Smart Sensors

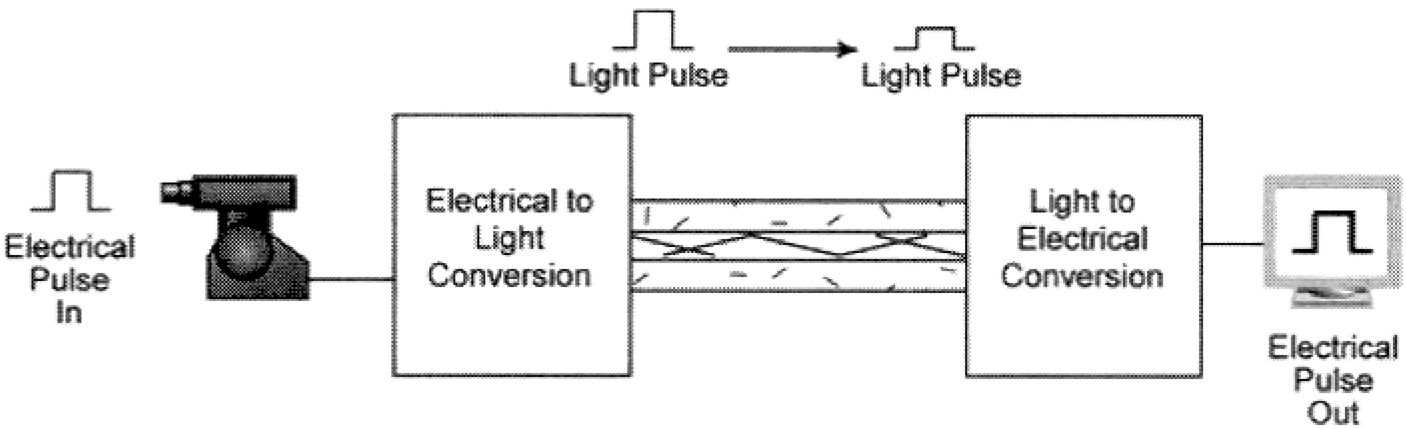
Optical Fibre

A flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair.

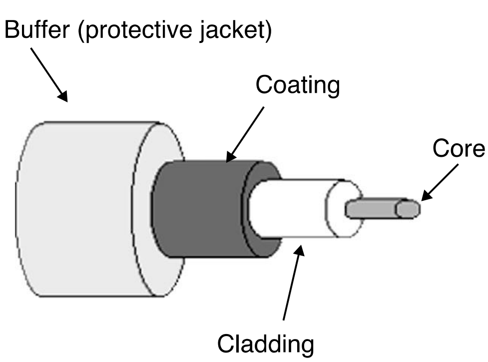
Used most often as a means to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths than electrical cables.

Fibers are used instead of metal wires because signals travel along them with less loss; in addition, fibers are immune to electromagnetic interference, a problem from which metal wires suffer excessively

Basics of Fibre Optics

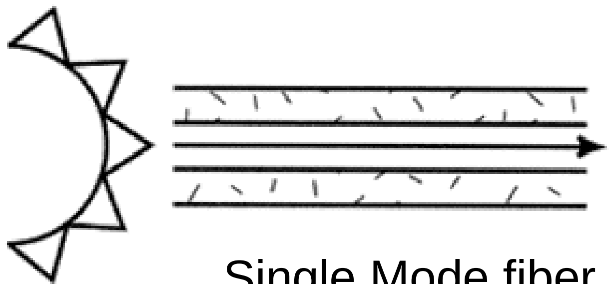


There are three types of fiber optic cable commonly used: single mode, multimode and plastic optical fiber (POF).



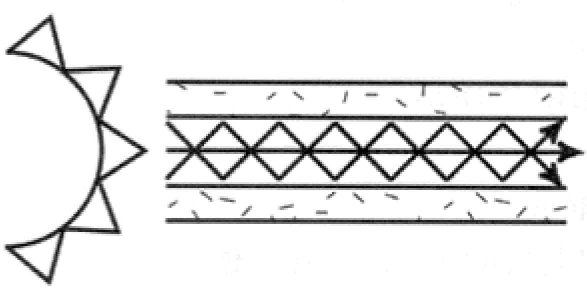
Sensor parameter	Single mode fiber (μm)	Multimode fiber (μm)	Material
Core	2–10	50–150	Silica-based
Cladding	80–120	100–250	Doped silica
Coating	250	250	Polymer
Buffer	900	900	Plastic

"Single mode fiber"
single path through the fiber



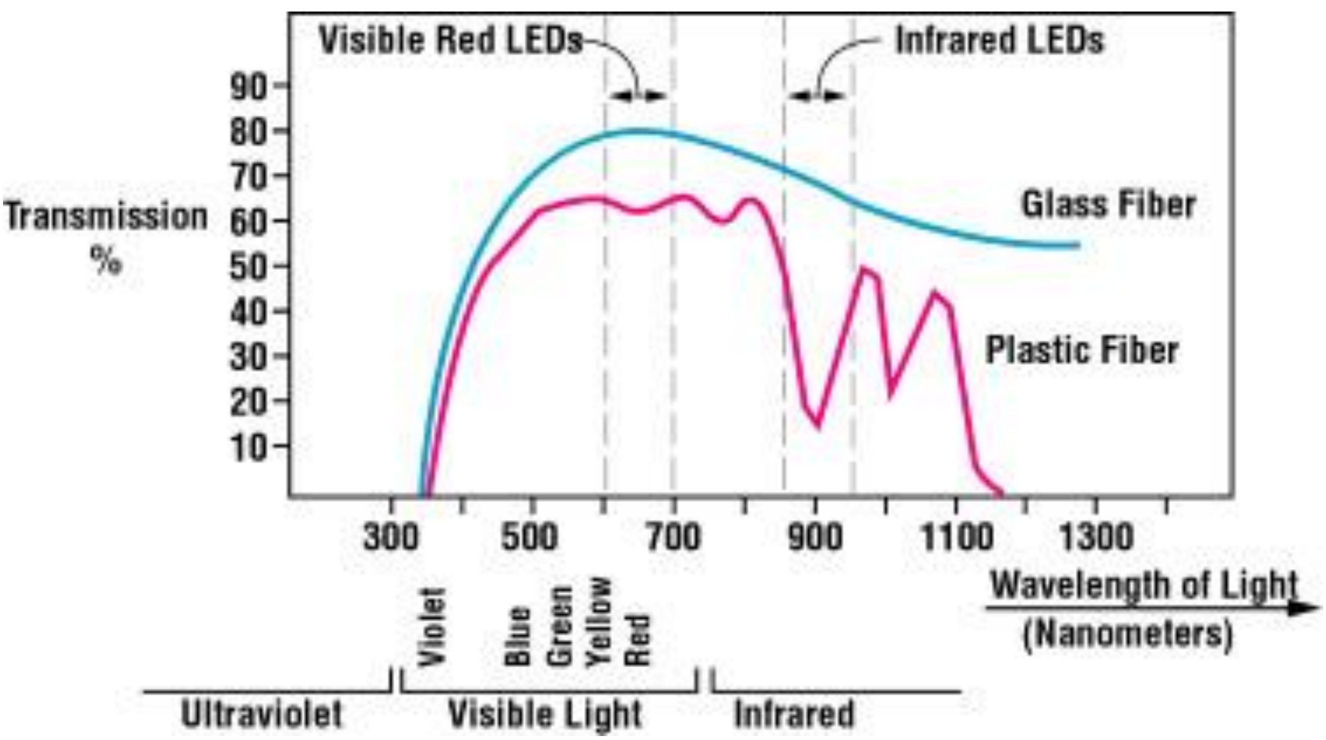
Single Mode fiber is usually 9/125 in construction. This means that the core to cladding diameter ratio is 9 microns to 125 microns.

"Multimode fiber"
multiple paths through the fiber



Light waves are dispersed into numerous paths, or modes, as they travel through the cable's core typically 850 or 1300nm. multimode fiber core diameters are 50, 62.5, and 100 micrometers.

GOF Vs POF



Visible Red LEDs
Infrared LEDs
Transmission %
90
80
70
60
50
40
30
20
10
Glass Fiber
Plastic Fiber
300
500
700
900
1100
1300
Wavelength of Light (Nanometers)
Violet
Blue
Green
Yellow
Red
Ultraviolet
Visible Light
Infrared

Advantages of POF

Plastic fibers survive well under repeated flexing. Pre-coiled plastic fiber optics are available for sensing applications on reciprocating mechanisms.

Because plastic absorbs certain bands of light wavelengths, including the light from most infrared LEDs, plastic fiber optics require a visible light source, such as a visible red LED, for effective sensing.

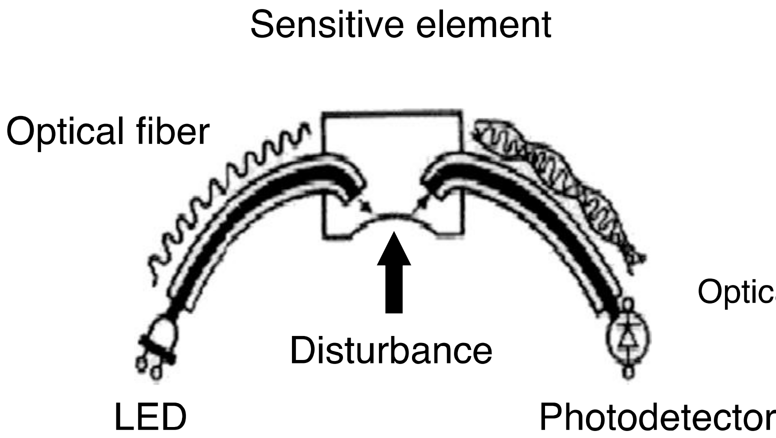
Also, in their simplest form, plastic fiber optics are less tolerant of temperature extremes, and are sensitive to many chemicals and solvents. Sheathing materials such as polypropylene, Teflon®, and nylon are used to shield plastic fiber optic assemblies in harsh environments.

When an optical fibre is subjected to perturbations of different kind, it experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation.

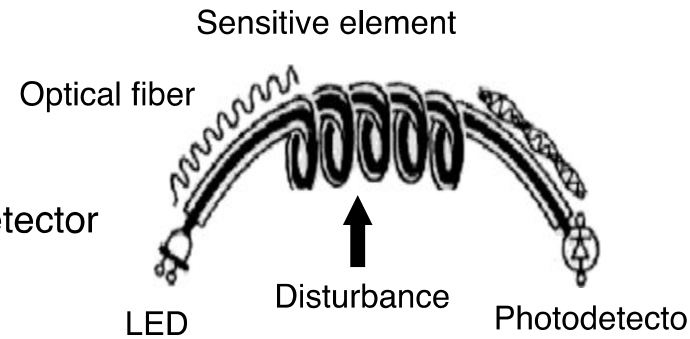
In fibre optic sensing, this response to external influence is deliberately enhanced so that the resulting change in optical radiation can be used as a measure of the external perturbation.

So the optical fibre serves as a transducer and converts measurands like temperature, stress, strain, rotation or electric and magnetic currents into a corresponding change in the optical radiation.

Since light is characterized by intensity, phase, frequency and polarization, any one or more of these parameters may undergo a change.



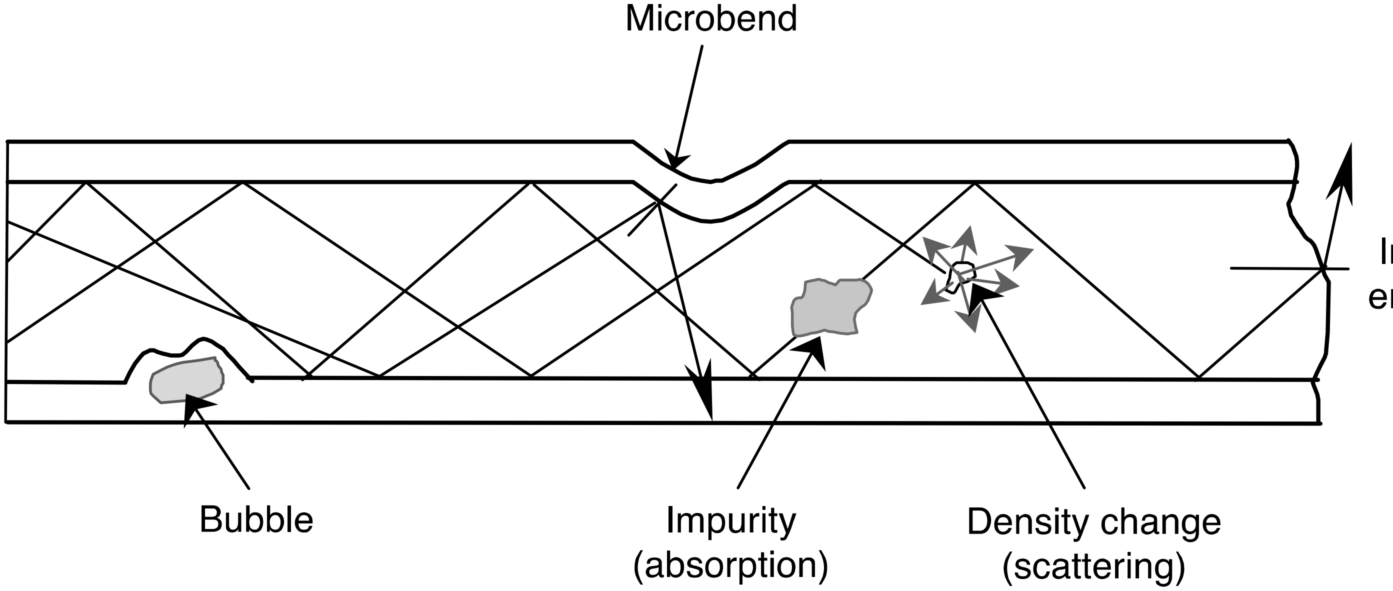
Extrinsic



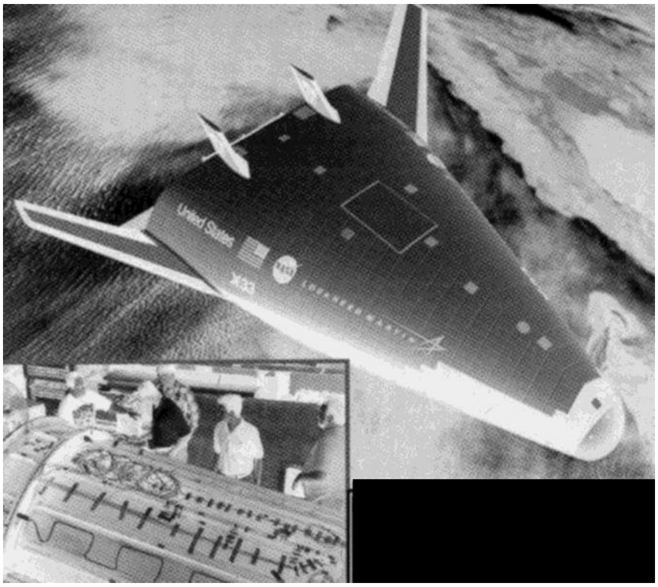
Intrinsic

Extrinsic sensors are those which use fiber to supply light to a sensing device and return signal light to a detection system, intrinsic sensors use the fiber itself as the transducer.

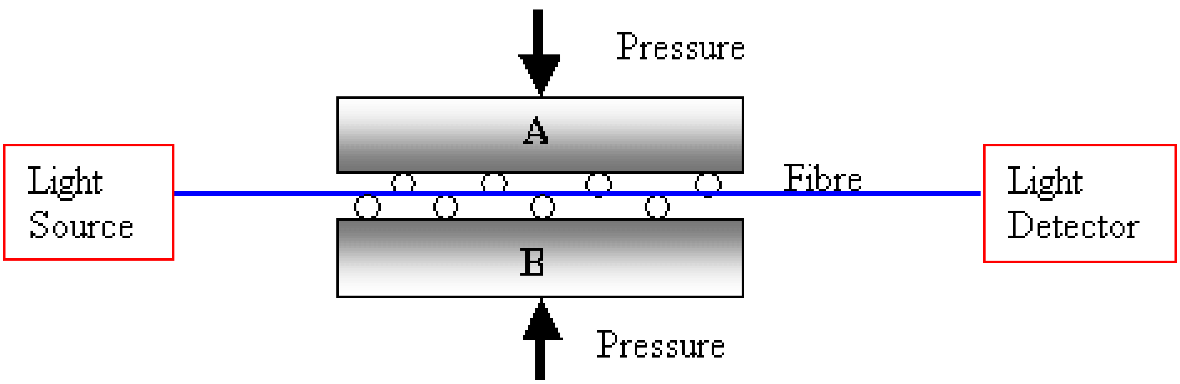
Sensors based on Intensity Attenuation



Like all intensity-modulated sensors, the signal can be affected by the light source's fluctuations affecting the accuracy of the measurement.
In addition, they are difficult to calibrate and require a fiber optic network to determine the location of the desired measurement (e.g., damage).
A classical application of these single use sensors is large area damage detection in structural components

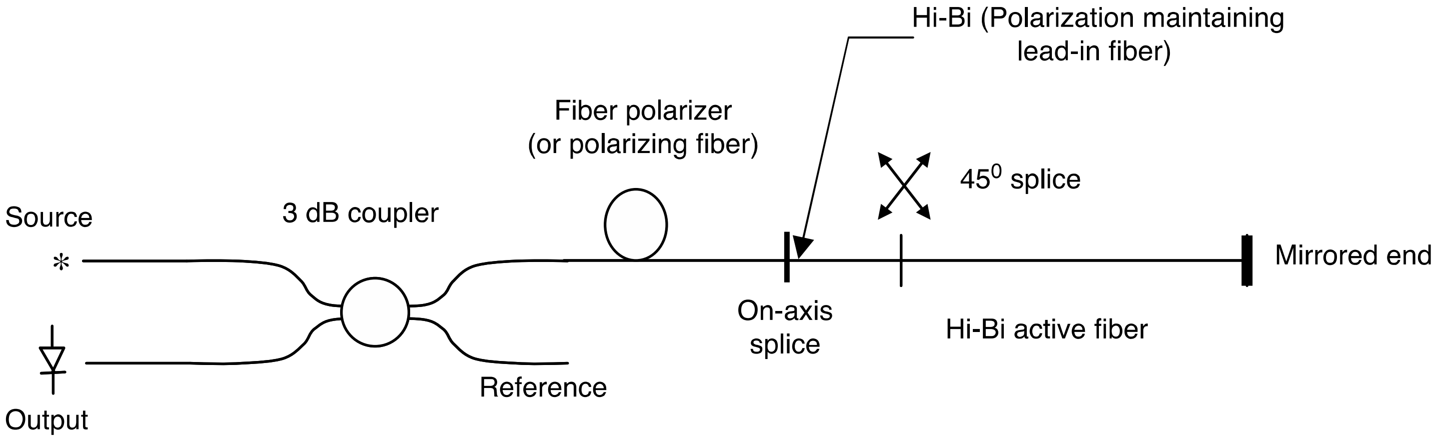


X-33, Reusable Space Vehicle: Composite Fuel Tank monitored by Optical Fibre



This type of sensor may be used to measure the force being exerted between the two objects A & B . As the pressure increases the fibre will become slightly deformed and experience increased microbending losses which results in a decrease in the light intensity received at the detector.

Sensors based on Polarization



Polarimetric sensors rely on coherent interference between two light beams from a common source traveling along two different (orthogonal) polarization axes of a common optical fiber.

This sensor uses a highly birefringent (HiBi) fiber that divides linearly incident polarized light into the two orthogonal modes traveling along the fiber at different phase velocities.

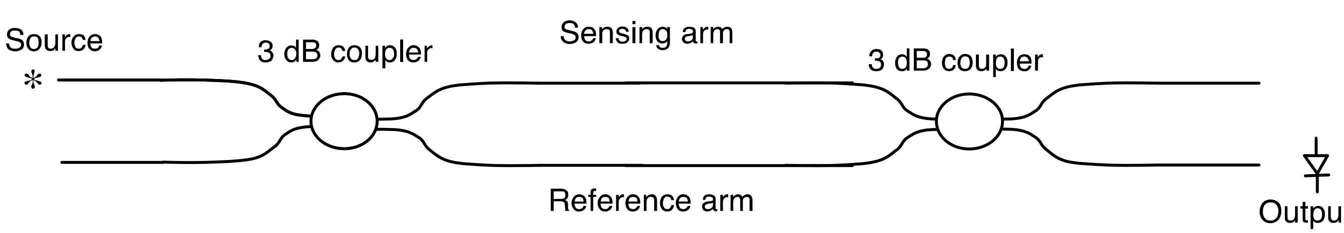
A transverse loading of the fiber will produce a change in the birefringence that manifests itself as a change in the polarization state at the fiber output.

Principle of Interferometry

Consider two monochromatic sources of light:

$$A1(x,t) = A_0 \mathrm{Cos}(\omega t \; - kx_1)$$

$$A2(x,t) = A_0 \mathrm{Cos}(\omega t \; - kx_2)$$



Where

$I_d = |A(x)|^2$; $A(x) = \sqrt{A_1^2 + A_2^2 + 2\, A_1\, A_2 \,\mathrm{Cos}\, k(x_1 - x_2)}$

$= A_1^2 + A_2^2 + 2\, A_1\, A_2 \,\mathrm{Cos}\, k(x_1 - x_2) = I_0(1+m)\,\mathrm{Cos}(k\, \Delta x)$

$m = \frac{2A_1A_2}{A_1^2+A_2^2}$

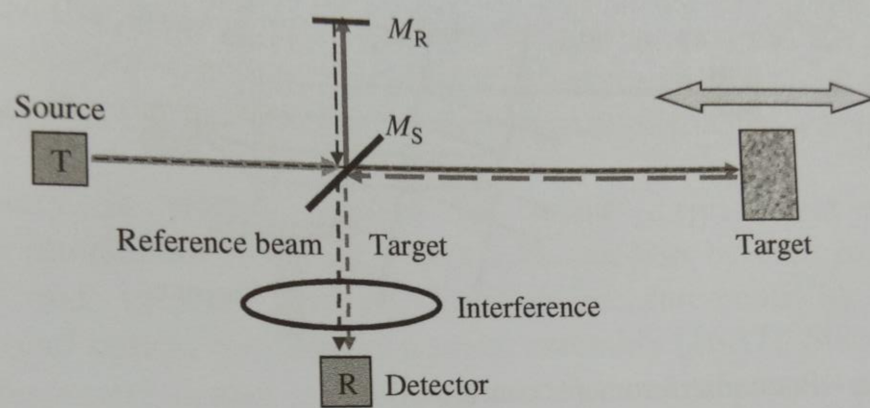


Figure 7.20 Classical interferometer configuration.

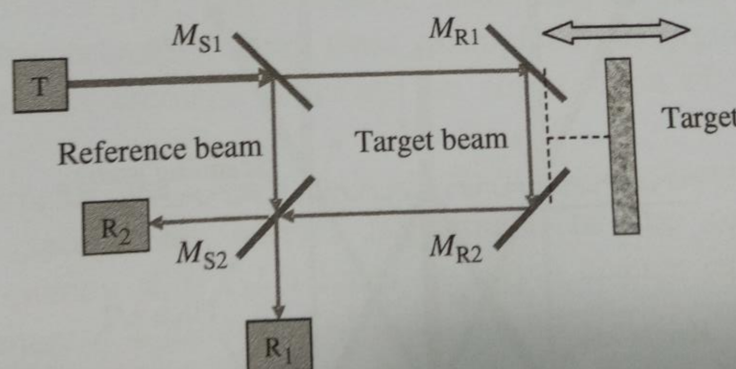
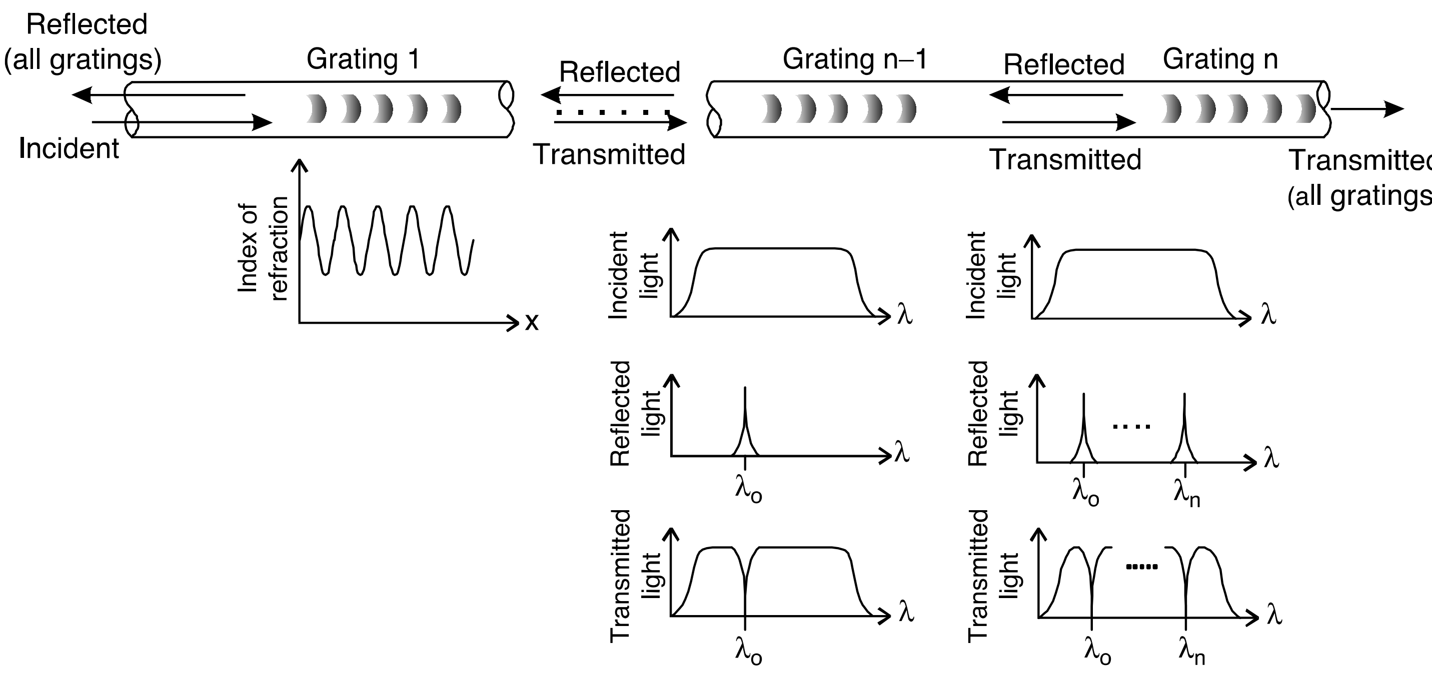


Figure 7.21 Mach–Zehnder interferometer configuration.

accurately aligned to achieve a proper

Fibre Bragg Grating Sensor



Laser Doppler Vibrometry

Features of Smart Materials

- These materials are a part of a group of materials broadly known as Functional Materials.
- The basic energy forms that gets interchanged are: thermal energy, electric energy, magnetic energy, sound energy & mechanical energy
- Analogous to Biological Materials: adaptivity, cellular function, self sensing, actuation & control
- Smart sensors & actuators are highly embeddable

Traditional vs. Smart System

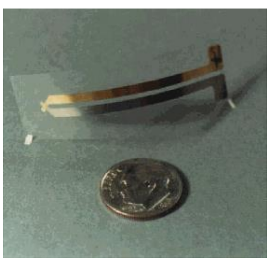
Traditional system

- Designed for certain performance requirements eg. load, speed, life span
- Unable to modify its specifications if there is a change of environment

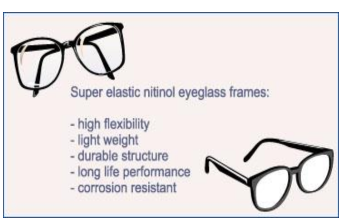
Smart System

- Can accommodate unpredictable environments
- Can meet exacting performance requirement
- Offer more efficient solutions for a wide range of applications

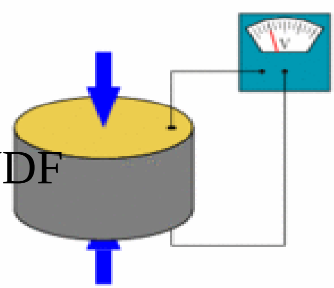
Smart Materials



- Piezoelectric film, PVDF



- SMA, Nitinol



Piezoceramic, PZT

- SMA, Nitinol

MS Material, Terfenol-D

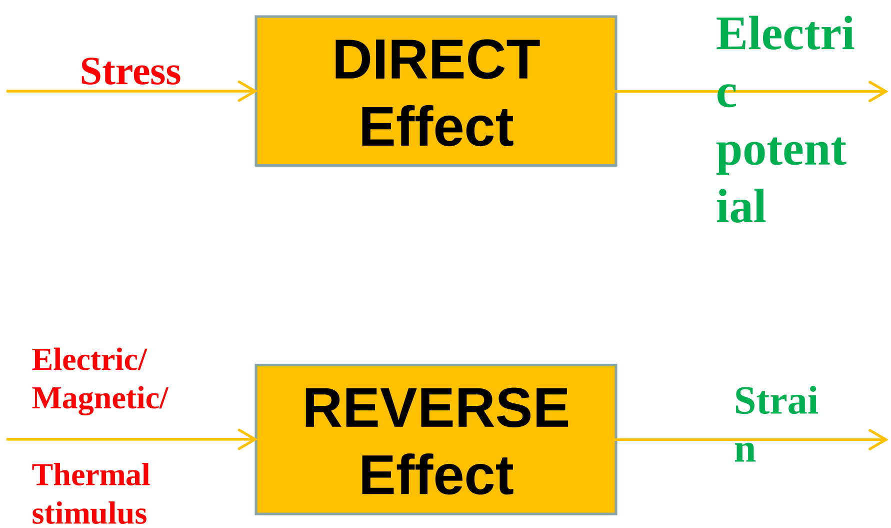
Why smart sensors and actuators ?

- Real time response
- Exploit functional properties
- Better embeddability
- Minimal effect on structural properties
- Reduction in weight
- Less power consumption
- Better reliability

Smart Materials for Sensing & Actuation

Output Input	Current/ Charge	Magnetization	Strain	Temperature	Light
Electric Field	Conductivity Permittivity	Electro-magnetic Effect	Reverse Piezo electricity	Ohmic Resistance	Electro-Optic effect
Magnetic Field	Eddy Current Effect	Permeability	Joule Effect Magnetostriction	Magneto caloric Effect	Magneto-Optic effect
Stress	Direct Piezo-Electric Effect	Villary Effect	Elastic Modulus	Thermo-Mechanical Effect	Photo-elastic Effect
Heat	Pyro-electric Effect	Thermo-Magnetization	Thermal Expansion Phase Transition	Specific Heat	Thermo-Luminecence
Light	Photo-Voltaic Effect	Photo-Magnetization	Photostriction	Photo-Thermal effect	Refractive index

Smart Materials as Sensors & Actuators



Traditional VS New Actuators

Drive	Device	Displacement	Accuracy	Torque/Generative Force	Response Time
Air Pressure	Motor	Rotation	degrees	50 Nm	10 sec
	Cylinder	100mm	100µm	10^{-1} N/mm^2	10 sec
Oil Pressure	Motor	Rotation	degrees	1000 Nm	1 sec
	Cylinder	1000mm	10µm	100 N/mm^2	1 sec
Electricity	AC Servo	Rotation	minutes	30 Nm	100 msec
	DC Servo	Rotation	minutes	200 Nm	10 msec
	Linear Stepper	1000mm	10µm	300 N	100 msec
	Voice-Coil	1mm	0.1µm	300 N	1 msec
Smart materials	Piezoelectric	100µm	0.01µm	30 N/mm^2	0.1 msec
	Magnetostrictive	100µm	0.01µm	100 N/mm^2	0.1 msec
	Ultrasonic Motor	Rotation	minutes	1 Nm	1 msec

Direct Effect

- All Piezoelectric Materials and PVDF
- Magnetostrictive Materials
- Optical Fibre

Converse/Reverse Effect

- Ferroelectrics Perovskites, Piezoceramics, PVDF respond to electric field by change in shape
- Terfenol-D, Amorphous Met-Glasses show a similar effect with the change in magnetic field
- Shape Memory Alloy respond in a similar manner but with the change in Thermal Field
- Electro/Magneto Rheological Fluids respond to electric/magnetic field by changing it’s viscosity

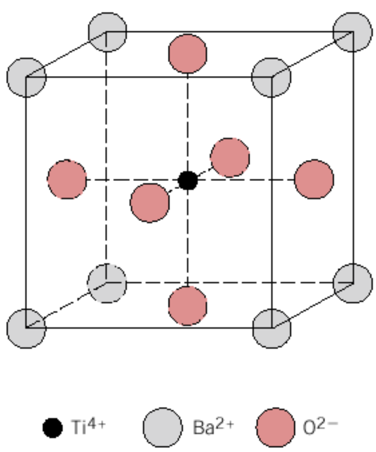
Properties of a few Smart Materials

Props.	PZT	PVDF	T-D	NiTiNOL
Free strain(ppm)	1000	700	2000	20000
E. Mod. (GPa)	62	2.1	48	27– M 89 - A
Band	.1Hz-GHz	.1Hz-GHz	.1Hz-MHz	0-10 Hz

Piezoelectricity in Perovskites (1949-60)

Perovskite: A Ternary (3 Component structure)

Example: $BaTiO_3$ a common piezoelectric material



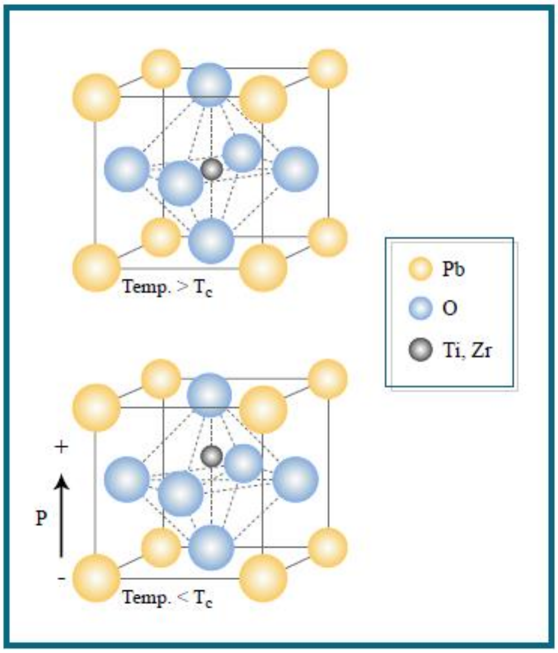
Tetragonal Symmetry with Dipole moment below Curie Temperature

Ba: 2^+ O: 2^- Ti: 4^+
Below Curie Point, the imbalance of charge centre creates dipole moment

Similar material: PZT family, LiNb family, PbNb family, YMn family, $(NH_4)Cd$ family (1970--)

Piezoelectricity in Perovskites (1980-)

Perovskite: PZT



PZT, $(Pb(Zr_{1-x}\ Ti_x)O3$, the most important piezoelecric material.

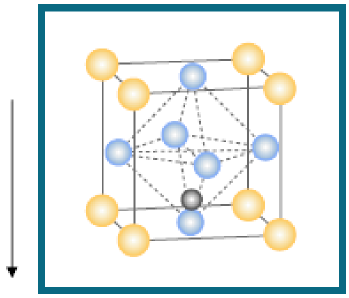
PbZrO3:PbTiO3 → 52:48

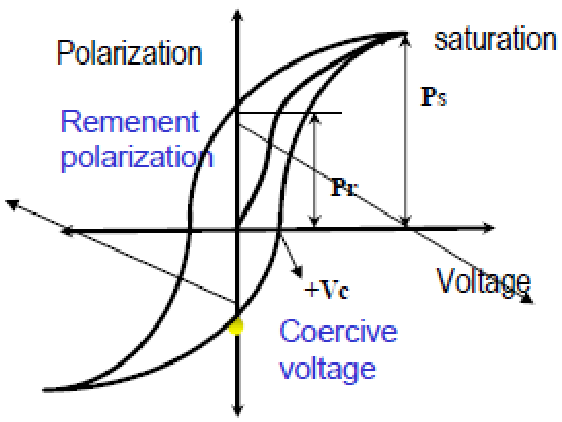
rhombohedral →cubic→tetrahedral

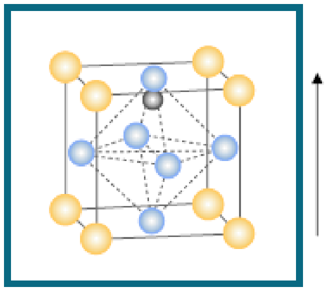
Curie Temperature

Piezoelectricity in Perovskites (1980-)

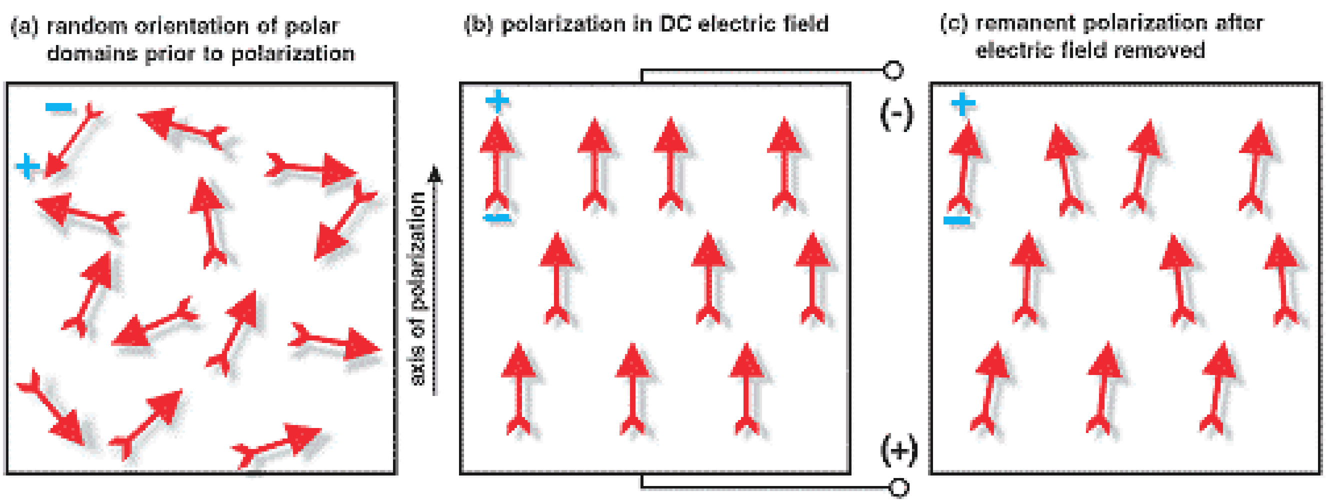
Nature of Polarization







Polarization of Piezoelectric Material



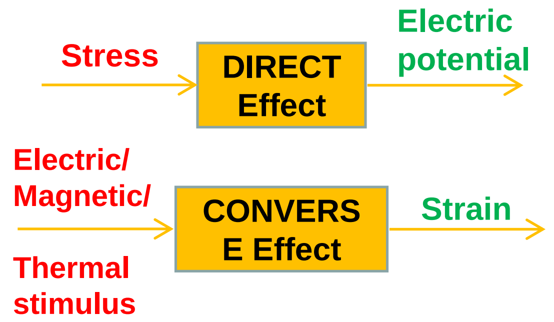
Constitutive Equation of Piezoelectricity

$$D = dT + \overset{X}{\varepsilon} E$$

Direct Effect

$$S = \overset{E}{s} T + dE$$

Converse Effect



T-stress,

***S*-strain,**

D-electric displacement / flux density,

s-compliance,

E-Electric field intensity,

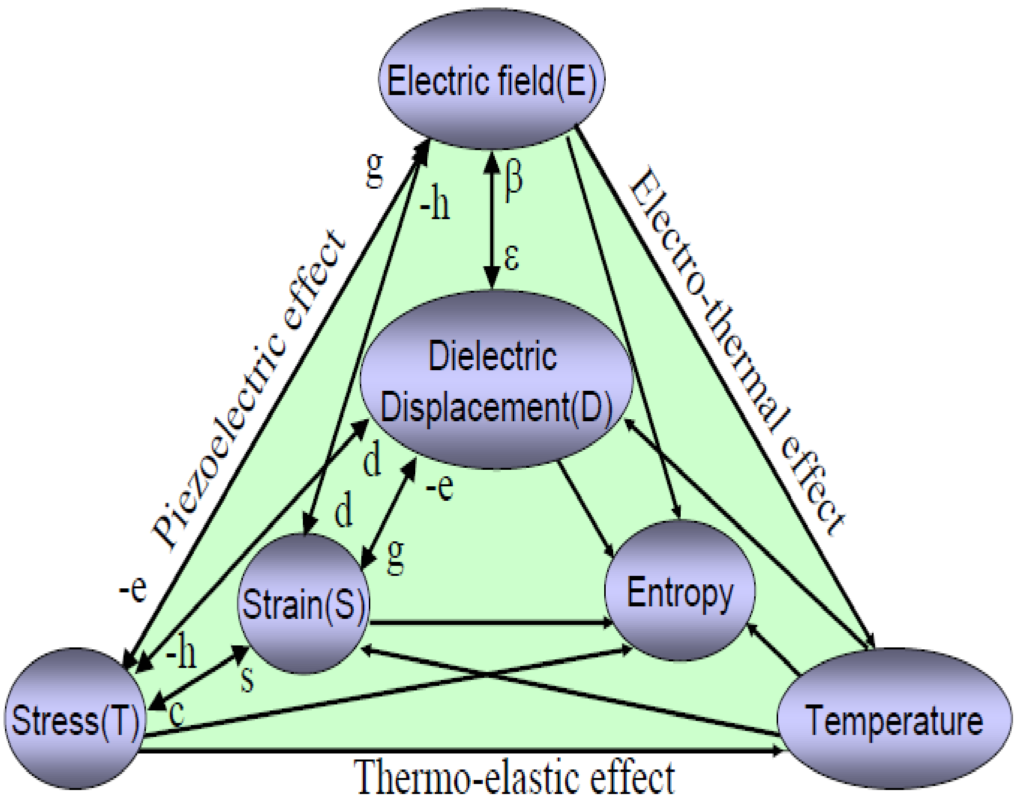
ε-permittivity,

d-piezoelectric constant.

Superscripts denote the measurement of permittivity at constant stress and compliance at constant electric field intensity

The Big Picture

Principles of piezoelectric



Expanded Relationship

$$D = dT + \varepsilon^T E$$

direct

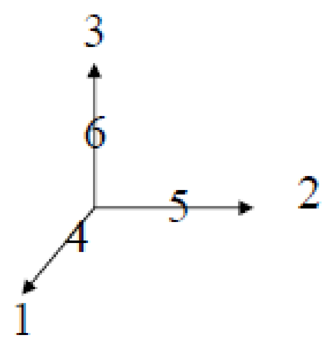
$$S = s^E T + dE$$

converse

Tensor to Matrix notation

For cylindrical symmetry, and poling in axis 3,

$$D_1 = \varepsilon_1 E_1 + d_{15} T_5$$
$$D_2 = \varepsilon_1 E_2 + d_{15} T_4$$
$$D_3 = \varepsilon_3 E_3 + d_{31}(T_1 + T_2) + d_{33} T_3$$
$$S_1 = s_{11} T_1 + s_{12} T_2 + s_{13} T_3 + d_{31} E_3$$
$$S_2 = s_{11} T_2 + s_{12} T_1 + s_{13} T_3 + d_{31} E_3$$
$$S_3 = s_{13}(T_1 + T_2) + s_{33} T_3 + d_{33} E_3$$
$$S_4 = s_{44} T_4 + d_{15} E_2$$
$$S_5 = s_{44} T_5 + d_{15} E_1$$
$$S_6 = s_{66} T_6$$



Electromechanical Coupling Coefficient

- Due to nonlinearity the equations are represented in Variational form:

$$\delta D = d\,\delta T + \varepsilon^{x}\delta E$$
$$\delta S = s^{E}\delta T + d\,\delta E$$

- Electromechanical coupling Coefficient:

$$k^{2} = W^{2}{}_{12} / W_{1}W_{2}$$

W_{12} – Piezoelectric Energy Density,

W_1 Mechanical and

W_2 Electrical energy density

Commercial Piezoelectric Material Property Set

Prop.	unit	**$BaTiO_3$**	**PZT-A**	**PZT-B**	**$Pb\ Nb_2O_6$**	**$LiNbO_3$**	**$Pb\ Ti\ O_3$**
ρ	**Mg/m^3**	5.7	7.9	7.7	5.9	4.6	7.1
k_{31}		.21	.33	.39	.04	.02	.05
k_{33}		.49	.68	.72	.38	.17	.35
d_{31}	pCN^{-1}	79	119	234	11	.85	7.4
s	$\mu m^{2/N}$	**8.6**	**12.2**	**14.5**	**29**	**5.8**	**11**

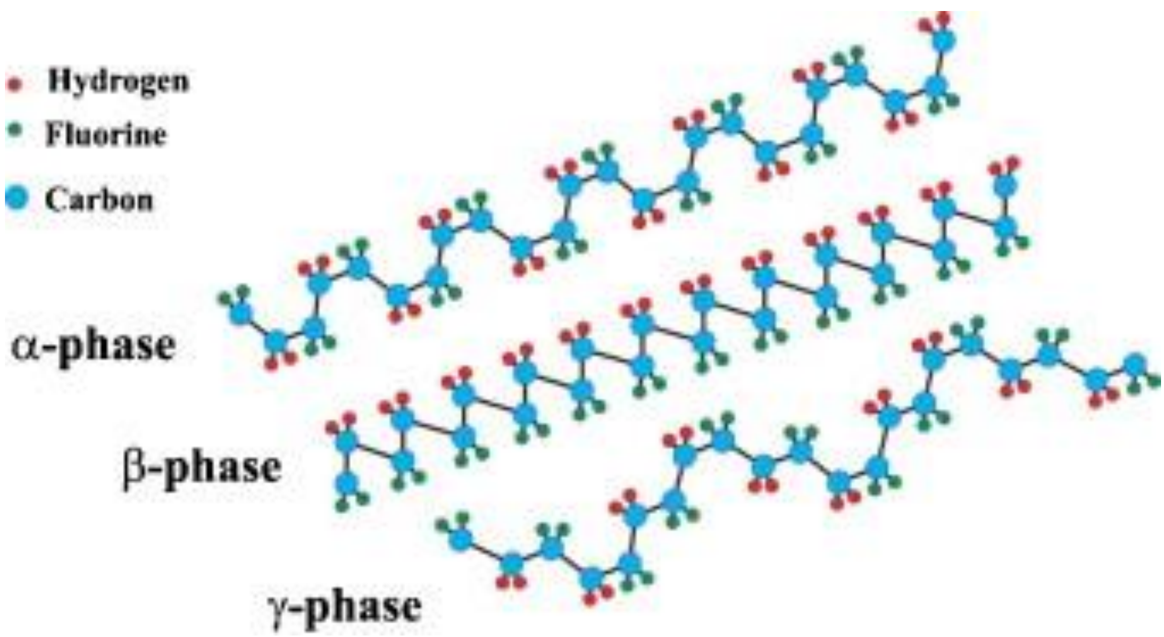
A few observations

- PZT family has highest piezoelectric coupling.
- Curie Point: PZT family 220-315^{o}C, Li family 600-1200^{o}C
- Instead of polycrystalline Piezoceramics, a single cut PMN could give k_{33} = 0.92 and d_{33} = 2070 pC/N

Piezoelectric Polymer

- PVF_2 (Poly Vinylidene Fluoride) a semi-crystalline polymer consist of long-chain molecules with the repeat unit of CF_2CH_2
- Form I PVDF (all trans) shows all chain oriented parallel to the axis of the unit cell and the dipoles pointing in the same direction
- d_{31} : 4.2-19 pC/N (for PZT ~ 234)
- K_{31} : 3-14.7%
- E : 1.6 – 3.8 GPa

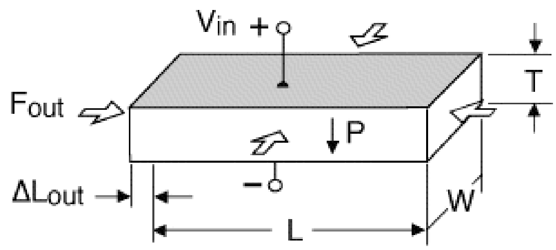
Various Forms of PVDF



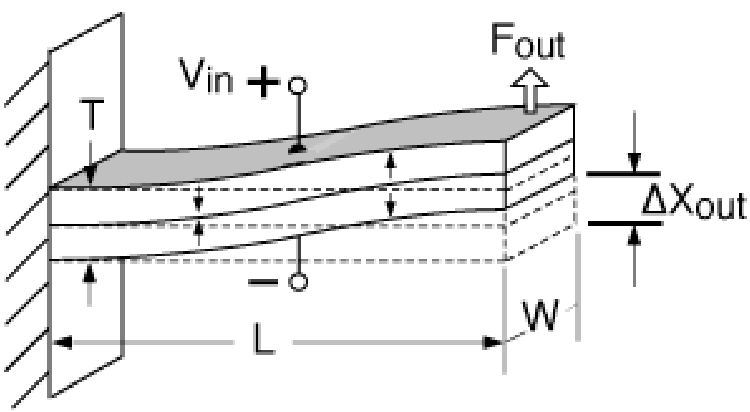
Piezoelectric Composite

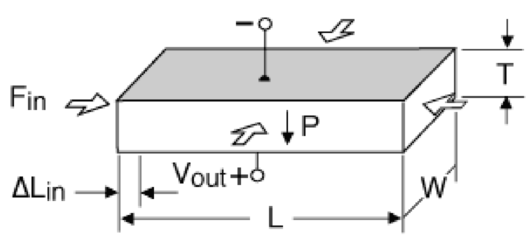
- Composite made of a polymer and PZT
- Polymer phase – lower density, permittivity and increased elastic compliance.
- Smaller PZT particles (5-10 μm) in Polyurethane (PU) matrix.
- Larger 120μm particles in a silicone rubber matrix.
- Skinner et al: Smaller particles generate series connectivity, while larger generate parallel connectivity.

Applications: Bimorph



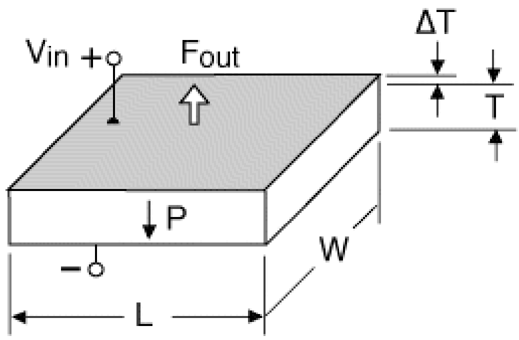
D_{31} Actuator



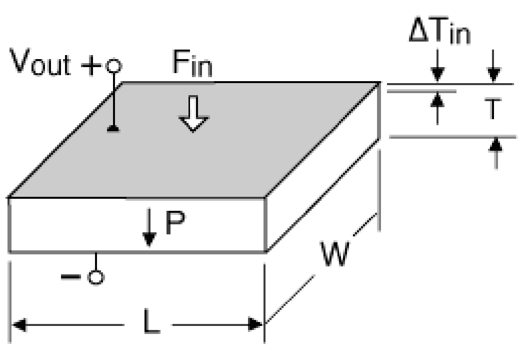


D_{31} Sensor

PIEZOSTACK



D_{33} Actuator



D_{33} Sensor

Operating Point