Absorption-Based Sensors

Light and Molecules:

Some molecules can "absorb" light, like how a sponge absorbs water.
The kind of light absorbed depends on the molecule.
Colors and Sensors:

Some sensors work by noticing a color change when they meet a specific material.
Others measure how much light is absorbed by the molecules.
Types of Light:

UV or Visible Light: Causes electronic energy to increase, like turning on a light bulb.
Infrared Light: Makes molecules vibrate, like dancing.
Microwave Light: Makes molecules rotate, like spinning a top.
Light's Journey Through a Material:

When light passes through a material, some of it is "used up" (absorbed) by the molecules.
Only the light that matches the molecule’s needs gets absorbed; the rest passes through.

Measuring Absorption:

The more molecules in the path, the more light gets absorbed.
Scientists use a special rule (called the Beer-Lambert law) to calculate how much light is absorbed:
Absorbance = ε × c × l
Where ε = a property of the molecule,
c = concentration of molecules,
l = length of the light path.
Optical Fiber Sensors:

Tiny light-guiding fibers can detect molecules by noticing changes in light when it interacts with them.
These sensors help in identifying substances by their light behavior!

$$A_b = \log\left(\frac{I_0}{I}\right) = \varepsilon l c$$

Luminescence-Based Sensors

What Happens When Light Hits a Molecule?

Light gives molecules energy and makes their electrons jump to a higher level (excitation).
When the electrons return to their normal level, they can release light. This is called luminescence.
Types of Luminescence:

Fluorescence:
Light comes out quickly after being excited.
It happens in a blink (about 10 nanoseconds).
Phosphorescence:
Light comes out slowly and can last from milliseconds to seconds.
It’s like a glow that lingers.
What’s Special About This Light?

The color (or frequency) of the light coming out is different from the light going in.

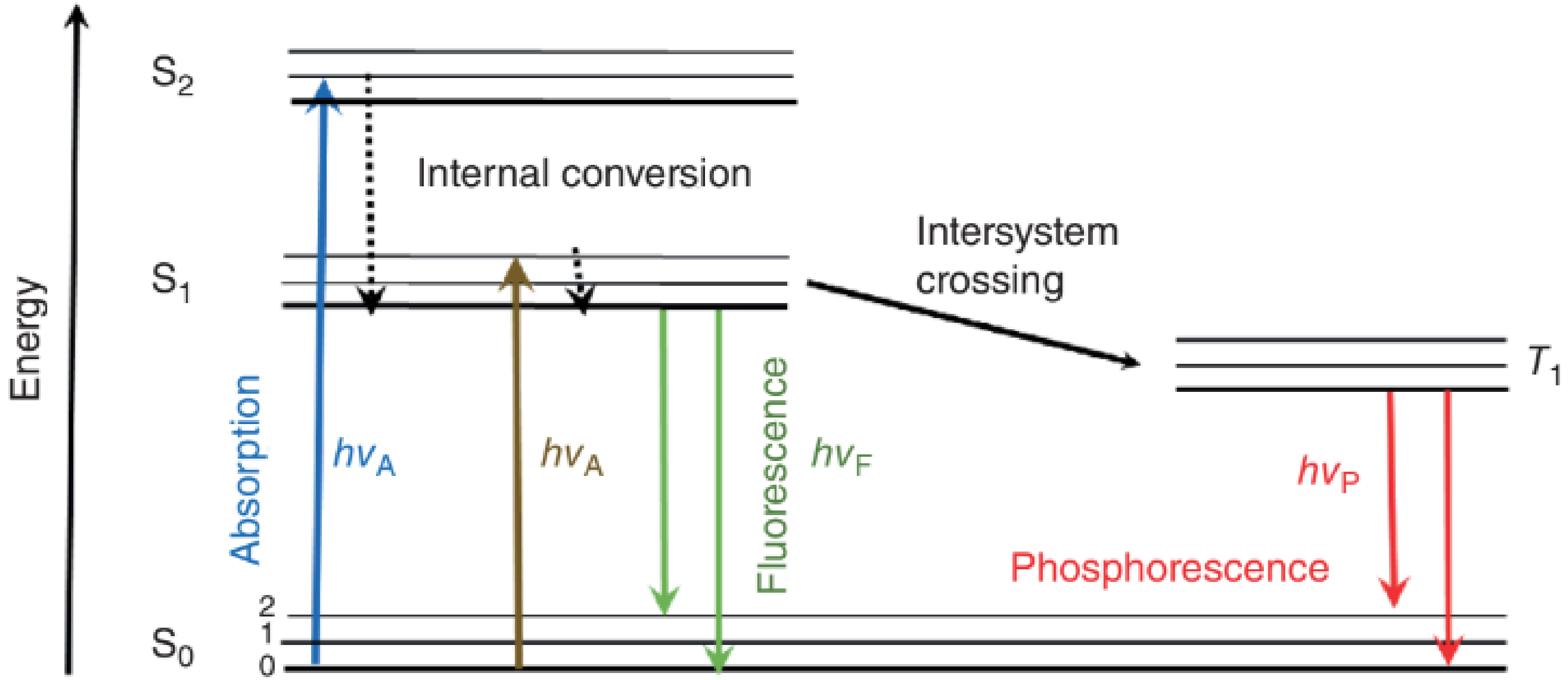


Figure 8.2 Partial energy diagram for a photoluminescence system.

What Controls Luminescence Intensity?

The brightness of the light depends on:
How strong the incoming light is.
How many molecules are there to light up.
Special properties of the molecules.
Quenching:

Sometimes, other molecules like oxygen can reduce the light.
This is called quenching, and scientists use it to measure the amount of these other molecules.
Special Luminescence from Reactions:

Some molecules glow after a chemical reaction. This glow is called chemiluminescence.
Fluorescence vs. Absorption:

Fluorescence measures the glowing light directly, making it very sensitive.
It’s better than just measuring how much light is absorbed.

Optical Fiber Sensors:

Special tiny fibers can detect glowing light:
They have materials that light up when they meet certain molecules.
These glowing signals travel through the fiber, helping us detect and measure different substances.
Design of Fiber Sensors:

Scientists can put glowing materials on the fiber’s surface or tip.
When these materials meet a target substance, they glow differently, and the fiber captures the change.
Why Is This Useful?

These sensors are super sensitive and help in detecting tiny amounts of substances, like oxygen or chemicals, in various places!

Surface Plasmon Resonance (SPR)-Based Sensors

What is SPR?

SPR happens when light makes electrons on a metal surface wiggle together in a special way.
This happens at the meeting point of two materials, like metal and glass or air.
How Does It Work?

Light hits the metal, and its energy creates waves of moving charges called surface plasmon waves (SPWs).
These waves stay near the surface and get weaker as they move into the materials on either side.
Special Angle (Resonance Angle):

There’s a magic angle called the resonance angle where light energy perfectly matches the surface wave.
At this angle, most of the light energy is used up to make the waves.

What Changes in SPR?

If the material touching the metal changes (like a liquid or gas), it changes how the light behaves.
Scientists measure this change to learn about the material (like its refractive index).
Where is SPR Used?

SPR helps scientists study chemicals and tiny biological materials like proteins and DNA.
It’s great because it doesn’t need extra dyes or labels—just the light and the material.
SPR Sensors with Optical Fibers:

Special tiny fibers are used instead of bulky equipment.
A thin layer of metal (like gold or silver) is added to the fiber where light interacts.
The fiber carries light and measures how it changes when meeting different materials.
LSPR (Localized SPR):

This is a mini version of SPR on tiny particles like gold nanoparticles.
It makes the waves stay in a very small space, perfect for sensing very tiny changes.

Other Label-Free Sensors:

Evanescent Wave Sensors: These sense light loss when light travels through a thin film.
All these sensors are useful in “lab-on-a-tip” devices, tiny tools for sensing at the end of an optical fiber.
Why is SPR Cool?

It’s label-free, meaning you don’t need to add anything to see the result.
It works in hard-to-reach places, making it super flexible for different uses!

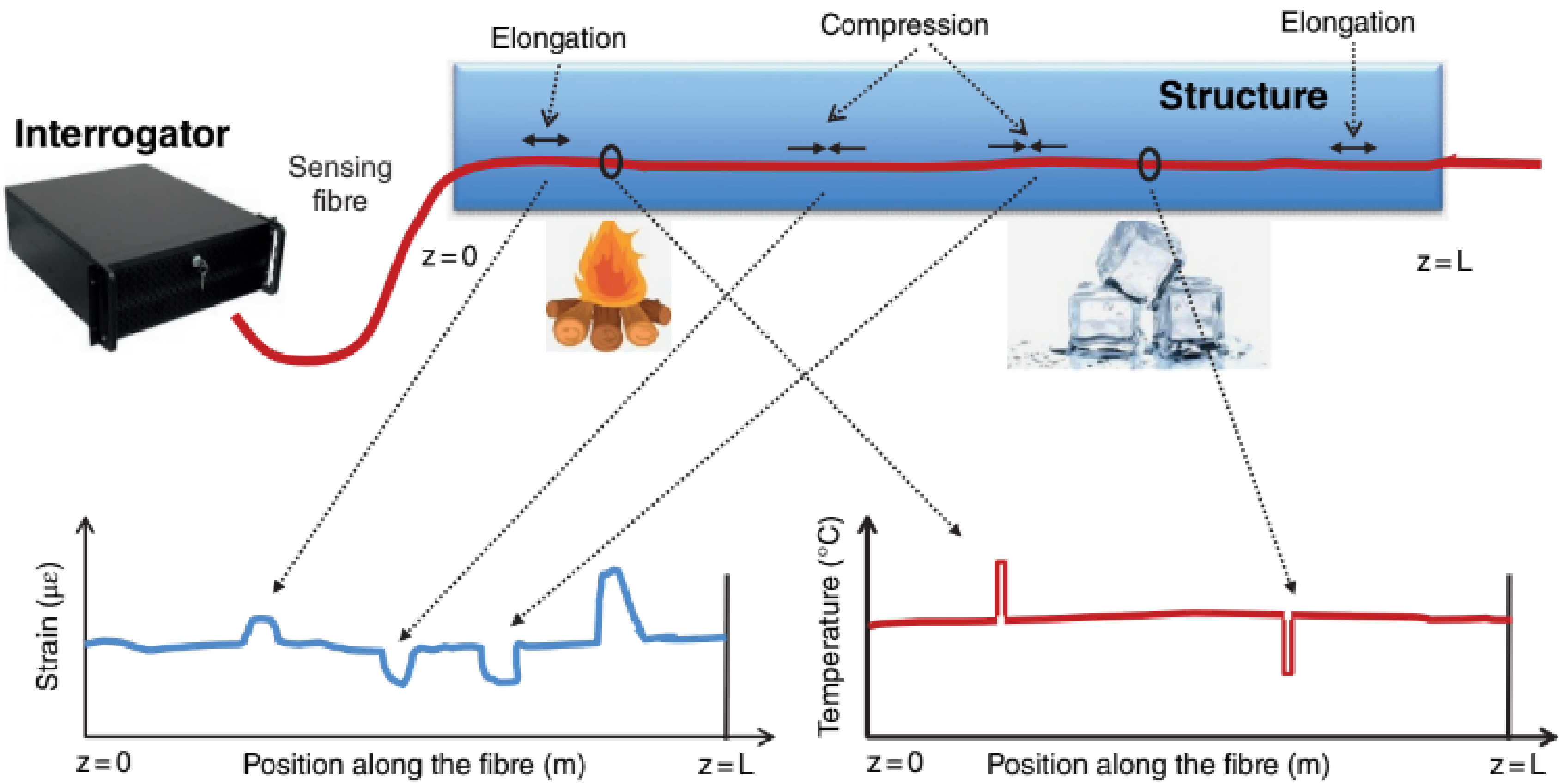


Figure 5.1 Configuration of a distributed fibre-optic sensor measurement system.

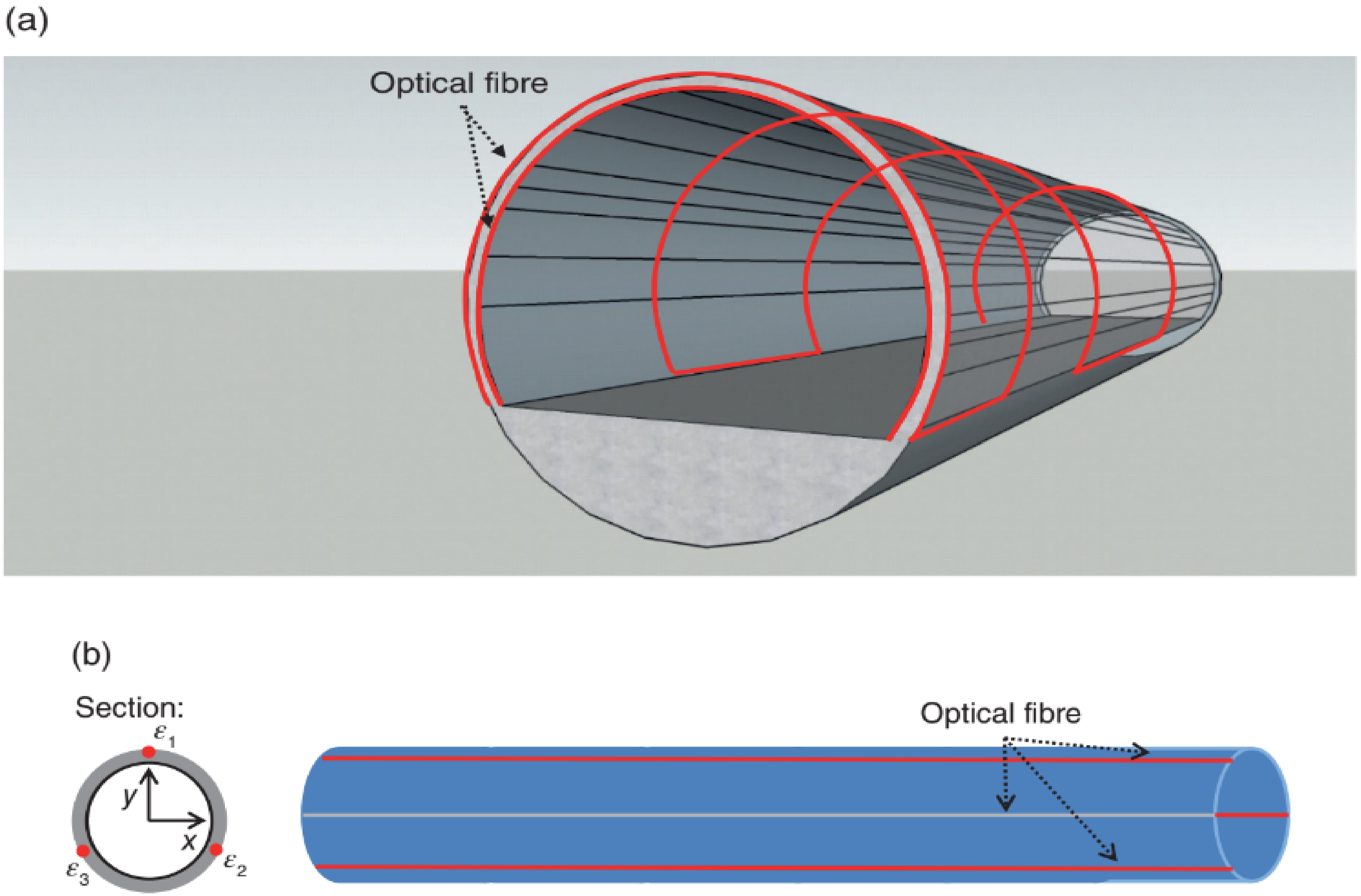


Figure 5.3 (a) Instrumentation of a tunnel with optical fibre to measure deformation. (b) Shape sensing using a tube instrumented with optical fibre for axial strain measurement.

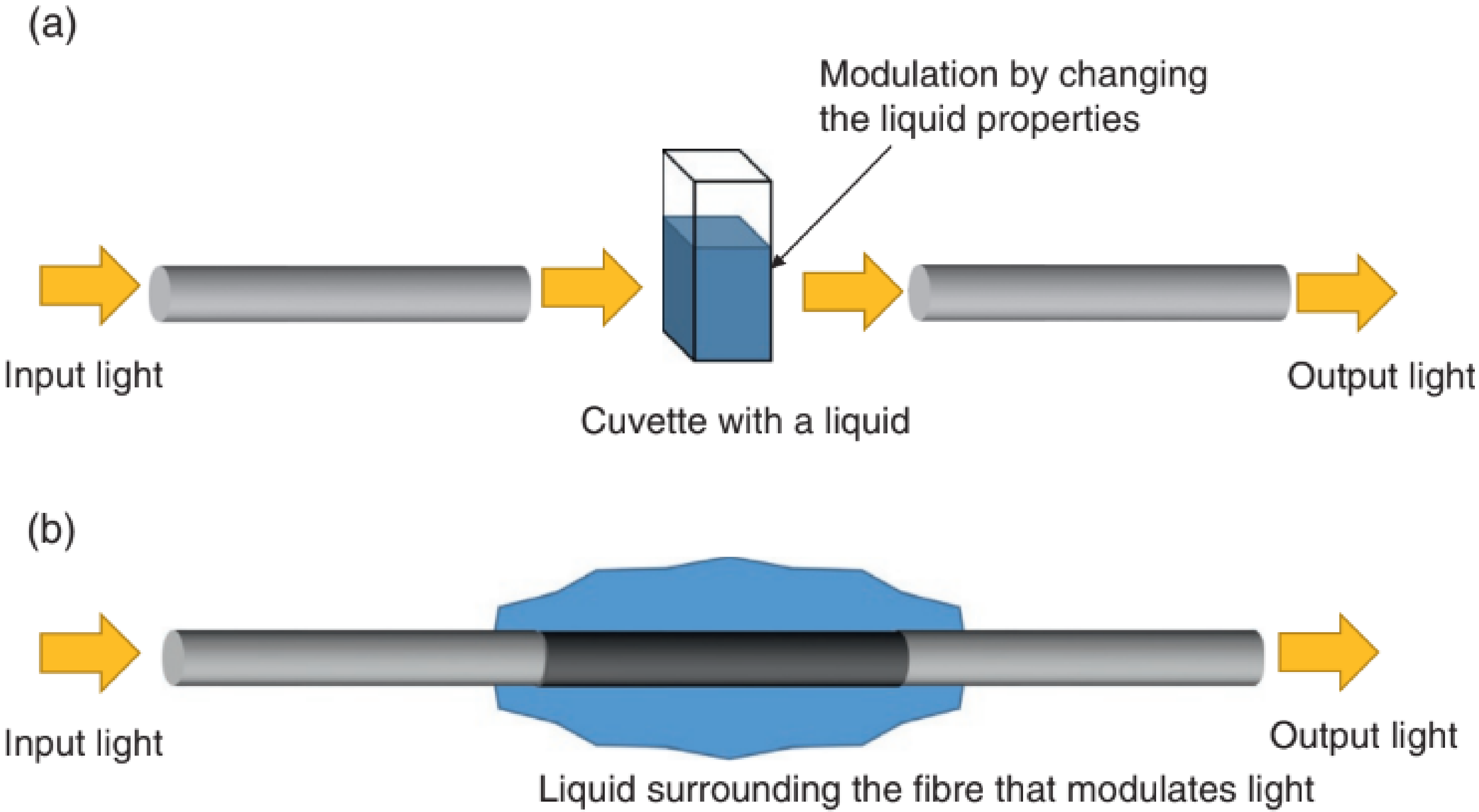


Figure 1.1 (a) Extrinsic sensor: light is modulated outside of the fibre. (b) Intrinsic sensor: light is modulated while it is transmitted through the fibre.

Classification of OFSs

1. **Main Classification**: Based on the location where light is modulated:
   1. **Extrinsic OFSs**
   2. **Intrinsic OFSs**
2. **Common Factor**:
   1. Both types use a parameter (physical, chemical, biological, etc.) to modulate light.

Extrinsic Optical Fibre Sensors (OFSs)

1. **Modulation Location**:
   1. Light is modulated outside the optical fibre (extrinsic to the fibre).
2. **Process**:
   1. Light is guided to an interaction region outside the fibre.
   2. After modulation, light is collected back into the fibre.
3. **Example**:
   1. Light modulated by an external liquid whose properties may change (e.g., due to temperature).

Intrinsic Optical Fibre Sensors (OFSs)

1. **Modulation Location**:
   1. Light is modulated within the optical fibre itself.
2. **Process**:
   1. Light is always guided by the fibre.
   2. Enhanced interaction occurs by splicing a fibre between input and output fibres.
3. **Example**:
   1. A liquid modulates light as it is transmitted through the fibre.

Advantages and Disadvantages of Optical Fibre Sensors

Advantages

Small Size and Lightweight:

Typical diameter ~100 μm, making them easy to embed in various structures.

Low Losses:

Enables remote sensing over long distances.

Immunity to Interference:

Resistant to electromagnetic and radio-frequency interference.

Passive Operation:

No electrical biasing required for light guidance, suitable for environments with explosion risks.

High Bandwidth:

Supports multiplexing and multi-parameter sensing.

Distributed Sensing:

Allows physical measurements along the fibre using modulation techniques.

Disadvantages

1. **Cost**:
    1. High cost compared to some alternative technologies.
2. **Complex Interrogation Systems**:
    1. Requires sophisticated methods for signal interpretation.

Applications of Optical Fibre Sensors

1. Civil Engineering

- **Leak Detection**: Dams and river embankments.
- **Structural Monitoring**: Cracks in bridges and concrete structures.
- **Health Monitoring**: Large civil projects.
- **Fire Safety**: Fire monitoring and alarms for roads, subways, and tunnels.

2. Petrochemical Industry

- **Leak Detection**: Oil and natural gas pipelines, storage tanks.
- **Temperature Monitoring**: Oil depots, oil pipes, and tanks.
- **Fault Detection**: Locating fault points.

3. Power Cable Industry

- **Surface Temperature Monitoring**: Power cables and accident point detection.
- **Temperature Monitoring**: Power plants and substations.
- **Fire Alarms**: Early detection and fault identification.

4. Aerospace

- **Aircraft Monitoring**: Pressure, temperature, fuel level, and landing gear status.
- **Material Monitoring**: Temperature and strain in composite skins.
- **Engine System Monitoring**: Stress and temperature in jet turbine systems.

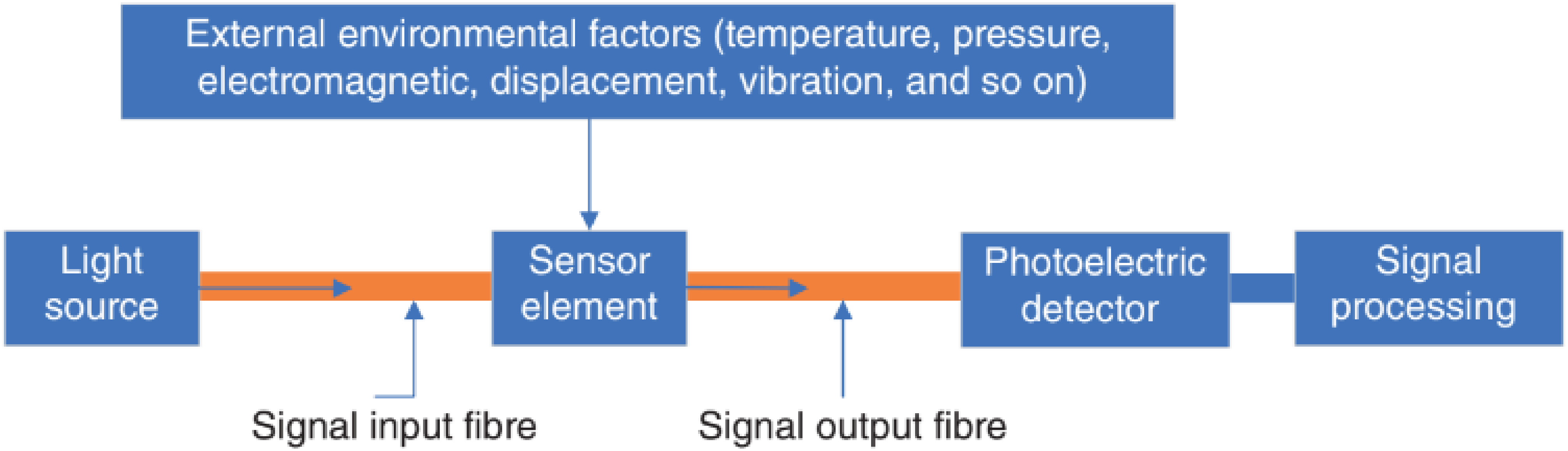


Figure 3.1 Detection principle of optical fibre sensor.

Components of a Fibre-Optic Sensing System

1. Key Components

- **Light Source**: Provides the initial radiation sent to the sensor element.
- **Signal Input Optical Fibre**: Guides light to the sensor.
- **Sensor Element**: Modulates optical properties of light (e.g., intensity, wavelength, frequency, phase, polarization).
- **Signal Output Optical Fibre**: Transmits the modulated light to the detector.
- **Optical Detector**: Analyzes the modulated light to extract measured parameters.

(Optional components: Optical modulator and demodulator for specific applications.)

Light Sources

- **Definition**: Devices capable of generating light radiation, natural or artificial.
- **Common Sources**:
    - **LEDs**: Light Emitting Diodes.
    - **LASERs**: Light Amplification by Stimulated Emission of Radiation.

Optical Detectors

- **Function**: Detect power returned from the sensor and analyze light.
- **Common Types**:
    - **Semiconductor Photodiodes**.
    - **Avalanche Photodiodes (APDs)**.
- **Key Properties**:
    - High sensitivity.
    - Fast response time.
    - Low noise.
    - Cost-effectiveness and reliability.
    - Compact size compatible with fibre core dimensions.

Optical Spectrometers

- **Definition**: Instruments measuring the intensity of light as a function of wavelength or frequency.
- **Functions**:
  - Analyze spectral characteristics of light (reflected, absorbed, scattered, or fluorescence).
  - Measure parameters like wavelength, intensity, and spectral line features.

Flow and Level Sensors

1. Measuring Flow Rate

Flow rate is determined by:

- Measuring the velocity of the fluid.
- Multiplying by the cross-sectional area of the measurement point.

Methods for Airflow Measurement

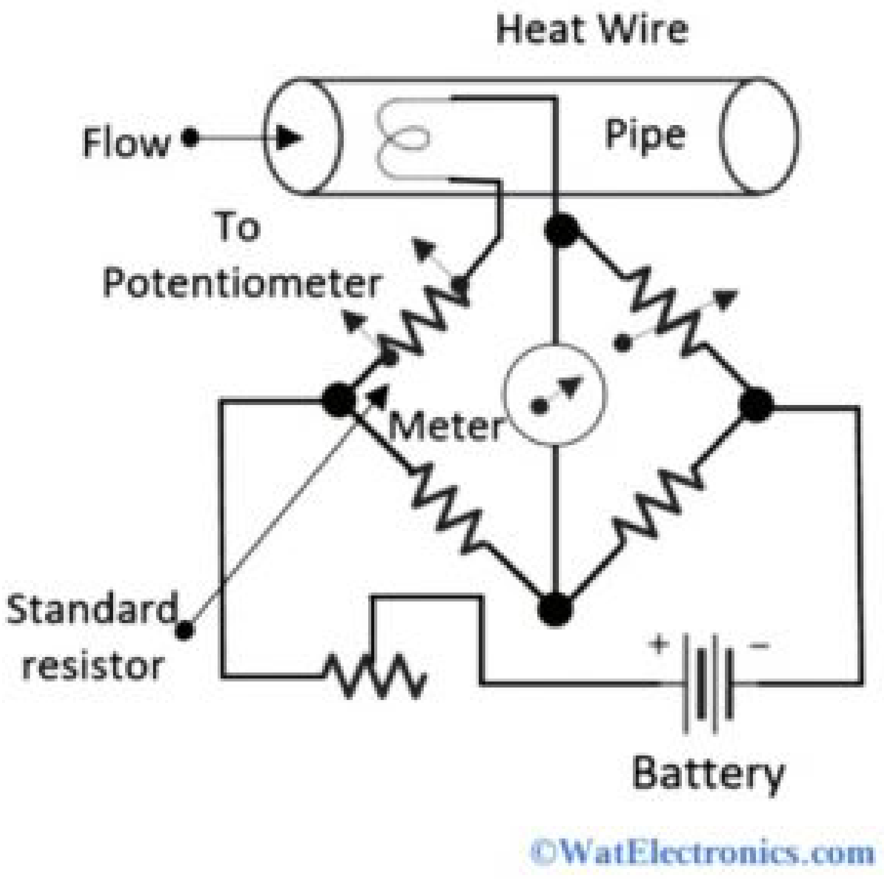
- Thermal Anemometers.
- Differential Pressure Measurement Systems.
- Vortex Shedding Sensors.

Methods for Liquid Flow Measurement

- Differential Pressure Measurement Systems.
- Vortex Shedding Sensors.
- Positive Displacement Flow Sensors.
- Turbine-Based Flow Sensors.
- Magnetic Flow Sensors.
- Ultrasonic Flow Sensors.

Types of Flow Sensors
Thermal Anemometers

- **Principle**: Heat removed from a heated sensor relates to fluid velocity.
- **Features**:
  - Uses an unheated temperature sensor for air temperature compensation.
  - Available as single-point or multi-point arrays.
  - Ideal for low airflow (50 to 12,000 ft/min).



Definition
Hot wire anemometers are thermal anemometers used to measure the direction and velocity of fluid flow by analyzing the heat loss from a heated wire placed in the fluid stream. They are extensively used in fluid mechanics as research tools.

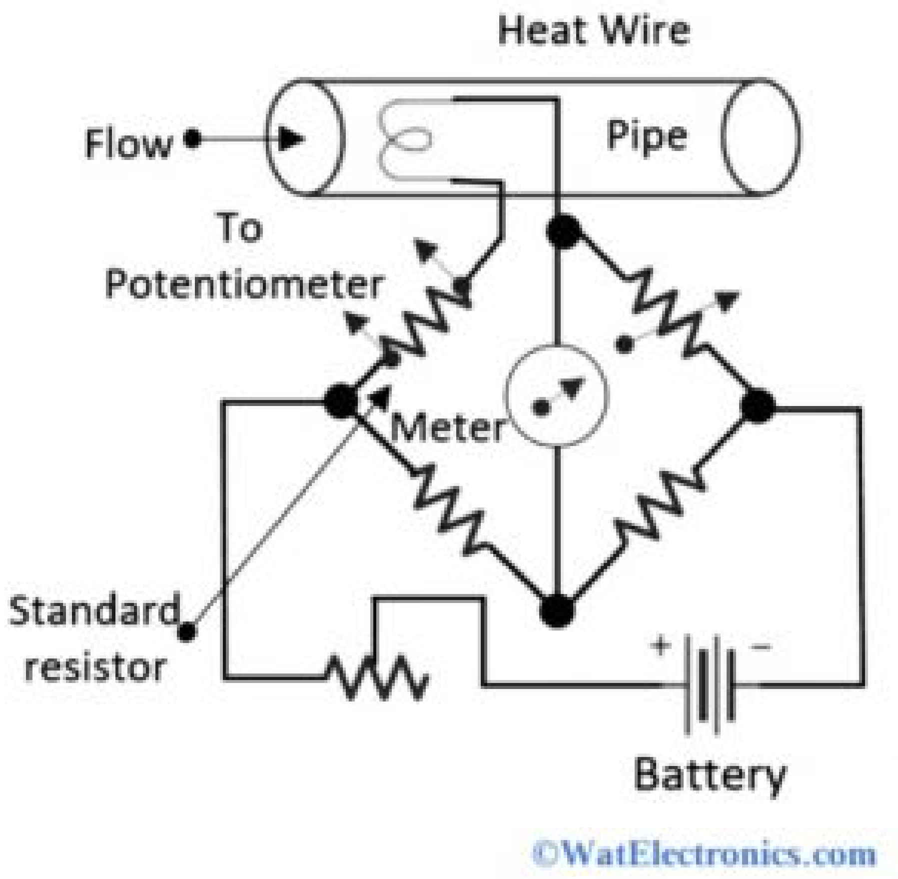
The working of a hot wire anemometer can be explained in two ways to measure the flow rate. They are,

- Constant current method
- Constant temperature method

Working Principle

The operation is based on the relationship between the temperature change of the wire and the fluid velocity:

1. A thin wire is electrically heated to a high temperature.
2. The fluid (air or liquid) flows over the wire, carrying away heat.
3. The rate of heat loss depends on the velocity of the fluid stream.
4. The resistance of the wire changes with its temperature, affecting the electrical current.
5. By monitoring the voltage or current, the instantaneous fluid velocity can be determined.



- **Applications**:
  - Research in **aerodynamics** and **fluid mechanics**.
  - Measurement of wind speed in **environmental studies**.
  - Turbulence analysis in **industrial processes**.

Vortex-Shedding Sensors

- **Principle**:
  - Eddies (vortices) are shed alternately downstream of an obstruction (bluff object).
  - Vortex shedding frequency is proportional to fluid velocity.
- **Features**:
  - Single sensors for small ducts; arrays for larger ducts.
  - Suitable for air velocities between 350 and 6000 ft/min.
  - Not ideal for slurries or high-viscosity fluids.
- **Applications**:
  - Flow rate and total flow measurements in air ducts.

Turbine-Based Flow Sensors

- **Principle**: Fluid flow rotates a turbine/propeller; rotational speed correlates with flow rate.
- **Features**:
  - Electrical pulses for counting and totalizing flow.
  - Available as full-bore or insertion types.
  - Good accuracy for low-viscosity fluids.
- **Applications**:
  - Insertion types: Easy to maintain and inspect without disrupting piping.
  - Full-bore types: Higher accuracy critical measurements.

Mass Flowmeters

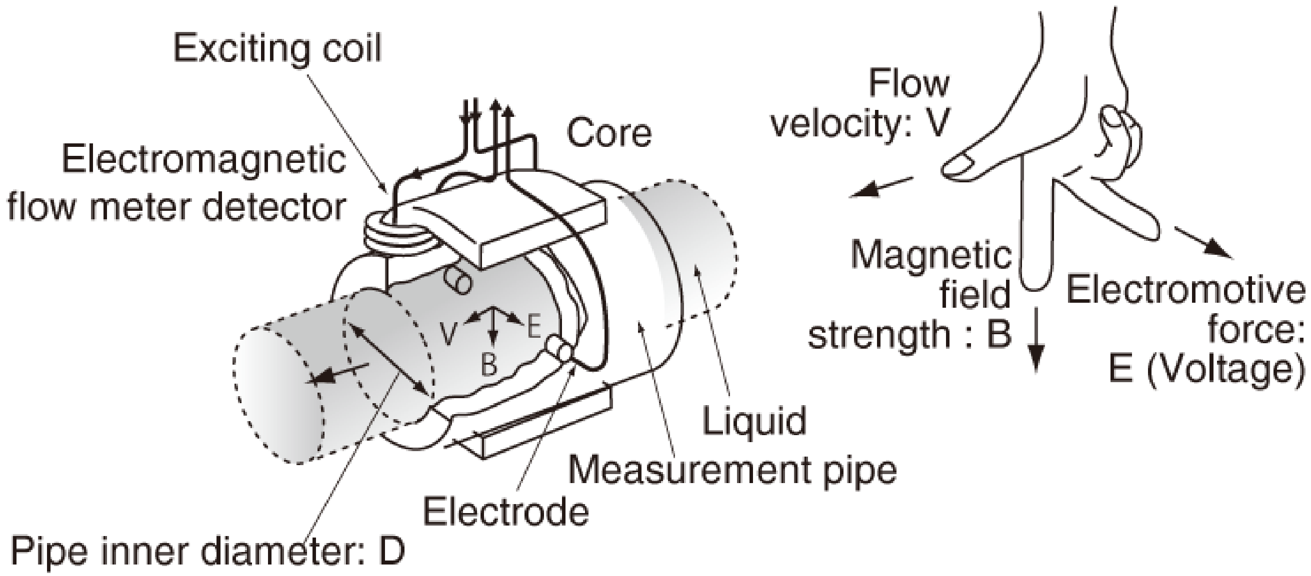
Mass flowmeters measure mass flow rate directly, offering high accuracy for processes sensitive to mass rather than volume.

Coriolis Flowmeters

- **Principle**: Operates on Coriolis force.
- **Features**:
    - Measures mass flow rate directly (no adjustment needed for temperature, pressure, or liquid properties).
    - Ideal for liquids with viscosity variations under changing conditions.
    - Linear response without calibration for different liquids.
- **Construction**:
    - U-shaped flow tube vibrated at natural frequency.
    - Magnetic sensors detect tube twist proportional to mass flow.
    - Electronics unit processes signals up to 500 feet away.
- **Applications**: Adhesives, coatings, and cryogenic liquids like liquid nitrogen.

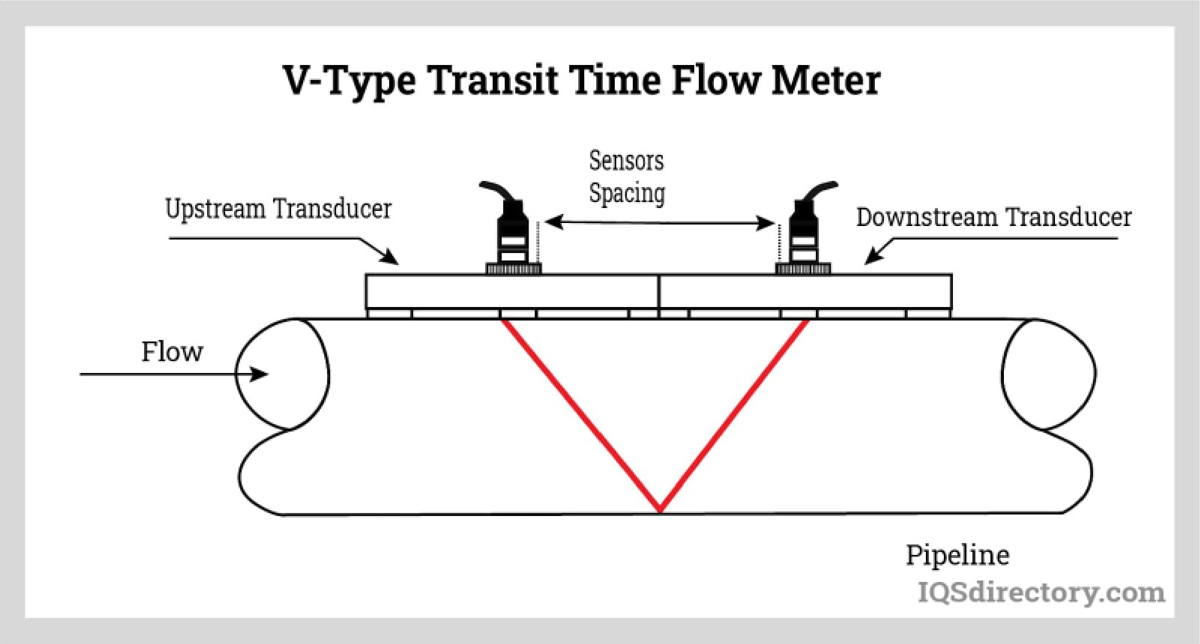
Electromagnetic Flow Sensors

- **Principle**: Based on Faraday's Law of Electromagnetic Induction (voltage induced when a conductor moves through a magnetic field).
- **Features**:
    - The liquid acts as the conductor.
    - Voltage proportional to flow rate.
    - Electrodes sense induced voltage.
- **Advantages**:
    - Measures difficult, corrosive liquids and slurries.
    - Can measure reverse flow.
    - Low maintenance and high reliability.
- **Limitations**:
    - Only applicable for conducting liquids.
    - High cost compared to other flowmeters.



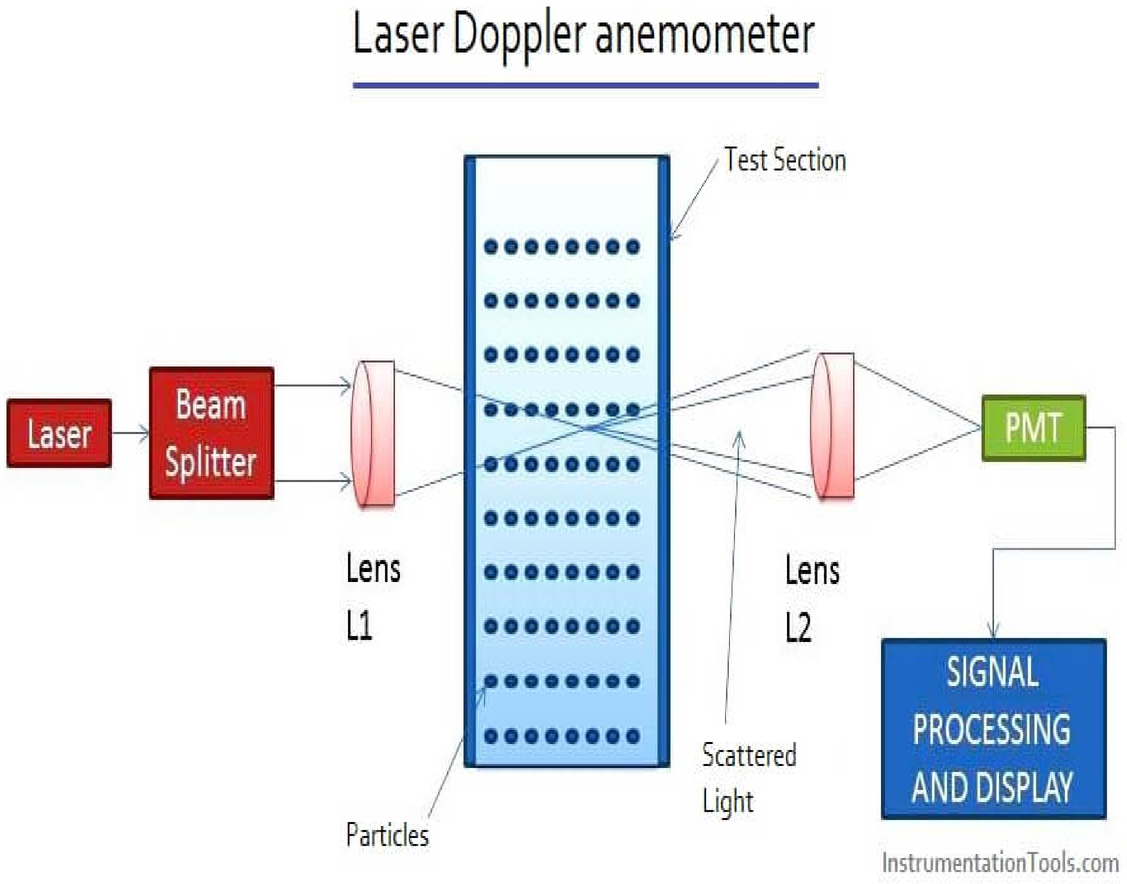
Ultrasonic Flow Sensors

- **Types**:
  - **Doppler Sensors**: Measure frequency shifts caused by flow-induced reflections.
  - **Transit (Time-of-Travel) Sensors**: Measure signal travel time between transducers mounted on either side of a pipe.
- **Features**:
  - Doppler: Requires bubbles or solids for reflection.
  - Transit: Relies on time differentials of sound waves; liquids must be relatively free of solids or gases to minimize scattering.
- **Advantages**:
  - Non-intrusive.
  - Moderate cost.
  - Easy installation (e.g., clamp-on designs).
- **Applications**: Flow measurement in clean or lightly contaminated liquids.



Laser Doppler Flow Measurement (LDA)

- **Principle**: Laser Doppler anemometry uses the Doppler effect to measure fluid velocity.
- **Features**:
  - Non-intrusive and highly directional.
  - Requires tracer particles in the flow to scatter light.
- **Advantages**:
  - Suitable for reversing flow, chemically reactive media, and high temperatures.
  - Ideal for use with rotating machinery.
- **Applications**: Fluid dynamics in liquids and gases, industrial and research setups.



Sensor Type	Key Features	Limitations	Applications
Coriolis	Measures mass flow directly.	Costly, bulky installation.	Viscous fluids, cryogenic liquids.
Electromagnetic	Ideal for conductive liquids.	Limited to conducting fluids.	Corrosive liquids, slurries.
Ultrasonic	Non-intrusive, easy installation.	Not suitable for solids or entrained gases.	Clean liquids, lightly contaminated flows.
Laser Doppler	High precision, directional sensitivity.	Requires tracer particles in flow.	High-temperature and rotating systems.

Level Sensors

Liquid level sensing is crucial for applications such as tank measurement and control operations. Various technologies are available for measuring liquid levels, each suited to specific needs.

1. **Ultrasonic Level Sensors**
    1. **Principle**: Sends ultrasonic waves to the liquid surface; the time it takes for the echo to return determines the level.
    2. **Features**:
        1. Non-contact measurement.
        2. Suitable for a wide range of liquids and environments.
    3. **Applications**:
        1. Wastewater treatment, chemical tanks, and food processing.

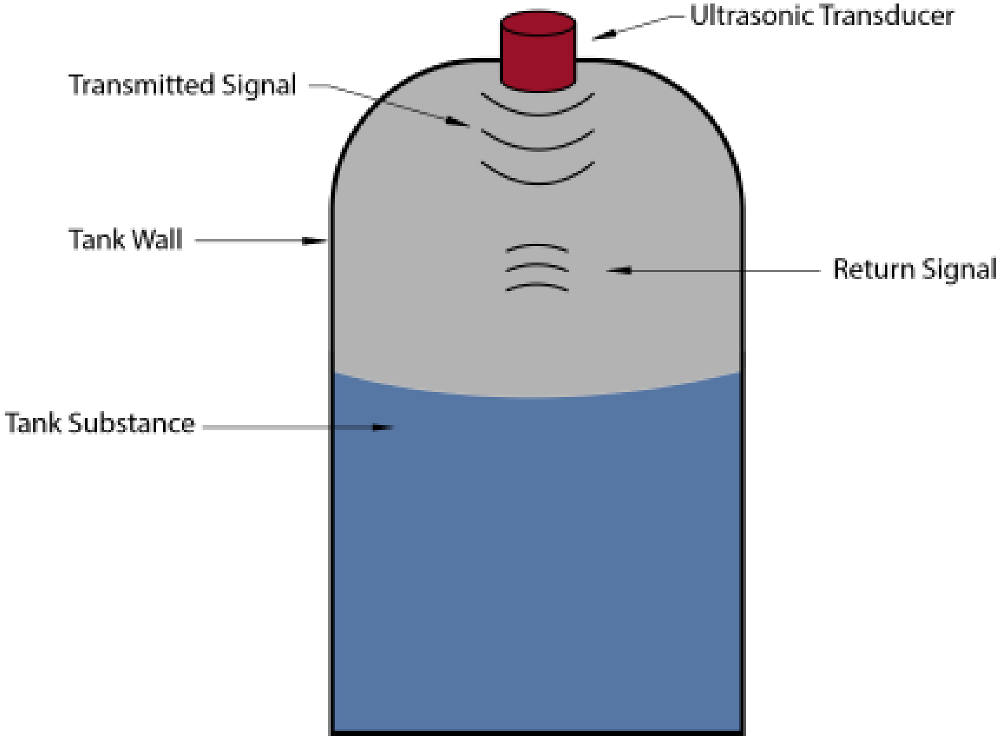
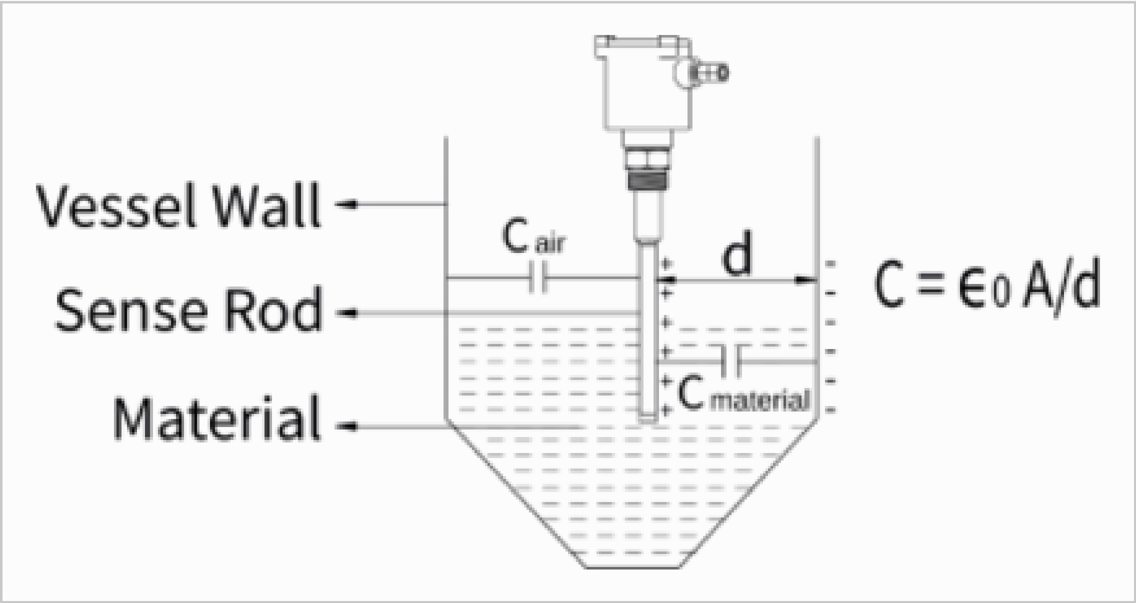


Figure 1: "Top-Down" Ultrasonic Sensor

https://www.youtube.com/watch?v=WY6Bj3f6piE

2. RF Capacitance Level Sensors

1. **Principle**: Measures changes in capacitance as liquid levels change around a probe.
2. **Features**:
    1. Accurate and unaffected by temperature or pressure.
    2. Requires conductive or dielectric liquids.
3. **Applications**:
    1. Industrial processes involving oils, slurries, and chemicals.

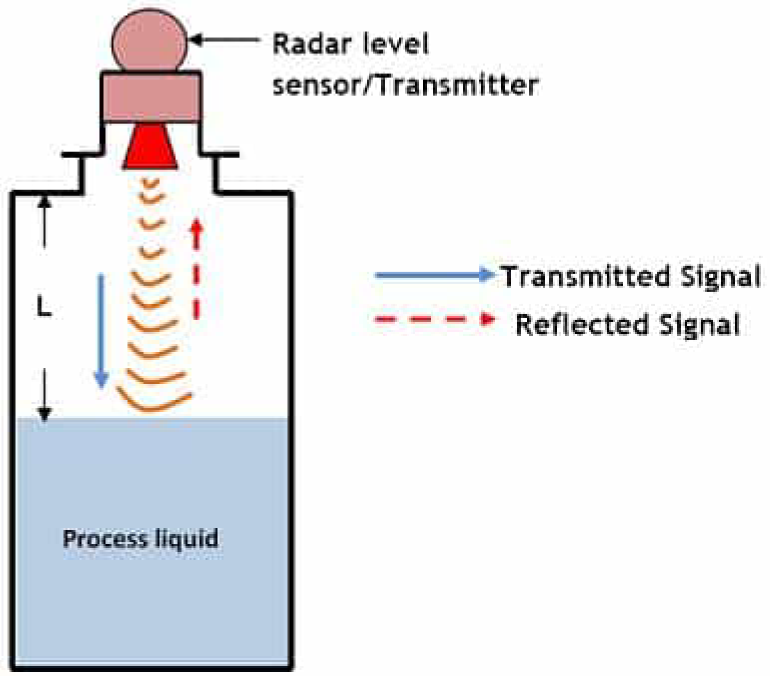


Capacitance Principle

https://www.youtube.com/watch?v=0du-QU1Q0T4

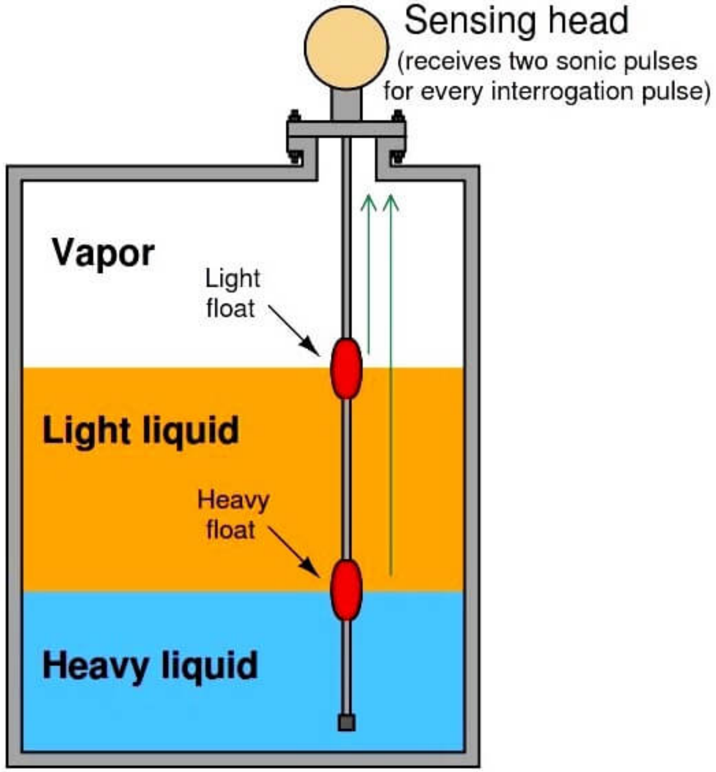
4. **Radar Level Sensors**

- **Principle**: Emits microwave signals towards the liquid surface; the time delay of the reflected signal determines the level.
- **Features**:
  - Highly accurate, non-contact.
  - Works well with varying pressures, temperatures, and foams.
- **Applications**:
  - High-temperature and high-pressure environments, such as oil and gas industries and marine applications.



3. Magnetostrictive-Based Level Sensors

1. **Principle**: Uses a float with a magnetic field; the position of the float along a probe generates a signal indicating the level.
2. **Features**:
   1. High precision and repeatability.
   2. Suitable for hazardous or corrosive environments.
3. **Applications**:
   1. Petrochemical tanks, oil refineries, and cryogenic systems.



https://www.youtube.com/watch?v=DQUDaHcbJkg

How Strain Gage Sensors Work:

Basic Principle: A strain gage consists of a thin, flexible metallic foil pattern attached to a backing material. When a force or load is applied to the object (such as a beam, shaft, or structure) where the strain gage is mounted, the object deforms. This deformation causes the metallic foil to stretch or compress, altering its resistance.

Resistance Change: The change in resistance is proportional to the amount of strain experienced by the material. The relationship between the change in resistance (ΔR) and the strain (ε) is given by:

$$\text{Strain } (\varepsilon) = \frac{\Delta R/R}{GF}$$

where , ΔR is the change in resistance, R is the original resistance, and GF is the gauge factor, a constant that relates the change in resistance to the strain.

What is a Strain Gauge?

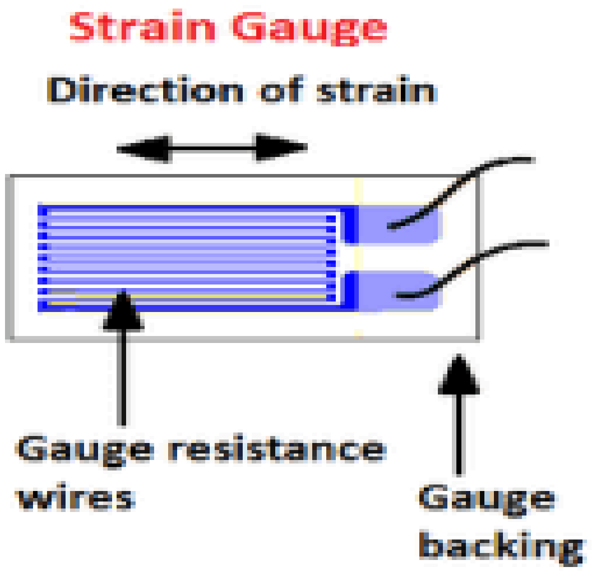


Figure #1

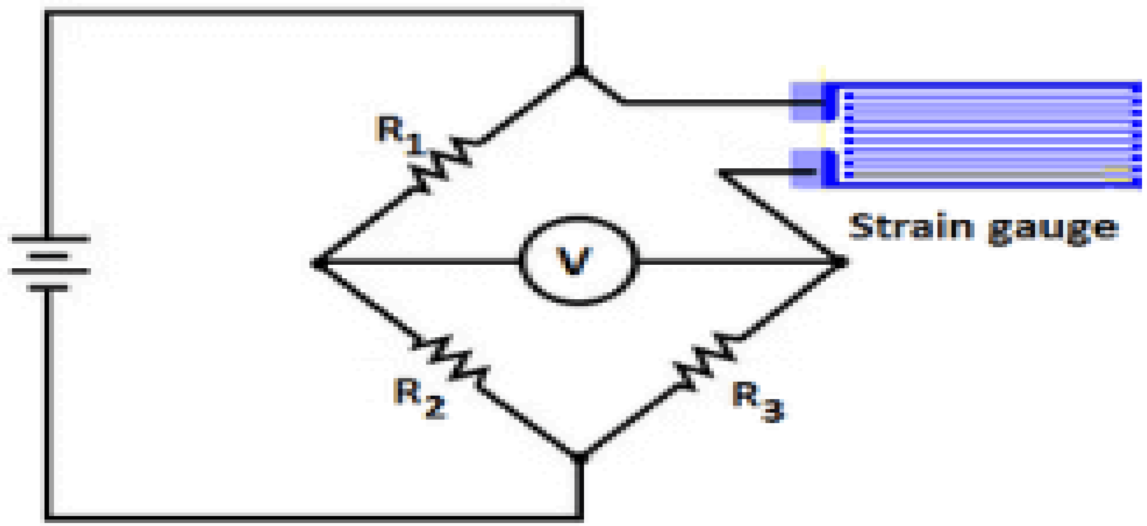


Figure #2

https://www.youtube.com/watch?v=GjmM6KKhgp0

Sensor Type	Key Features	Limitations	Applications
Hydrostatic Pressure	Simple and cost-effective.	Affected by liquid density variations.	Static liquids in tanks.
Ultrasonic	Non-contact, versatile.	Can be affected by foam or turbulence.	Chemical tanks, food processing.
RF Capacitance	High accuracy and reliability.	Limited to conductive/ dielectric liquids.	Oils, slurries, and industrial chemicals.
Magnetostrictive	Precision and repeatability.	Requires specific installation conditions.	Hazardous or corrosive environments.
Radar	Accurate in extreme conditions.	Higher cost relative to other technologies.	Oil, gas, and marine industries.

Measurement Circuit: A Wheatstone bridge circuit is typically used to measure the small changes in resistance. This circuit provides a highly sensitive way to detect changes in resistance due to strain, amplifying the signal for easier measurement.

Applications:

- **Structural Monitoring**: Strain gages are commonly used in civil engineering for monitoring bridges, buildings, and dams to assess the strain on these structures under varying loads.
- **Material Testing**: Used in laboratories for material testing, such as testing the tensile strength of metals, polymers, or composites.
- **Industrial Equipment**: Strain gages are used in machinery, aerospace, and automotive industries to measure forces acting on components like engine parts, wings, or turbines.
- **Load Cells**: Strain gages are the core component in load cells, devices that measure force or weight in scales, weighing systems, and robotics.