

An acousto-optic cell can be used as an interconnection optical switch that routes information carried by one or more optical beams to one or more selected directions.

An acousto-optic cell in which the frequency of the acoustic wave is one of N possible values $f_1, f_2, \dots f_N$ deflects an incident optical beam to one of N corresponding directions $\theta_1, \theta_2, \dots \theta_N$. By applying an acoustic wave of frequency f_i, the optical beam is deflected by an angle θ_i and routed to point i.
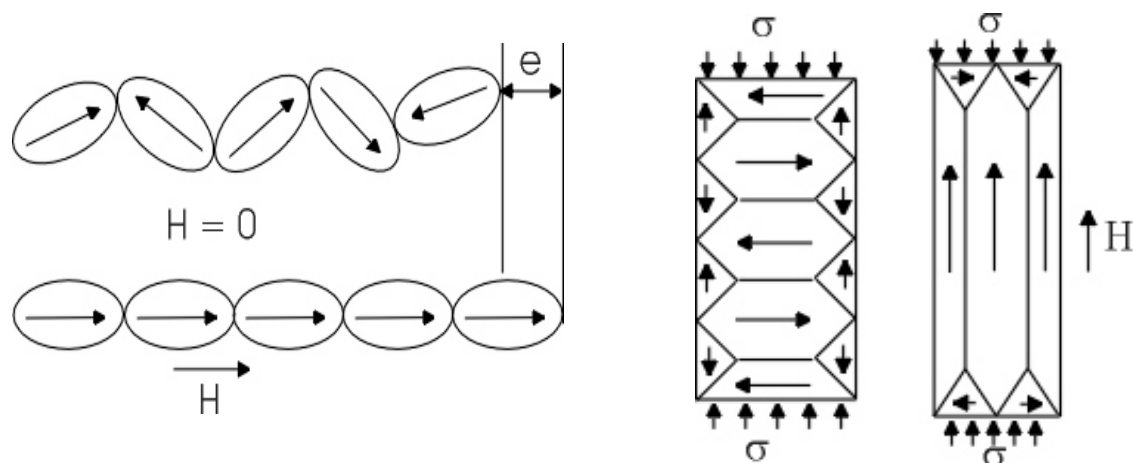
Magnetostriction

Magnetostriction is a property of materials that causes them to change their shape or dimensions when it is subjected to a magnetic field. Most ferromagnetic materials such as iron, nickel, and cobalt exhibit some measurable magnetostriction. This effect was first identified by James Joule (1842) when observing a sample of iron.

This effect causes energy losses due to frictional heating in susceptible ferromagnetic cores. The effect is also responsible for the high pitch buzzing sound that can be heard near transformers carrying alternating current, near fluorescent light ballast.

Principle

The magnetostrictive effect is due to the interaction of an external magnetic field with the internal domains. Internally, ferromagnetic materials have a structure that is divided into domains, each of which is a region of uniform magnetic polarization. When a material is not magnetized, the internal magnetic domains are randomly arranged. When the material is magnetized, the domains are oriented with their axes approximately parallel to one another. This orientation and reorientation causes micro strain in the dimension of the material. The following figures show the change in dimension (e) due to the field H.
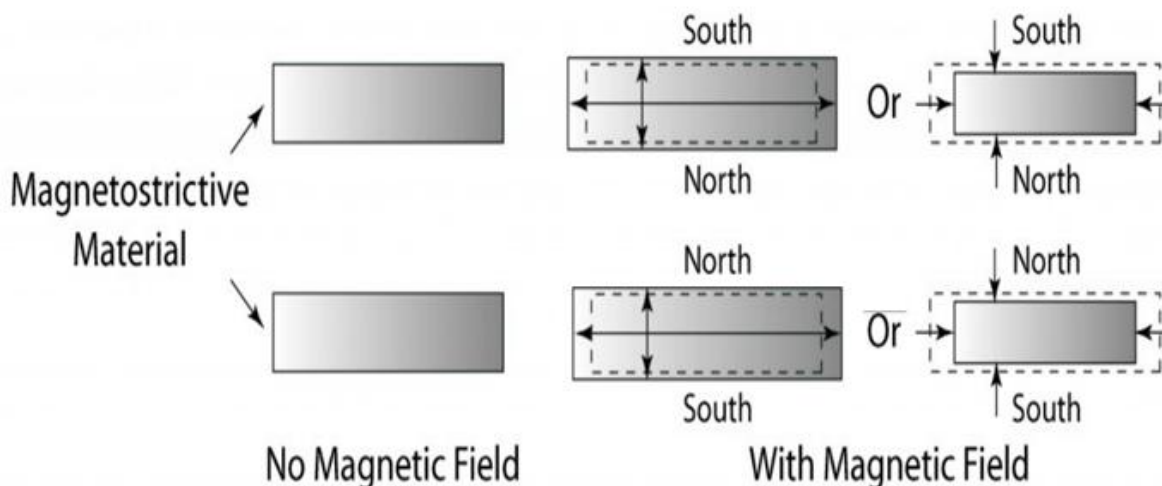
Fig. Volume change of MS material.

The volume change can be positive or negative depending on the material. The effect is the same regardless of the polarity of the magnetic field.

The mechanism of Magnetostriction at an atomic level is relatively complex but on a macroscopic level it may be segregated into two distinct processes.

1) The first process is dominated by the **migration of domain walls** within the material in response to external magnetic fields.
2) Second, is the **rotation of the domains.**

These two mechanisms allow the material to change the domain orientation which in turn causes a dimensional change.

There are two kinds of Magnetostriction.

(i)   **Volume (isotropic) Magnetostriction**.

(ii)   **Joule (anisotropic) Magnetostriction**.

In Volume magnetostriction the magnetic fields leads to an isotropic change of the shape in all dimensions. The volume change is described by the magnetostriction factor
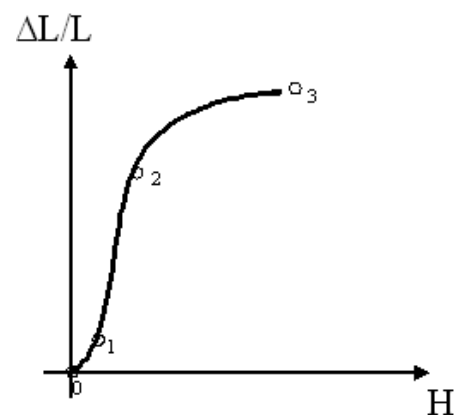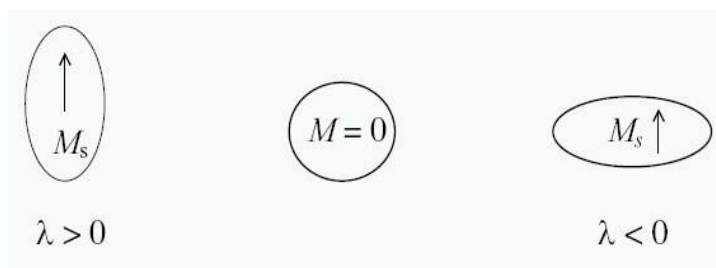
$$\omega = \Delta V/V \,.$$

Joule magnetostriction leads to a change of shape in the direction of the magnetic field, while maintaining a constant volume. A magnetostriction factor λ (strain) can be defined:

$$\lambda = \Delta L / L$$

In general Volume magnetostriction is far smaller than Joule magnetostriction (λ>>ω).

The magnetostriction coefficient λ can be positive or negative. For a positive λ the material expands in the direction of the applied magnetic field, while for a negative λ it shrinks.

Magnetostrictive coefficient L is defined as the fractional change in length as the magnetization increases from zero to its saturation value. The coefficient L may be positive or negative, and is usually on the order of 10^{-5}.

Materials

At room temperature the highest magnetostriction obtained in pure cobalt (Co) is very small and is about 60 microstrain. But by alloying elements it is possible to achieve very high magnetostriction under relatively small fields.

The highest known magnetostriction materials are those Iron alloys containing the rare earth elements Dysprosium (Dy) or Terbium (Tb) : DyFe2, and TbFe2. However, these materials have tremendous magnetic anisotropy which needs a very large magnetic field to drive the magnetostriction.

Terfenol-D (Alloy containing Fe, Dy and Tb: $Tb_xDy_{1-x}Fe_2$), strains to about 2000 microstrain in a field of 2 kOe at room temperatures.

For typical transducer and actuator applications, Terfenol-D is the most commonly used engineering magnetostrictive material.

Inverse Magnetostrictive effect: Villari effect

The reciprocal effect, the change of the susceptibility (change in magnetic property) of a material when subjected to a mechanical stress is known as Villari effect.
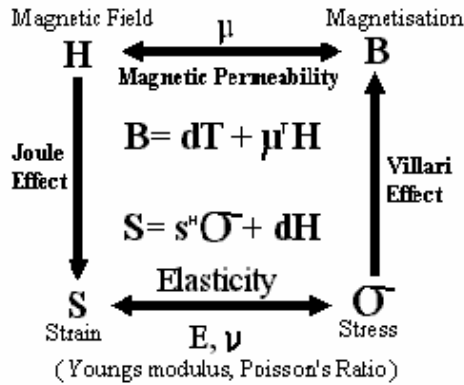
The Wiedemann effect

The twisting of a ferromagnetic rod through which an electric current is flowing when the rod is placed in a longitudinal magnetic field. It is one of the manifestations of magnetostriction in a field formed by the combination of a longitudinal magnetic field and a circular magnetic field that is created by an electric current.

If the electric current (or the magnetic field) is alternating, the rod will begin torsional oscillation.

Applications

Magnetostrictive materials transduce or convert magnetic energy to mechanical energy and vice versa. This ability to convert an amount of energy from one form into another allows the use of magnetostrictive materials in actuator and sensor applications. Following Fig. shows various physical effects which are related to the magnetostrictive effect.
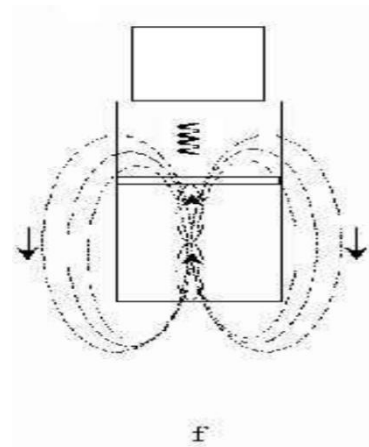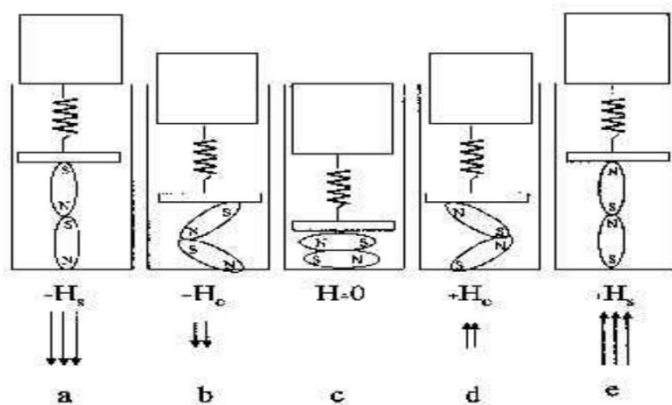
Magnetostriction can be used to create **vibrators** - some lever action is used in conjunction with the magnetic deformation to increase the resultant amplitude of vibration.

Used to produce ultrasonic vibrations either as a sound source or as ultrasonic waves in liquids which can act as a cleaning mechanism in ultrasonic cleaning devices.

Sensors and Actuators

The change in flux density can be detected by a pickup coil and is proportional to the level of the applied stress. Thus the Villari effect is used in sensor applications.

- Stress sensor used in applications such as monitoring stresses in bridge cables and nuclear power plant structures.
- Used in automobile suspension systems

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.

The static magnetostrain of the materials permits building linear actuators offering large displacements (in μm) and large forces (500-5000N) at low voltages. They can also be used as components of more complex actuators such as inchworm motors.
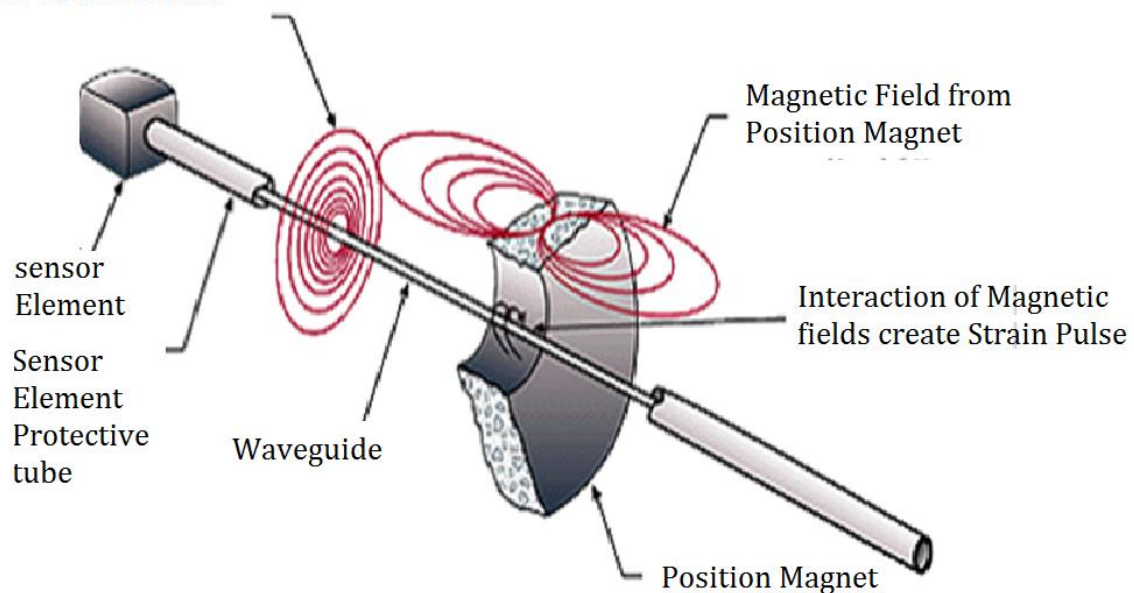
Terfenol-D based actuators are available giving displacements up to 250μm and forces up to 2,200N, and operating at frequencies up to 2500 Hz. The operational temperature of this actuator is typically in the range from -20°C up to +100°C. In addition ultrasonic actuators for higher frequencies are available.

Terfenol-D is also used to build compact linear motors. The central feature of this linear motor is a rod of Terfenol-D surrounded by an electric coil which, when energized, causes the rod to elongate. The actuator is mounted between two clamps. By operating the actuator and the clamps in an appropriate sequence the rod of smart material moves forwards or backwards.

Position Sensors

The interaction of a current pulse with the position magnet generates a strain pulse that travels down the waveguide and is detected by the pickup element.

Interrogation pulse forms magnetic field along entire waveguide for 1 to 3 microseconds

Magnetic Field from Position Magnet

sensor Element

Sensor Element Protective tube

Interaction of Magnetic fields create Strain Pulse

Waveguide

Position Magnet

The axial magnetic field is provided by a position magnet. The position magnet is attached to the machine tool, hydraulic cylinder, or whatever is being measured. The waveguide wire is enclosed within a protective cover and is attached to the stationary part of the machine, hydraulic cylinder, etc.

The location of the position magnet is determined by first applying a current pulse to the waveguide. At the same time, a timer is started. The current pulse causes a sonic wave to be generated at the location of the position magnet Wiedemann effect. The sonic wave travels along the waveguide until it is detected by the pickup. This stops the timer. The elapsed time indicated by the timer then represents the distance between the position magnet and the pickup.

The sonic wave also travels in the direction away from the pickup. In order to avoid an interfering signal from waves travelling in this direction, their energy is absorbed by a damping device (called the damp).

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.

The pickup makes use of the Villari effect. A small piece of magnetostrictive material, called the tape, is welded to the waveguide near one end of the waveguide. This tape passes through a coil and is magnetized by a small permanent magnet called the bias magnet. When a sonic wave propagates down the waveguide and then down the tape, the stress induced by the wave causes a wave of changed permeability (Villari effect) in the tape. This in turn causes a change in the tape magnetic flux density, and thus a voltage output pulse is produced from the coil (Faraday effect). The voltage pulse is detected by the electronic circuitry and conditioned into the desired output.

Electrostriction

When an electric field is applied to an electrical insulator, that insulator might deform or change shape in some way. This property of the electrical insulator is called electrostriction. Specifically, electrostriction is the coupling between strain and electric field, or between strain and polarization; this coupling takes place only when an electric field is applied to the material.

The Electrostrictive behavior (or electrostriction) is a phenomenon in which the dimension of material object changes in response to an applied electric field. It is due to the energy increase associated with the polarization induced by the external electric field in the material. The polarization may be due to atoms becoming egg-shaped rather than spheres, bonds between ions changing in length, or orientation of the permanent electric dipoles in the material.

An electrostrictive material is centrosymmetrical in crystal structure, in contrast to piezoelectric or ferroelectric materials, which are non centrosymmetrical. The dimensional changes can be in all directions, in

contrast to the directional dimensional change in piezoelectricity or ferroelectricity. Also in contrast to piezoelectric or ferroelectric behavior, no voltage of field is created by electrostriction and an applied stress does not cause an electric field **(i.e., no converse effect)**. Thus, electrostriction can be **used for actuation, but not sensing**.

Electrostriction is a second-order effect (quadratic, nonlinear), i.e., the strain is proportional to the square of the electric field, or

$$S = ME^2$$

where **S** is the strain, E is the electric field and **M** is the electrostrictive coefficient.

(In contrast, piezoelectricity or ferroelectricity is a first order effect- Linear). The strain due to electrostriction is small compared to that due to piezoelectricity or ferroelectricity. For example, a field of 10^4 V/m produces 23 nm per meter in quartz (piezoelectric effect), but electrostrictive glass produces only 1 nm per meter. However, electrostrictive materials exhibit essentially no hysteresis upon cycling the electric field.

Materials

Although all dielectrics exhibit some electrostriction, certain engineered ceramics, known as relaxor ferroelectrics, have extraordinarily high electrostrictive constants.

The most important electrostrictive materials are ceramics based on $Pb(Mg_{1/3}Nb_{2/3})O_3$, i.e., **PMN** or Lead Magnesium Niobate, which exhibits strains as high as 0.1% (i.e., 10 μm per cm) at moderate fields ($\leq 10^6$ V/m). The phenomenon is called giant electrostriction. These materials are also relaxor ferroelectrics. (i.e.) they are ferroelectrics below the Curie temperature, but electrostrictive above the Curie temperature. Also Lead Magnesium Niobate- Lead Titanate (PMN-PT) and Lead Lanthanum Zirconate Titanate (PLZT) are some other useful materials.

Applications

Electrostrictive materials can be used to construct actuators, which can be used in control circuits where a small amount of force is required to turn on the circuit. These materials also react to electric fields very quickly, which makes these materials suitable for high-speed control circuits.

An electrostrictive actuator is often made of electrostrictive polymer materials. Each polymer exhibits electrostriction differently. For example, silicone polymers might exhibit high strain performance when compared with other electrostrictive polymers.

A polymer that has high strain performance is better suited to an environment in which mechanical strain might be an issue than a polymer with low strain performance. Other electrostrictive polymers — such as polyurethane — are capable of producing more force under the same electrical conditions than other polymers. Such a polymer allows more of the input electrical energy to be converted into mechanical work.

Electrostrictive materials are often used in mechanical applications such as microangle adjusting devices, oil pressure servovalves and field-tunable piezoelectric transducers.

Advantages

Electrostriction occurs in certain materials that are poor conductors of electrical current. When a voltage differential is applied to electrostrictive materials, these materials undergo a temporary change in shape. Unlike magnetostriction, which is linear in nature, electrostriction is quadratic in nature. This nonlinear property of electrostriction allows the

electrostrictive materials to exhibit a reproducible strain response to electric fields without the losses to hysteresis — and the resulting waste heat — that magnetic materials produce.

Electrostrictive materials have a high response speed — often less than 10 milliseconds — when an electric field is applied to the material. Quick-response electrostrictive materials can be used in mechanical and electromechanical devices that require ultrafast circuit response times, such as precision instruments.

Piezo Electric Effect

The piezoelectric effect describes the relation between a mechanical stress and an electrical voltage in solids. Piezoelectricity is the ability of some materials such as crystals and certain ceramics, to generate an electric potential in response to applied mechanical stress. If the piezo crystals are not short-circuited, the applied stress induces a voltage across the material. It is simply, the appearance of an electric potential across certain faces of a crystal when it is subjected to mechanical pressure.

A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied (the substance is squeezed or stretched) – used in sensor app.

Converse PE effect

A mechanical deformation (the substance shrinks or expands) is produced when an electric field is applied – (useful in actuator application). The piezoelectric effect is a linear phenomenon where deformation is proportional to an electric field

$S = pE$ and

$D = dT$

Where

S is the mechanical strain

p is the piezoelectric coefficient

E is the electric filed

D is the displancement (or charge density) linearly

T is the stress

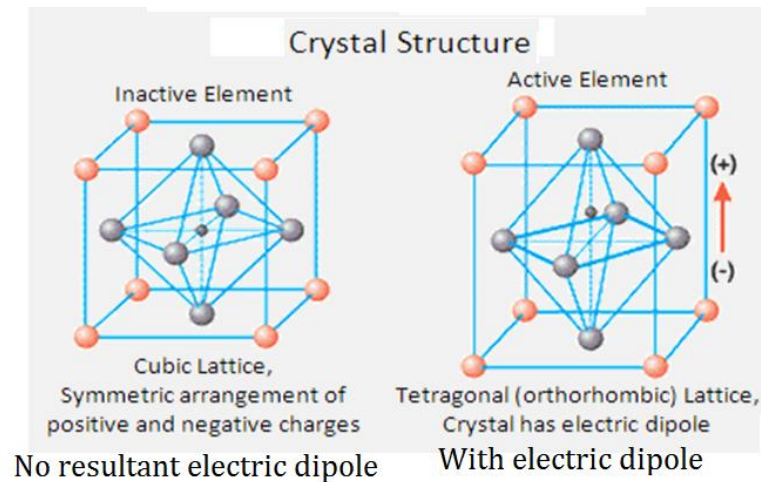These equations are known as direct and converse piezoelectric effect respectively.

Piezoeletric materials

Piezoelectric materials can be divided in 3 main groups: crystals , ceramics and Polymers

- Crystals
    - Quartz SiO_2
    - Gallium orthophosphate $GaPO_4$
- Ceramics
    - Barium Titanate $BaTiO_3$
    - Lead Zirconate Titanate PZT
- Polymers
    - Polyvinylidene DiFluoride PVDF

Theory of Piezoelectric Effect

In order for a crystal to show the piezoelectric property it must have a polar axis. In order to have a polar axis the crystal must belong to a non-centrosymmetric crystal class (no center of symmetry)

When a crystal is subject to stress it may deform elastically. Ions will move. If opposite charges move away from or toward each other, a current is developed. If both charges move in the same direction no net current will develop. The current lasts only as long as the ions are in motion.
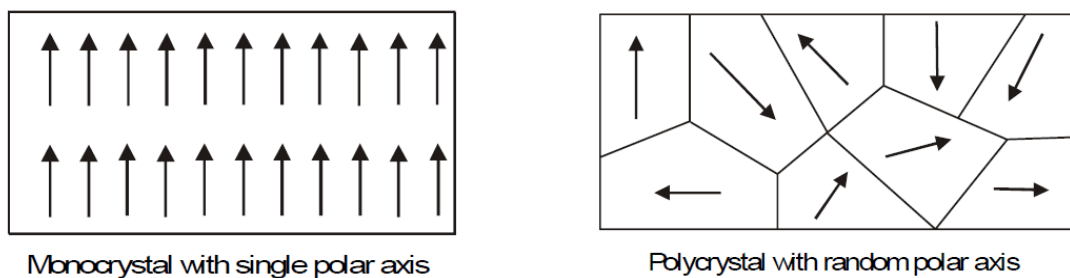

Figure 1: Mono vs. Poly Crystals

Consider the individual molecules that make up the crystal. Each molecule has a polarization, one end is more negatively charged and the other end is positively charged, and is called a dipole. - This is a result of the atoms that make up the molecule and the way the molecules are shaped. The polar axis is an imaginary line that runs through the center of both charges on the molecule.

In a monocrystal the polar axes of all of the dipoles lie in one direction. The crystal is said to be symmetrical because if the crystal is cut at any point, the resultant polar axes of the two pieces would lie in the same direction as the original.

In a polycrystal, there are different regions within the material that have a different polar axis. It is asymmetrical because there is no point at which the crystal could be cut that would leave the two remaining pieces with the same resultant polar axis.
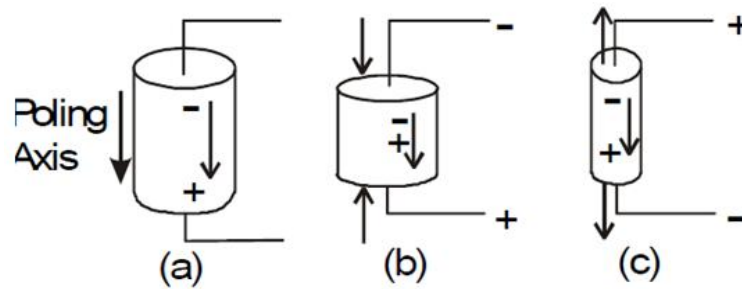

(a) (b) (c)

Fig a. shows the piezoelectric material without a stress or charge.

Fig b. If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes .

Fig c. If stretched, a voltage of opposite polarity will appear.

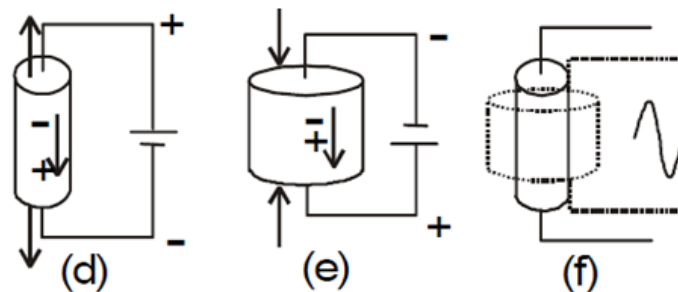Conversely, if a voltage is applied the material will deform

(d) (e) (f)

Fig d. A voltage with the opposite polarity as the poling voltage will cause the material to expand.

Fig. e. A voltage with the same polarity will cause the material to compress.

Fig. f. If an AC signal is applied then the material will vibrate at the same frequency as the signal

Applications

- Generation of high voltage power sources – Energy harvesting
- Electronic frequency generation,
- Microbalances, and
- Ultra fine focusing of optical assemblies.
- Sensors

    Detection and Generation of Sonar Waves
- Actuators
    - Piezoelectric Motors
    - Loudspeaker
    - AFM and STM
    - Inkjet Printers

- The piezoelectric crystal bends in different ways at different frequencies. This bending is called the vibration mode. The crystal can be made into various shapes to achieve different vibration modes like benders. To realize small, cost effective, and high performance products, several modes have been developed to operate over several frequency ranges (KHz- MHz) .

    The ceramic piezoelectric materials are useful to build ceramic resonators, ceramic bandpass filters, ceramic discriminators, ceramic traps, SAW filters, and buzzers.

Piezoelectric Actuator Types

Piezoelectric effect is the simple way of producing displacement useful in various actuator and motor concepts.

Advantages of PE actuators

Simple mechanical structure

A short response time,

An ability to create high forces,

A high efficiency and a high mechanical durability.

Drawbacks

PE actuators have small strains: only 0.1- 0.2%

High supply voltage needed – typically between 60 and 1000 Volts

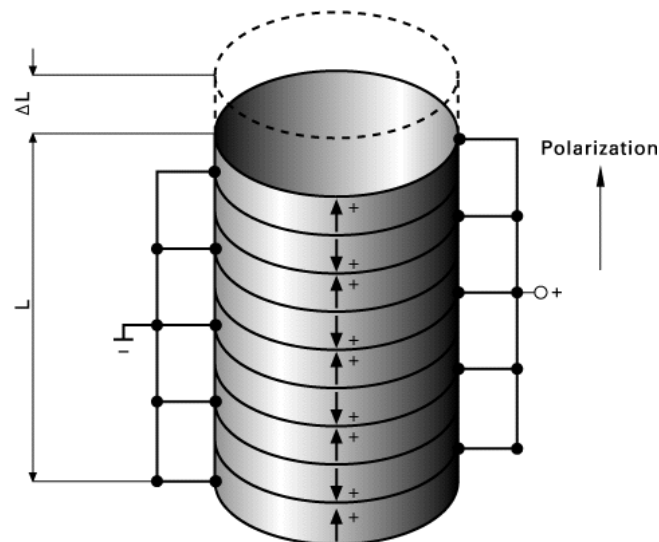Hysteresis introduces a typical drift of a piezoelectric actuator.

Types

The three basic types of piezoelectric actuators are

Stacks, Benders and Linear motors.

Piezoelectric Stack Actuators

The easiest way to produce a linear motion by the piezoelectric effect is to use a stack actuator, which is a multilayer construction: each stack is composed of several piezoelectric layers, as depicted in Figure . The required dimensions of the stack can be easily determined from the requirements of the application. The height is determined in respect to the desired movement and the cross–sectional area in respect to the desired force. The stack having dimensions of 5x5x18 mm^3 provides a movement of 14.5 μm and a blocked force of 840 N.

Piezoelectric Benders

Piezoelectric bending actuators (or piezoelectric cantilevers, or piezoelectric bimorphs) bear a close resemblance to bimetallic benders. The application of an electric field across the two layers of the bender result in one layer to expand, while the other contracts. The net result is a curvature much greater than the length or thickness deformation of the individual layers. With a piezoelectric bender, relatively high displacements can be achieved, but at the cost of force and speed.
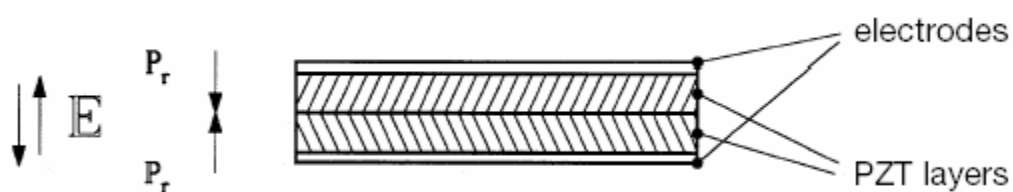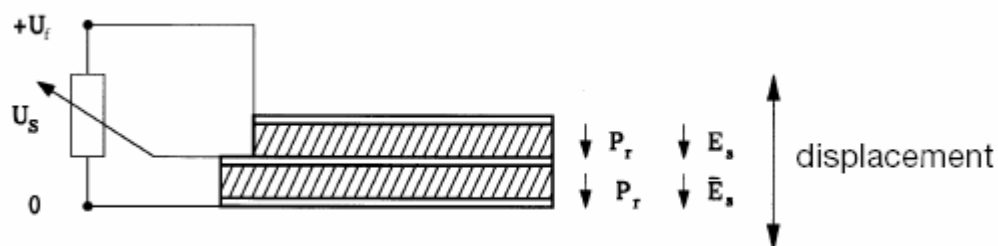

Fig.1. A serial bender arrangement with an anti-parallel polarization

There are some benders that have only one piezoelectric layer on top of a metal layer (unimorph), but generally there are two piezoelectric layers and no metal (bimorph). This way, the displacement is doubled in comparison to a single layer version. If the number of piezoelectric layers exceeds two, the bender is referred as a multilayer. With thinner piezo layers, a smaller voltage is required to produce the same electric field strength, and therefore, the benefit of the multilayer benders is their lower

operating voltage. Bimorph and multilayer benders can be built into one of the two types: a serial or parallel bender. In a serial bender, there are two piezoelectric layers with an anti-parallel polarization connected to each other, and two surface electrodes, as shown in Figure 1. In this arrangement, one of the electrodes is connected to the ground and the other to the output of a bipolar amplifier.

Parallel benders

Parallel benders can be distinguished from serial benders by their three electrodes. In between the two parallel-polarized piezoelectric layers is a middle electrode, to which the actual control signal is supplied. The two surface electrodes are connected to the ground and to a fixed voltage. The control voltage is applied to the middle electrode, and it varies between zero and a fixed voltage. The parallel bender can also be connected in such a way that the two surface electrodes are connected to the ground and a bipolar signal is applied to the middle electrode.

Piezoelectric Resonators/Filters

Resonators are used to either generate waves of specific frequencies or to select specific frequencies from a signal. Musical instruments use acoustic resonators that produce sound waves of specific tones.

When a piezoelectric body vibrates at its resonant frequency it absorbs considerably more energy than at other frequencies resulting in a dramatic decrease in the impedance. This phenomenon enables piezoelectric
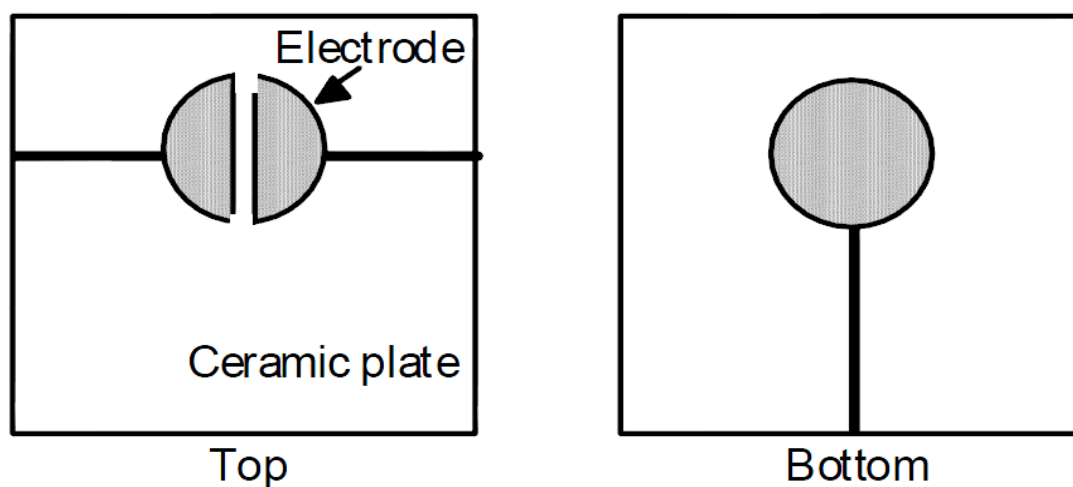
materials to be used as a wave filter. A filter is required to pass a certain selected frequency band or to block a given band. The band width of a filter fabricated from a piezoelectric material is determined by the square of the coupling coefficient k, that is, it is nearly proportional to k^2.

Quartz crystals with a very low k value of about 0.1 can pass very narrow frequency bands of approximately 1% of the center resonance frequency. On the other hand, PZT ceramics with a planar coupling coefficient of about 0.5 can easily pass a band of 10% of the center resonance frequency. The sharpness of the passband is dependent on the mechanical quality factor Qm(Mechanical Quality factor) of the materials. Quartz also has a very high Qm of about 106 which results in a sharp cut-off to the passband and a well-defined oscillation frequency.

A simple resonator is a thin disc type, electroded on its plane faces and vibrating radially, for filter applications with a center frequency ranging from 200 kHz to 1 MHz and with a bandwidth of several percent of the center frequency.

For a frequency of 455 kHz the disc diameter needs to be about 5.6 mm. However, if the required frequency is higher than 10 MHz, other modes of vibration such as the thickness extensional mode are exploited, because of its smaller size. The trapped-energy type filters made from PZT ceramics have been widely used in the intermediate frequency range for applications such as the 10.7 MHz FM radio receiver and transmitter. When the trapped-energy phenomena are utilized, the overtone frequencies are suppressed. The plate is partly covered with electrodes of a specific area and thickness. The fundamental frequency of the thickness mode of the ceramic beneath the electrode is less than that of the unelectroded portion, because of the extra inertia of the electrode mass. The lower-frequency wave of the electroded region cannot propagate into the unelectroded region. The

higher-frequency overtones, however, can propagate away into the unelectroded region. This is called the *trapped-energy principle*. Following figure shows a schematic drawing of a *trapped-energy filter*. In this structure the top electrode is split so that coupling between the two parts will only be efficient at resonance. More stable filters suitable for telecommunication systems have been made from single crystals such as quartz or LiTaO$_3$.
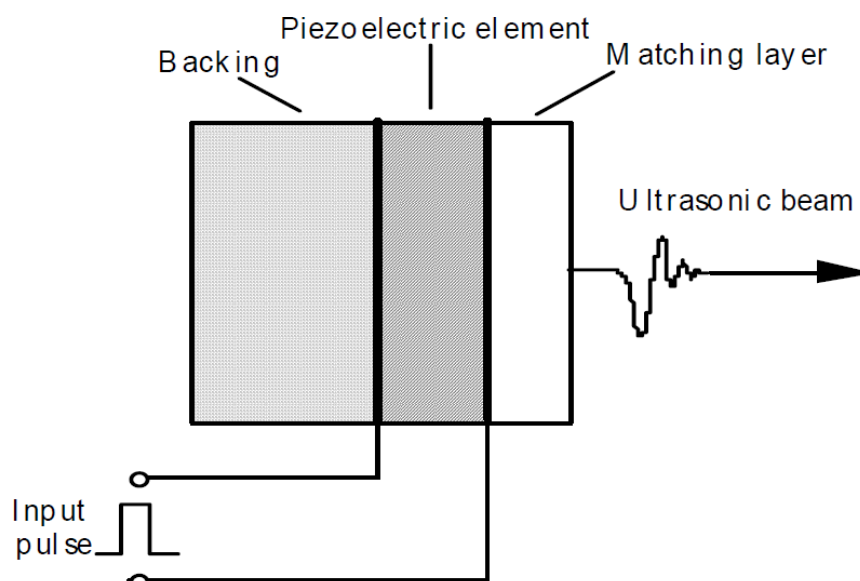

Schematic drawing of a trapped-energy filter

Piezo Ultrasonic Transducers

Ultrasonic waves are now used in various fields. The sound source is made from piezoelectric ceramics as well as magnetostrictive materials. Piezoceramics are generally superior in efficiency and in size to magnetostrictive materials. In particular, hard piezoelectric materials with a high QM are preferable. A liquid medium is usually used for sound energy transfer. Ultrasonic washers, ultrasonic microphones for short-distance remote control and underwater detection, such as sonar and fish finding, and nondestructive testing are typical applications.

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.

Ultrasonic scanning detectors are useful in medical electronics for clinical applications ranging from diagnosis to therapy and surgery. One of the most important applications is based on ultrasonic echo field. Ultrasonic transducers convert electrical energy into mechanical form when generating an acoustic pulse and convert mechanical energy into an electrical signal when detecting its echo. The transmitted waves propagate into a body and echoes are generated which travel back to be received by the same transducer. These echoes vary in intensity according to the type of tissue or body structure, thereby creating images. An ultrasonic image represents the mechanical properties of the tissue, such as density and elasticity. We can recognize anatomical structures in an ultrasonic image since the organ boundaries and fluid-to-tissue interfaces are easily discerned. The ultrasonic imaging process can also be done in real time. This means we can follow rapidly moving structures such as the heart without motion distortion. In addition, ultrasound is one of the safest diagnostic imaging techniques. It does not use ionizing radiation like x-rays and thus is routinely used for fetal and obstetrical imaging. Useful areas for ultrasonic imaging include cardiac structures, the vascular systems, the fetus and abdominal organs such as liver and kidney.

Class Notes prepared by K.Elampari, Associate. Prof. of Physics, S.T.Hindu College, Nagercoil.
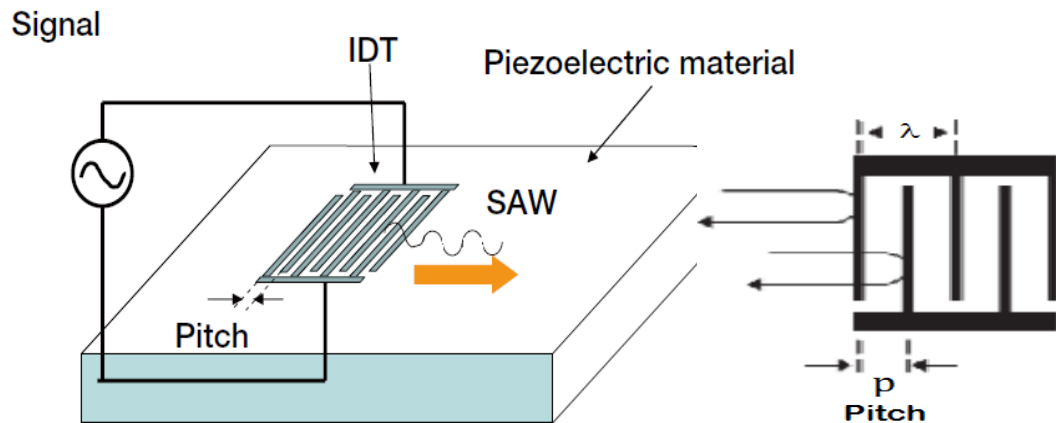
Surface Acoustic Wave Devices (SAW Devices)

SAW

A surface acoustic wave is an acoustic wave (mechanical wave) travelling along the surface of a material exhibiting elasticity, with an amplitude that typically decays exponentially with depth into the substrate. Ripple in water, waves travel along the surface of earth due to quake are all surface waves. Surface acoustic waves were discovered in 1885 by Lord Rayleigh, and are often named after him: Rayleigh waves.

SAW devices have found numerous different applications in the field of communications and signal processing. SAW devices were initially used in radar, oscillators, and band pass filters for radio, TV and cellular telephones. In the last decade considerable work has been done in the development of SAW sensors of different types of high quality. Today SAW devices are used as temperature, pressure and stress sensors as well as chemical and biosensors.

Principle of operation and Structure

The operation of the SAW device is based on acoustic wave propagation near the surface of a piezoelectric solid. Piezoelectric materials are used for as electrical signals need to be transformed into the surface acoustic wave and vice versa. This implies that the wave can be trapped or otherwise modified while propagating. The displacements decay exponentially away from the surface, so that the most of the wave energy (usually more than 95%) is confined within a depth equal to one wavelength.

Electronic SAW devices normally use one or more Inter Digital Transducers (IDTs). The IDT consists of a series of interleaved electrodes made of a metal film deposited on a piezoelectric substrate. The frequency of the generated waves can be changed by changing the pitch (inter electrode gap) of the input IDT electrode. Similarly, when SAW arrive at the output IDT, if the pitch of the IDT and SAW match, an electrical signal is generated between the IDT electrodes. The minimal electrode width which is obtained in industry is around 0.3µm, which determines the highest frequency of around 3 GHz.
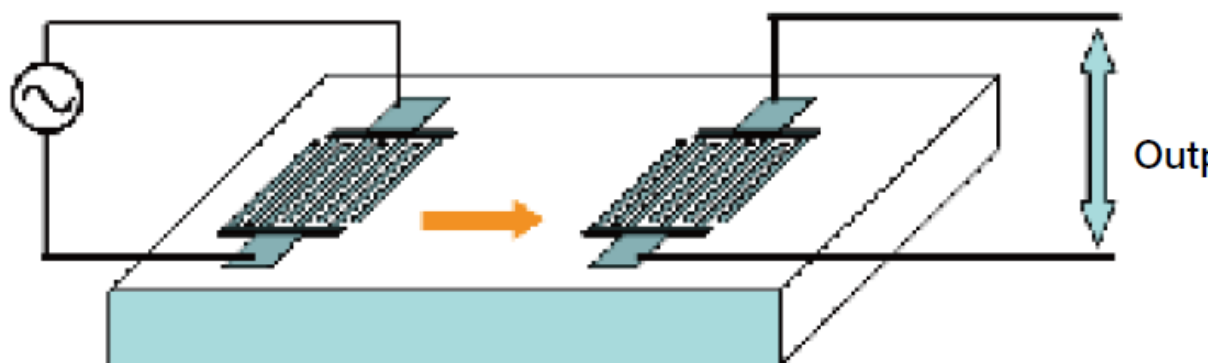
The input IDT is used to launch acoustic waves and the output IDT receives the electrical signals by the piezoelectric effect. The acoustic wave velocity depends on some extent on the type of piezoelectric substrate or kind of wave utilized. Even in the same substrate, the propagation characteristics (such as velocity, electromechanical coupling coefficient, temperature coefficient, propagation delay) of the SAW vary with the cutting angle or propagation direction.

The input and output transducers may be equal or different. It depends upon the function which the SAW device has to perform. Usually they differ in electrode overlaps, number and sometimes positioning.

Working Principle

A sinusoidal voltage *v* of frequency *f* applied to the input IDT forms an electric field which, through the piezoelectric effect causes a strain pattern of periodicity 2p, where p denotes the distance between the centres of the electrodes. If the frequency *f* is such that 2p is close to the surface wave wavelength, a surface wave will be launched in two opposite directions away from the transducer. The surface wave causes the corresponding electric field in the second transducer and correspondingly the voltage at the impedance *ZL*.
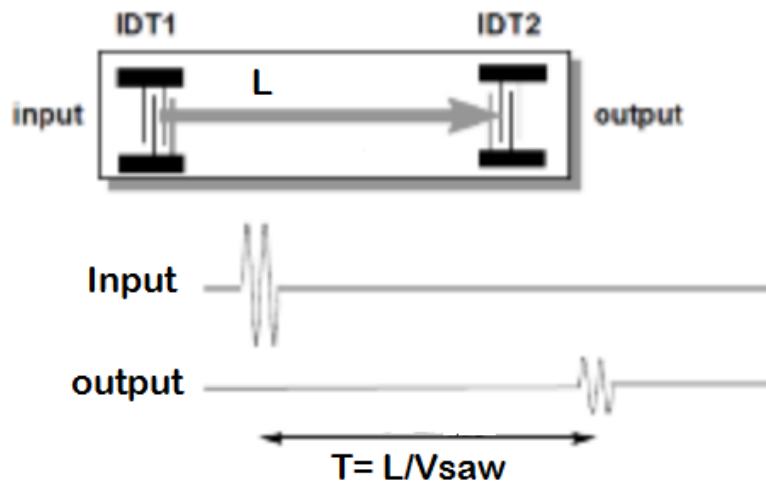

Materials

The commonly used substrate crystals are: quartz, lithium niobate, lithium tantalate, zincoxide and bismutgermanium oxide. They have different piezoelectric coupling coefficients and temperature sensitivities. ST quartz is used for most temperature stable devices.

Applications

Delay Lines

The velocity of the acoustic wave (V_{saw}) is a function of the substrate material and is in the range of 1500m/s to 4800m/s, which is 10^5 times lower than the electromagnetic wave velocity. This enables the construction of a small size delay line of a considerable delay (few Km).

Delay lines are very useful in producing echo effect, radar communications etc.,

Filter

The magnitude of the output signal is the function of the ratio of the signal wavelength and the distance 2p. If the distance 2p is equal to the wavelength, the magnitude of the output voltage is maximal. The corresponding frequency is then called central or synchronous frequency of the device. The magnitude of the output voltage decays as the frequency shifts from the central frequency. It means that basically a SAW device is a transversal band pass filter. The phase characteristic is a function of the distances between the electrodes and the amplitude characteristic is a function of the electrodes number and lengths. If the electrodes are uniformly spaced, the phase characteristic is a linear function of frequency, e.g. the delay is constant in the appropriate frequency range. For an elemental SAW bandpass filter, the spacing between IDT fingers of alternating polarity is $\lambda/2$ at filter centre frequency $f = v/\lambda$.
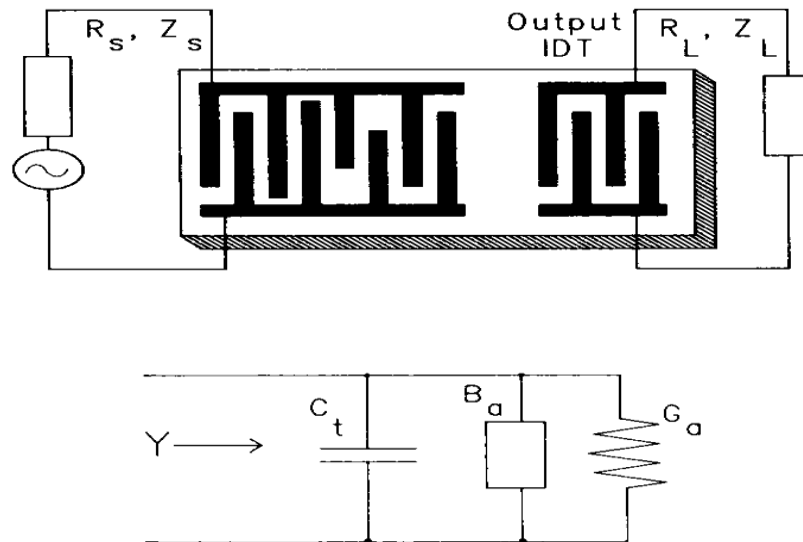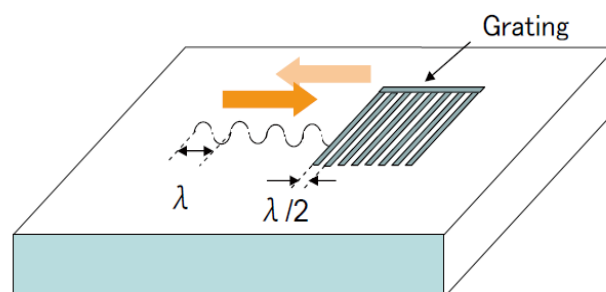
Fig. SAW filter and Equivalent circuit

Transversal filters have been commonly used as IF filters for TVs or filters in tuners for satellite broadcasting. They can be designed flexibly in frequency characteristics with some methods including varying the electrode finger overlap in the IDT.
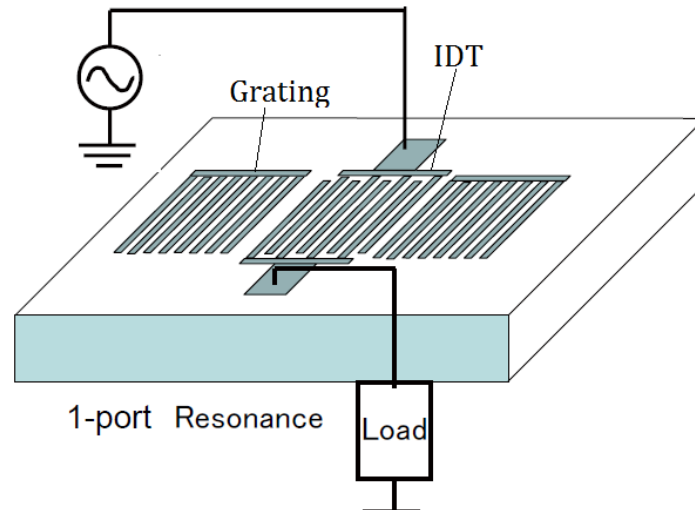
Resonators

IDTs are only used as converters of electrical to mechanical signals and vice versa. Grating elements are used to get the reflections of the wave. Resonance can be generated by placing a grating at the propagation direction of a SAW excited by IDT. To reflect a surface acoustic wave with a wavelengh of λ, the pitch of the grating λ/2 can be used.

A SAW resonator is a device that applies this phenomenon. A device with one IDT is called a one-port resonator, and a device with two IDTs for

input and output terminals between gratings is called a two-port resonator. The latter can be used as a filter for its propagation characteristics between IDTs.

When the SAW resonator is used instead of the resistor and capacitor, the frequency is stabilized to the desired value. The signal frequency and the harmonics are optimized by fine tuning.

SAW Sensors

SAW devices are very sensitive and they are affected by stress, pressure, proximity of chemical substances, temperature, mass change etc. They are used as Sensors in applications include all areas of sensing (such as chemical, optical, thermal, pressure, acceleration, torque and biological).

SAW sensors are a class of micro electro mechanical systems (MEMS) which rely on the modulation of surface acoustic waves to sense a physical phenomenon. The mechanical wave can be easily influenced by physical phenomena unlike an electrical signal. The device then transduces this wave back into an electrical signal. Changes in amplitude, phase, frequency, or time-delay between the input and output electrical signals can be used to measure the presence of the desired phenomenon.

Mass

The accumulation of mass on the surface of an acoustic wave sensor will affect the surface acoustic wave as it travels across the delay line. The velocity v of a wave travelling through a solid is given by the expression

$$V \; \alpha \sqrt{E/\rho}$$ where E is Young's modulus and ρ is density of the material.

Therefore, the wave velocity will decrease with added mass. This change can be measured by a change in time-delay or phase-shift between input and output signals.

Chemical Vapours

Chemical vapour sensors use the application of a thin film polymer across the delay line which selectively absorbs the gas or gases of interest. An array of such sensors with different polymeric coatings can be used to sense a large range of gases on a single sensor with resolution down to parts per trillion.

Biological Matter

A biologically-active layer can be placed between the interdigitated electrodes which contains immobilized antibodies. If the corresponding antigen is present in a sample, the antigen will bind to the antibodies, causing a mass-loading on the device. These sensors can be used to detect bacteria and viruses in samples, as well as to quantify the presence of certain mRNA and proteins.

Humidity

Surface acoustic wave humidity sensors require a thermoelectric cooler in addition to a surface acoustic wave device. The thermoelectric cooler is placed below the surface acoustic wave device. Both are housed in a cavity with an inlet and outlet for gases. By cooling the device, water vapour will tend to condense on the surface of the device, causing a mass-loading.

Ultraviolet Radiation

Surface acoustic wave devices can be made sensitive to optical wavelengths through the phenomena known as acoustic charge transport (ACT), which involves the interaction between a surface acoustic wave and photo generated charge carriers from a photo conducting layer. Ultraviolet radiation sensors employ the use of a thin film layer of zinc oxide across the delay line. When exposed to ultraviolet radiation, zinc oxide generates charge carriers which interact with the electric fields produced in the piezoelectric substrate by the travelling surface acoustic wave. This interaction decreases the velocity and the amplitude of the signal.

Magnetic Fields

Ferromagnetic materials, such as iron, nickel, and cobalt, exhibit a characteristic called magnetostriction, where the Young's modulus of the material is dependent on magnetic field strength. If a constant stress is maintained on such a material, the strain will change with a changing Young's modulus. If such a material is deposited in the delay line of a surface acoustic wave sensor, a change in length of the deposited film will stress the underlying substrate. This stress will result in a strain on the surface of the substrate, affecting the phase velocity, phase-shift, and time-delay of the signal.

Viscosity

Surface acoustic wave devices can be used to measure changes in viscosity of a liquid placed upon it. As the liquid becomes more viscous the resonant frequency of the device will change in correspondence. A network analyser is used to view the resonant frequency.

Advantages of SAW devices

- versatile response function obtainable with little or no trimming necessary,

- design - straightforward fabrication compatible with IC technology,

- good repeatability,

- small size and weight,

- passive (except for programmable filters),

- good dynamic range (80 dB),

- good temperature stability and radiation resistance.

Because of all these qualities SAW devices became vital parts of modern communication systems in the VHF and UHF range.
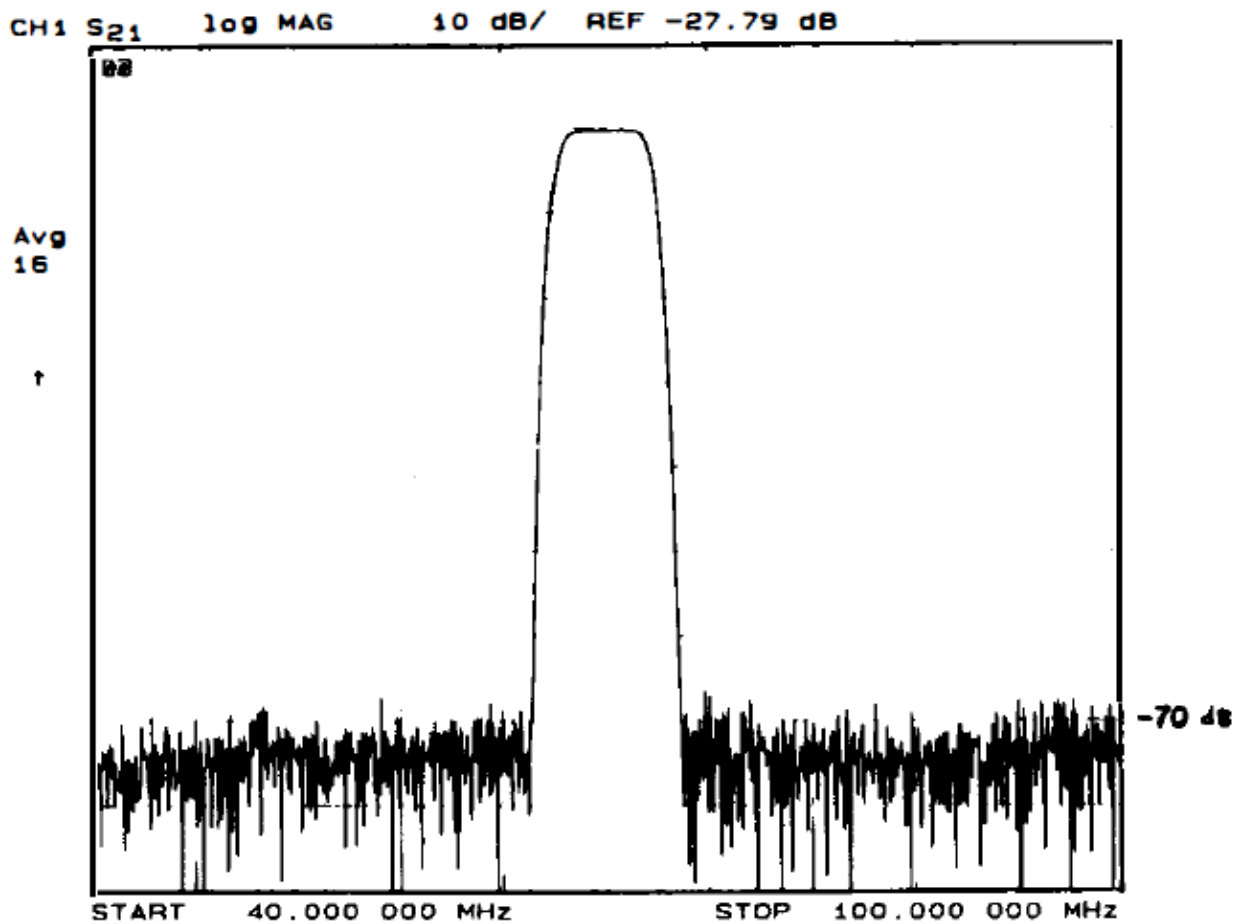
Fig. 1. Frequency response of a precision SAW filter with 70-dB out-of-band rejection. Horizontal scale: 40–100 MHz; vertical scale: 10 dB/div. (Courtesy of Crystal Technology, Inc., Palo Alto, CA.)