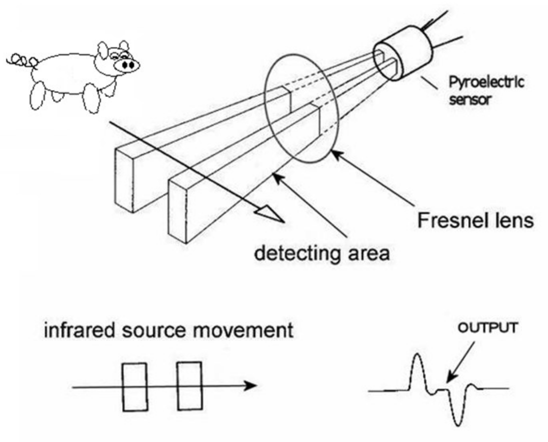
L6- Optical and IR Sensors

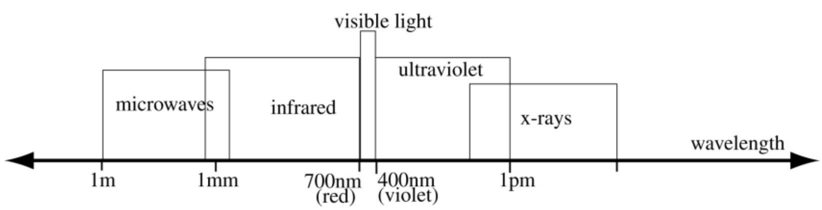


Optical sensors

- Optical sensors are those sensors that detect electromagnetic radiation in the broad optical range – from far infrared to ultraviolet
- Approximate range of wavelengths from **1mm** (3x10^{11} Hz or far infrared) to **1 nm** (3x10^{17} Hz or upper range of the ultraviolet range).
- **Direct methods** of transduction from light to electrical quantities (photovoltaic or photoconducting sensors)
- **Indirect methods** such as conversion first into temperature variation and then into electrical quantities (PIR sensors).

Spectrum of "optical" radiation

- Nomenclature:
  - Visible light
  - Infrared radiation (not infrared "light")
  - Ultraviolet radiation (not UV "light")
- Ranges shown are approximate and somewhat arbitrary



Infrared radiation

- Approximate spectrum
  - 1mm (300 GHz) to 700nm (430 THz)
- Meaning: below red
- Near infrared (closer to visible light)
- Far infrared (closer to microwaves)
- Invisible radiation, usually understood as "thermal" radiation
- 1nm=10^{-9}m 1GHz=10^{9} Hz, 1THz=10^{15} Hz

Visible light

- Approximate spectrum
  - 700nm (430 THz) to 400nm (750 THz)
- Based on our eye's response
- From red (low frequency, long wavelength)
- To violet (high frequency, short wavelength)
- Our eye is most sensitive in the middle (green to yellow)
- Optical sensors may cover the whole range, may extend beyond it or may be narrower

- For a sensor, we're interested in the light power that falls on a unit area, and how well the sensor converts that into a signal.
- A common unit is **the lux** which measures apparent brightness (power multiplied by the human eye's sensitivity).
- Sunlight corresponds to about 50,000 lux
- Artificial light typically 500-1000 lux

Ultraviolet (UV) radiation

- Approximate spectrum
  - 400nm (750 THz) to 400pm (300 PHz)
- Meaning - above violet
- Understood as “penetrating” radiation
- Only the lower end of the UV spectrum is usually sensed
- Exceptions: radiation sensors based on ionization

Optical sensing

- Based on two principles
  - Thermal effects of radiation
  - Quantum effects of radiation
- Thermal effects: absorption of radiation of the medium through increased motion in atoms. This may release electrons (heating)
- Quantum effects: photon interaction with the atoms and the resulting effects, including release of electrons.

The photoelectric effect

- Photons collide with electrons at the surface of a material
- The electrons acquire energy and this energy allows the electron to:
  - Release them selves from the surface of the material by overcoming the ***work function*** of the substance.
  - Excess energy imparts the electrons kinetic energy.

Photo-conducting effect

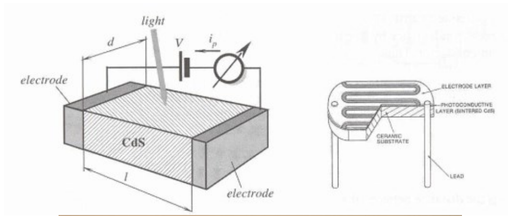
- Conductivity results from the charge, mobilities of electrons and holes and the concentrations of electrons, n and p from whatever source.
- In the absence of light, the material exhibits what is called dark conductivity, which in turn results in a dark current.
- Depending on construction and materials, the resistance of the device may be very high (a few MegaOhms (MΩ) or a few kΩ.
- When the sensor is illuminated, its conductivity changes depending on the change in carrier concentrations (excess carrier concentrations).

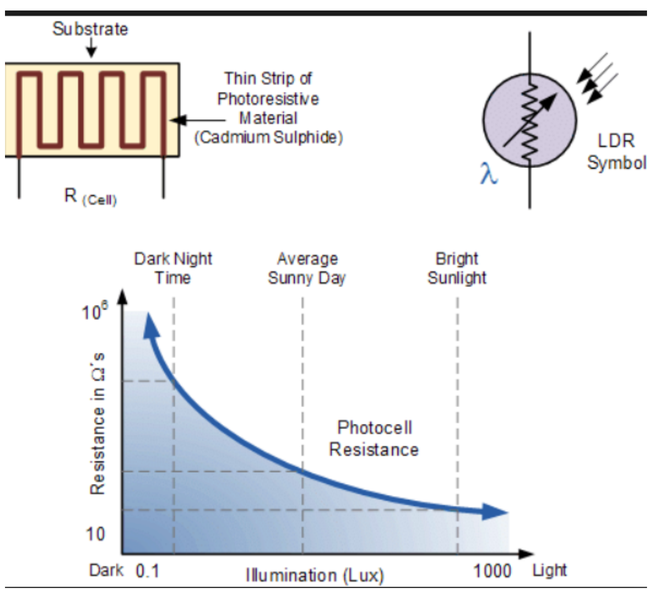
Light Sensors/Detectors

- Simplest light sensor is an LDR (Light-Dependent Resistor).
- Optical characteristics close to human eye.
- Common material is CdS (Cadmium Sulphide)
- Sensitivity:

Typical

dark 1 MΩ,
10 lux 40 kΩ,
1000 lux 400 Ω.



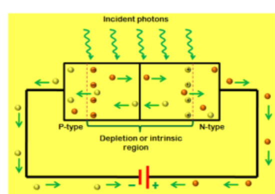


Photodiodes

- Semiconductor diode exposed to radiation
- Excess carriers due to photons add to the existing charges in the conduction band exactly in the same fashion as for a pure semiconductor.
- The diode itself may be reverse biased, forward biased or unbiased
- **Forward biased mode is** not useful as a photosensor
  - Number of carrier in conducting mode is large
  - Number of carrier added by radiation small
  - Sensitivity is very low

The working principle of a photodiode:

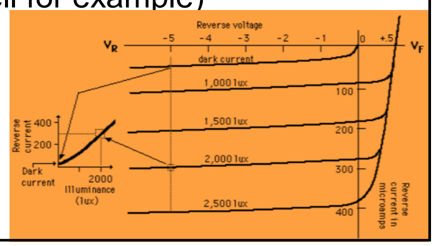
- When a photon with enough energy strikes the diode, it makes a pair of electron-hole. This mechanism is also called as the inner photoelectric effect.
- If the absorption happens in the depletion region, then the carriers are removed from the junction by the built-in electric field of the depletion region.
- Therefore, holes in the region move toward the anode, and electrons move toward the cathode, and a photocurrent will be generated.
- The entire current through the diode is the dark current in absence of light and the photocurrent.



PN Junction Diode

Photodiode - two modes

- 1. Photoconductive mode
  - Diode is reverse biased
  - Operates similarly to a photoconductor
  - The reverse voltage application will increase the depletion layer's width, which in turn decreases the response time & the junction capacitance. This mode is fast and displays electronic noise
- 2. Photovoltaic mode
  - Diode is not biased
  - Operates as a source (solar cell for example)
- It gives a very small dynamic range & non-linear characteristic



Photodiode - construction

- Any diode can serve as a photodiode if:
  - n region, p region or pn junction are exposed to radiation
  - Usually exposure is through a transparent window or a lens
  - Sometimes opaque materials are used (IR, UV)
- Specific structures have been developed to improve one or more of the characteristics
  - PIN diode: Addition of the intrinsic p layer increases resistance
  - Reduces dark current
- Phototransistors and photo-Darlington transistors are also available.
- Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.

Photodiodes - construction

- Available in various packages and for various applications
  - Individual diodes in cans with lenses
  - Surface mount diodes used in infrared remote controls
  - Arrays (linear) of various sizes for scanners
  - Infrared and UV diodes for sensing and control

- Photodiode as used in in a CD player

Photodiode array used a scanner

Photovoltaic diodes

- The diode is not biased
- Serves as a generator
  - Carriers generated by radiation create a potential difference across the junction
  - Any photodiode can operate in this mode
  - Solar cells are especially large-surface photodiodes

Light sensors – high end

- At the cutting edge of light sensor sensitivity are **Avalanche photodiodes**.
- Large voltages applied to these diodes accelerate electrons to "collide" with the semiconductor lattice, creating more charges.
- These devices have quantum efficiencies around 90% and extremely low noise.
- They are now made with large collection areas and known as LAAPDs (Large-Area Avalanche Photo-Diode)

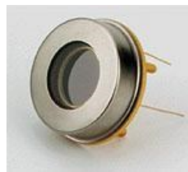


Photo Interrupt

- Uses emitter and detector photo diode pair
- With no obstruction detector is high
- When an object blocks the light the detector is low
- Advantages
  - Simple to interface
  - Inexpensive
  - Reliable

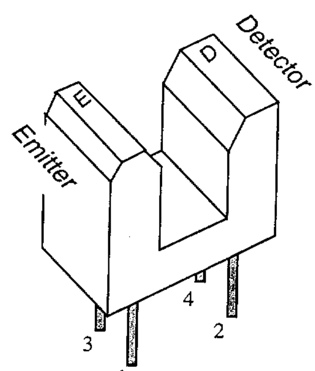


Photo Interrupt
Types

- Wide variety of packages and orientations
- Types
  - Logic (digital ±5 volts)
  - Transistor/diode (analog)
- Manufacturers
  - Fairchild
  - Honeywell

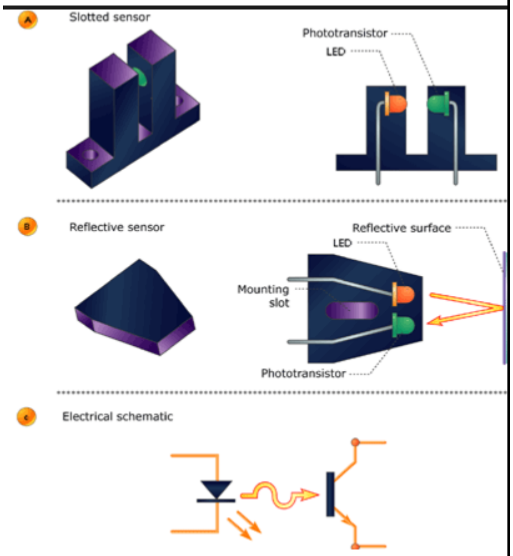
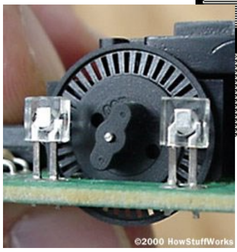
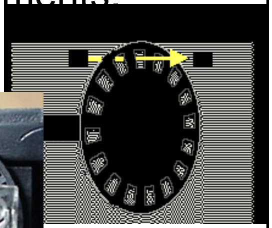


Photo Interrupt
Applications

- Encoder wheel for angular measurements.
- Computer mouse with a ball

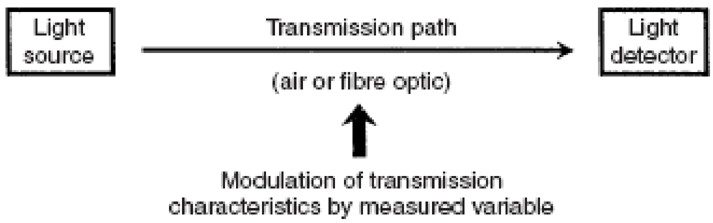




- Detect holes or slots for positioning as in elevators
- Detect the location of products on and assembly line

Optical sensors

- Optical sensors are based on the modulation of light travelling between a light source and a light detector.
- The transmitted light can travel along either an **air path or a fibre-optic cable.**
- Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in hazardous environments.



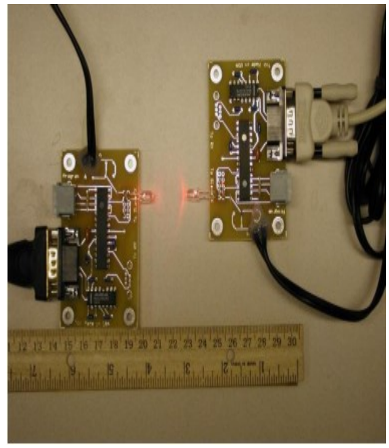
Optical Sensors: Advantages and applications

- ELECTROMAGNETIC IMMUNITY
- ELECTRICAL ISOLATION
- COMPACT AND LIGHT
- WIDE DYNAMIC RANGE

- Example Apps:

Temperature; Pressure; Flow; Liquid Level; Displacement; Vibration; Rotation; Acceleration; Magnetic Field; Humidity; Strain;

Optical sensors



- Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs).
- However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources.
- Hence, **infrared LEDs or infrared laser diodes are usually preferred**.
- These emit light in a narrow frequency band in the infrared region and are not affected by sunlight

- Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration

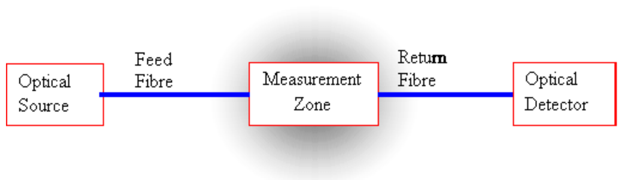
Fibre-Optic Sensors

- **As an alternative to using air as the transmission medium, optical sensors can use fibre-optic cable instead to transmit light between a source and a detector**.
- In such sensors, the variable being measured causes some **measurable change in the characteristics of the light transmitted by the cable**. The proportion of light entering the cable must be maximized
- The basis of operation of fibre-optic sensors is the translation of the physical quantity measured into a change in one or more parameters of a light beam.

Fibre-optic sensors characteristic

- Fibre-optic sensors characteristically enjoy long life. For example, the life expectancy of reflective fibre-optic switches is quoted at ten million operations.
- Their accuracy is also good, with, for instance, +/- 1% of full-scale reading being quoted as a typical inaccuracy level for a fibre-optic pressure sensor.
- Further advantages are their simplicity, low cost, small size, high reliability and capability of working in many kinds of hostile environment.

WORKING PRINCIPLE

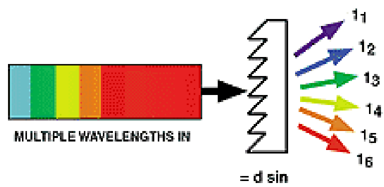


- **Light beam changes by the phenomena that is being measured**
- **Light may change in its five optical properties i.e intensity, phase, polarization , wavelength and spectral distribution**

SENSING DETAILS

$$E_p(t)\cos[\omega t+\theta(t)]$$

- Intensity based sensors – E_p (t)
- Frequency varying sensors - $\omega_p(t)$
- Phase modulating sensing- $\theta(t)$
- Polarization modulating fiber sensing



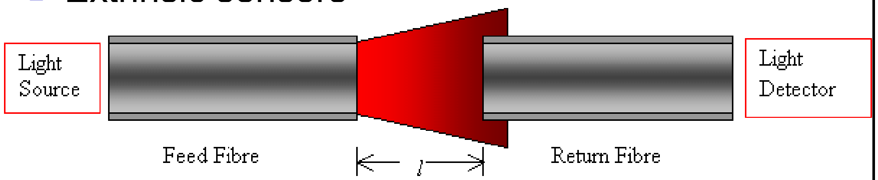
38

Fibre-optic sensors Classification

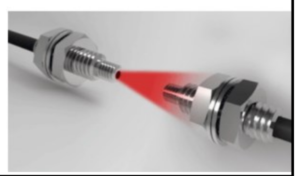
- Two major classes of fibre-optic sensor exist, **intrinsic** sensors and **extrinsic** sensors.
- In *intrinsic sensors*, the fibre-optic cable itself is the sensor,
- whereas in *extrinsic sensors*, the fibre-optic cable is only used to guide light to/from a conventional sensor.

CLASSIFICATION

- Extrinsic sensors

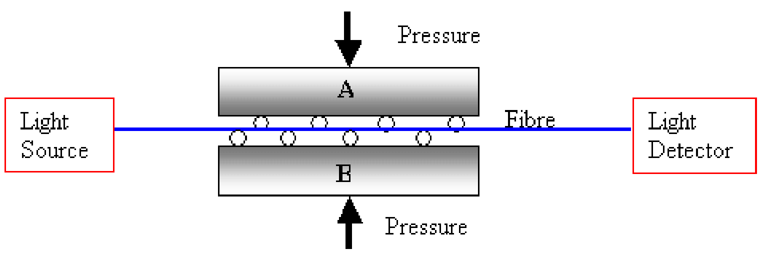


where the light leaves the feed or transmitting fiber to be changed before it continues to the detector by means of the return or receiving fiber



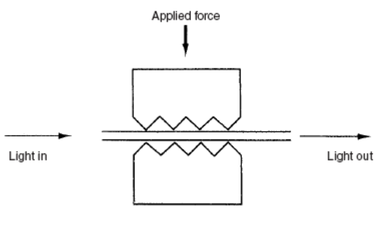
CLASSIFICATION (contd.)

- INTRINSIC SENSORS



intrinsic sensors are different in that the light beam **does not leave the optical fiber** but is changed whilst still contained within it.

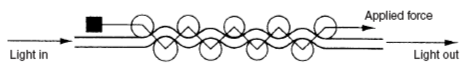
- In pressure sensors, the refractive index of the fibre, and hence the intensity of the light being transmitted, varies according to the mechanical deformation of the fibres caused by pressure

- 

(a)

  ← simple pressure sensor

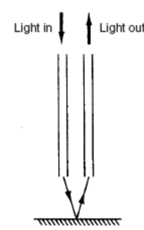
- Roller-chain pressure sensor →



Fibre-optic sensors

- Proximity sensor

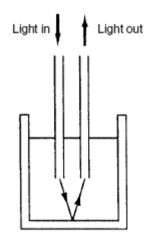
The amount of light reflected varies with the distance between the fibre ends and a boundary



(c)

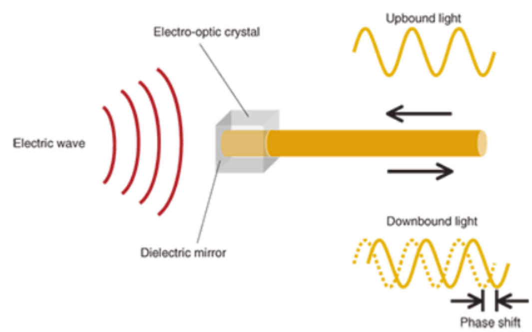
- pH sensor

The amount of light reflected back into the fibers depend on the pH-dependant color of the chemical indicator in the solution around the probe tip



(d)

- **Optical Fiber Electric Field Sensor for Antenna Measurement**



Infrared Sensors

- An infrared sensor is an electronic instrument that is used to sense certain characteristics of its surroundings by either emitting and/or detecting infrared radiation.
- It is also capable of measuring heat of an object and detecting motion.
- Infrared waves are not visible to the human eye.
- In the electromagnetic spectrum, infrared radiation is the region having wavelengths longer than visible light wavelengths, but shorter than microwaves.
- The infrared region is approximately demarcated from 0.75 to 1000µm.
- The wavelength region from 0.75 to 3µm is termed as near infrared, the region from 3 to 6µm is termed mid-infrared, and the region higher than 6µm is termed as far infrared.

46

Infrared Sensor

- Infrared technology is found in many of our everyday products.
- For example, TV has an IR detector for interpreting the signal from the remote control.
- **Key benefits of infrared sensors include low power requirements, simple circuitry, and their portable feature.**

47

Types of Infra-Red Sensors

- Infra-red sensors are broadly classified into two types:
- **Thermal infrared sensors** – These use infrared energy as heat. Their photo sensitivity is independent of wavelength. Thermal detectors do not require cooling; however, they have slow response times and low detection capability.
- **Quantum infrared sensors** – These provide higher detection performance and faster response speed. Their photo sensitivity is dependent on wavelength. Quantum detectors have to be cooled so as to obtain accurate measurements. The only exception is for detectors that are used in the near infrared region.

48

Working Principle

- A typical system for detecting infrared radiation using infrared sensors includes the infrared source such as blackbody radiators, tungsten lamps, and silicon carbide.
- In case of active IR sensors, the sources are infrared lasers and LEDs of specific IR wavelengths.
- Next is the transmission medium used for infrared transmission, which includes vacuum, the atmosphere, and optical fibers.

49

Working Principle

- Thirdly, optical components such as optical lenses made from quartz, CaF_2, Ge and Si, polyethylene
- Fresnel lenses, and Al or Au mirrors, are used to converge or focus infrared radiation. Likewise, to limit spectral response, band-pass filters are ideal.
- Finally, the infrared detector completes the system for detecting infrared radiation.
- The output from the detector is usually very small, and hence pre-amplifiers coupled with circuitry are added to further process the received signals

50

Applications

- Tracking and art history
- Climatology, meteorology, and astronomy
- Thermography, communications, and alcohol testing
- Heating, hyper-spectral imaging, and night vision
- Biological systems, photo-bio-modulation, and plant health
- Gas detectors/gas leak detection
- Water and steel analysis, flame detection
- Anesthesiology testing and spectroscopy
- Petroleum exploration and underground solution
- Rail safety.

51

Heat vision

- Heat can be "seen" at a distance. Recall temperature = heat/atom. At room temp each atom has average energy 6.3×10^{-21} J
- Some of this energy is emitted as photons.
- A photon of energy E and frequency f satisfies:

$$E = h f$$

where h is Planck's constant = 6.63×10^{-34} J sec
- Thermal photons have frequency ~ 10^{13} Hz and wavelength ~ 30 μm
- This is in the far infrared range. Sensors that respond to those wavelengths can "see" warm objects without other illumination.

Thermal Imagers

- Far infrared CCD cameras exist for 10 μm and above, but are much more sophisticated (and expensive) than near-infrared CCDs.
- Generally many $1000s

Thermal sensors

- PIR (Pyroelectric InfraRed) sensors can detect IR heat radiation (7-20 μm typical).
- They are simple, cheap and common. The basis of security system “motion detectors”.
- Most PIR sensors contain two or four sensors with different viewing regions.
- They detect a change in the difference between the signals and give a binary output.

What is a Passive/Pyroelectric Infrared (PIR) Sensor?

- Used to detect motion
- Basically made up of pyroelectric sensors
  - Detect levels of infrared radiation
- Does not emit any radiation, only detects, hence passive
- Note: PIR sensors are slow with time constants ~ 1 sec
- Eltec two-element sensor, shown with matching fresnel IR lens and mounting:

- NAIS ultra-compact PIR sensor

Practical Applications

- Motion Detection
  - Automatic doors
  - Interactive Rooms
    - Activate when person enters room
  - Remote triggered cameras
    - Take photos/start recording when person enters room
- Measuring Temperature Differentials
  - Measure temperatures of remote objects

3/1/2020 Slide-56

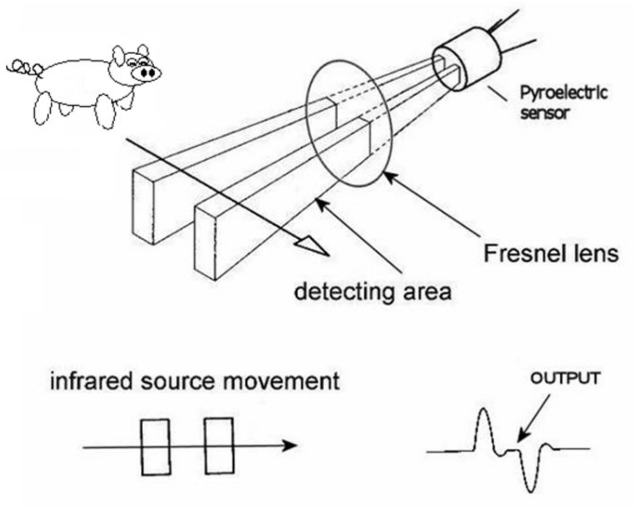
How It Works – Theory

- Infrared radiation exists in the EM spectrum
  - Can't be seen, but can be detected
- Objects that generate heat also generate IR radiation
- PIR sensor consists of two sensing elements
  - One gives a frame of reference and the other detects the change
  - Can only detect the difference in temperatures between the two sensors

How It Works – Theory (cont.)

- **For example:** A PIR sensor is pointed into a room. An animal, with a temperature greater than the wall, walks into the room.
- As the animal crosses the first sensor, a positive pulse is produced.
- When the animal is in front of both sensors, there is no sensed change.
- As it crosses the second sensor, a negative pulse is emitted. These pulses are what is detected.
- An illustration of this example is shown on the next slide

How It Works – Theory (cont.)

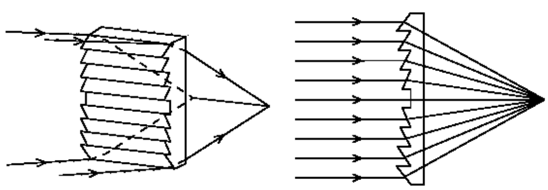


http://www.glolab.com/pirparts/infrared.html

3/1/2020 Slide-59

How It Works – Fresnel Lens

- Captures more IR radiation
- Focuses the radiation into a smaller point
- Condenses the light and provides a larger range of IR to the sensor



http://www.ladyada.net/learn/sensors/pir.html

3/1/2020 Slide-60

How It Works – Fresnel Lens (cont.)

- Usually thin and flexible
  - About 0.015 inches thick
- Made of material opaque to visible light
  - Materials that pass visible light will not pass infrared radiation (e.g. glass, plastic, etc.)

Major Specifications

- Power requirements
- Communication (Output):single bit high/low output
- Dimensions
- Operating Temperature
- Range and Detection Angle

Limitations

- Sensing can be confused
  - Motion too close to sensor
  - Motion is not passed through sensor one at a time
  - Cannot detect slow moving or stationary objects
  - Sensor is approached straight on
- Limited range in most sensors
- Temperature sensitive