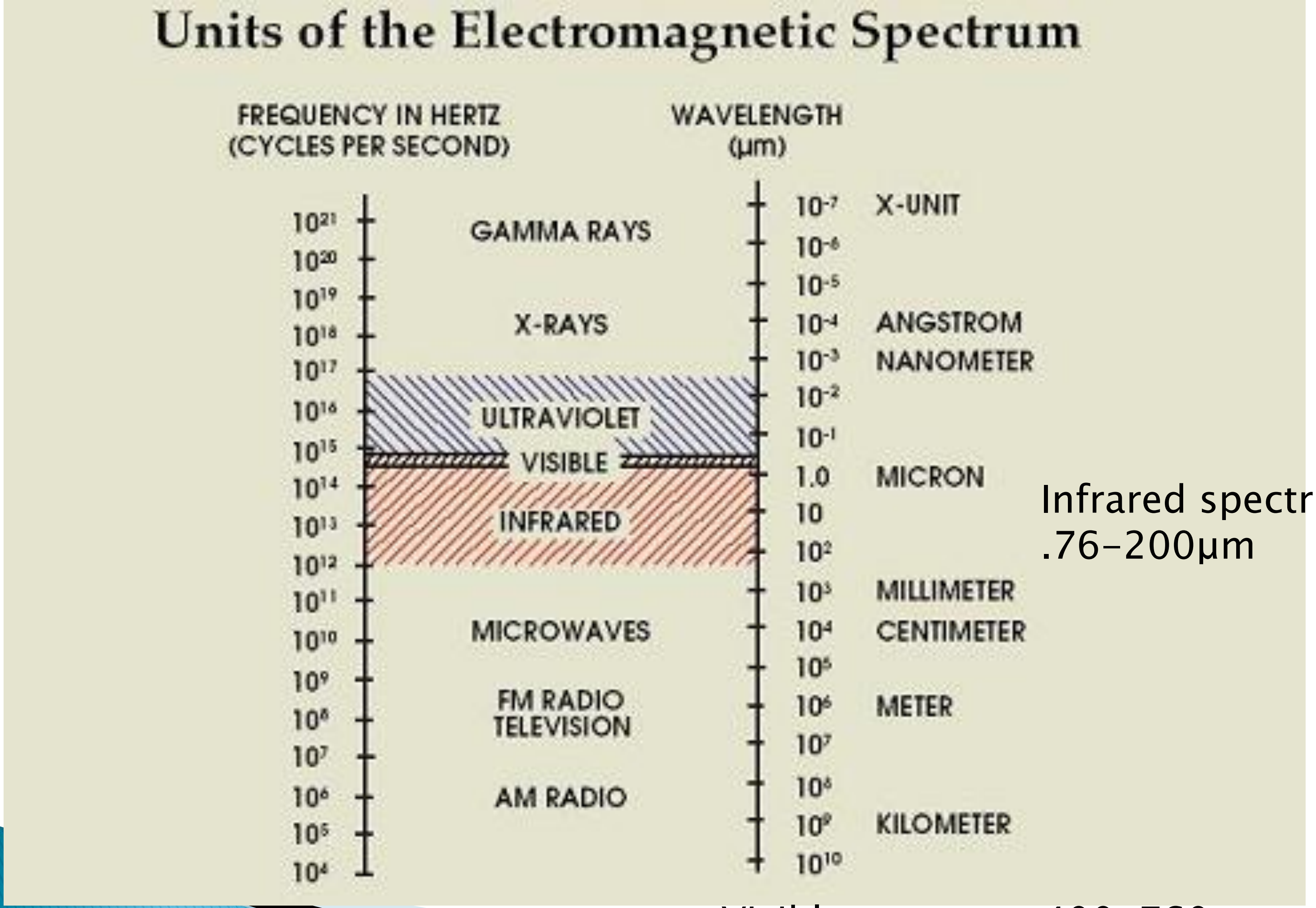
Optical Sensors

- Describe EM radiation in terms of frequency and wavelength
- Define the energy of EM radiation
- Compare photoconductive, photovoltaic and photodiode
- Distinguish incandescent, atomic and florescent sources

Frequency and Wavelength

- C=λ.f
- **λ is wavelength**
- f frequency
- C is speed of light in vacuum (3*10^8 m/s)
- Refractive index n=c/*ν* where *ν* is the velocity of EM radiation in the material
- Photon energy W=h.f=hc/λ (Joule)
- Intensity (I)=power in watt/beam cross sectional area in squared meter

Radiation Sensors



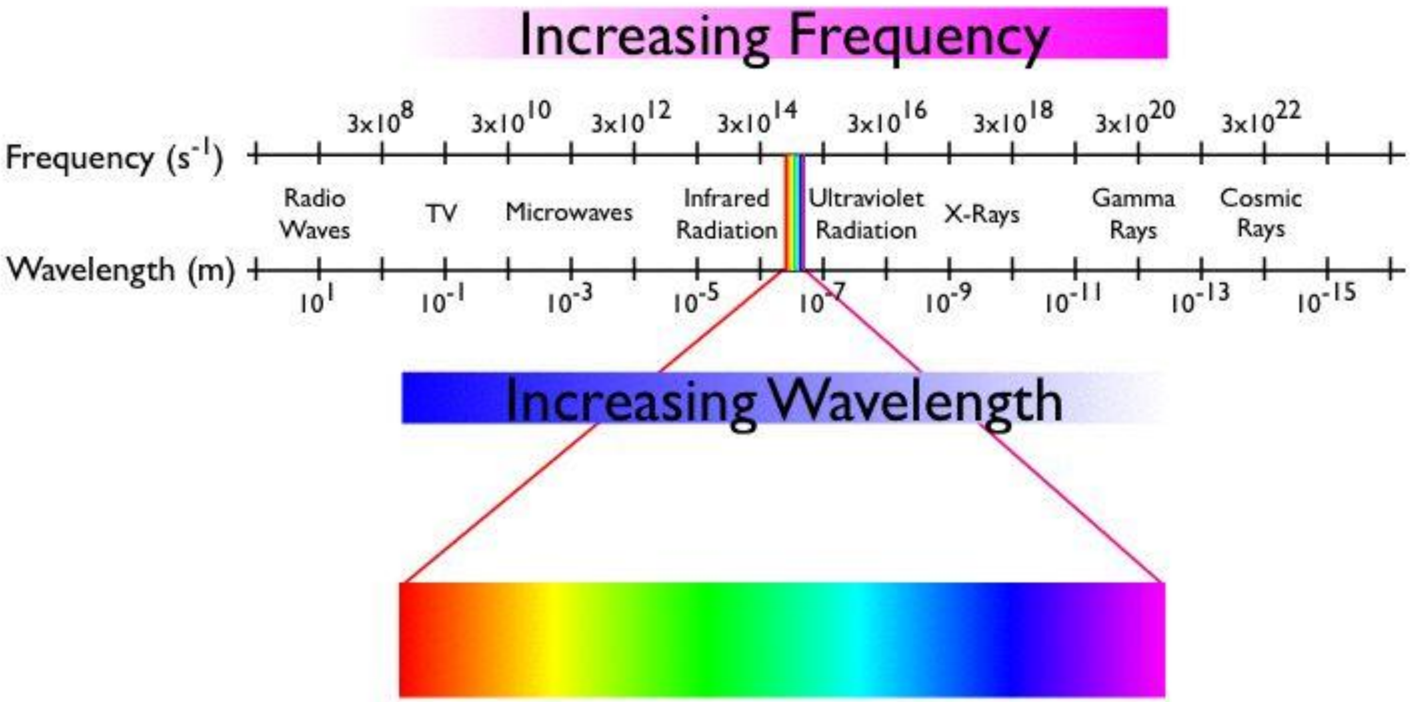
Infrared spectrum
.76-200µm

Visible spectrum 400-760nm

Spectrum

Band	Wavelength	Frequency
MF medium frequency		300-3000 kHz
HF high frequency		3-30 MHz
Radio	20 cm - 20 m	15 MHz - 1.5 GHz
FM	2.5-3.5 m	85-120 MHz
ShortWave	20 cm - 2.5 m	120 MHz - 1.5 GHz
Microwave	0.01-20 cm	1.5-3000 GHz
EHF extremely high frequency		30-300 GHz
Far Infrared	20,000-100,000 nm	3000-15000 GHz
Near Infrared	700-20,000 nm	15000-430,000 GHz
Visible	400-700 nm	430,000-750,000 GHz
Red	620-760 nm	
Orange	570-620 nm	
Yellow	550-570 nm	
Green	470-550 nm	
Blue	440-470 nm	
Violet	380-440 nm	
Ultraviolet	50-190-400 nm	10^{15} - 10^{17} Hz
Soft XRay	1-20 nm	10^{17} - 10^{20} Hz
Hard XRay	0.1-1 nm	
Gamma ray	0.1 - 0.000001 nm	Highest 10^{20} - 10^{24} Hz

Spectrum


Increasing Frequency
3x10^8
3x10^10
3x10^12
3x10^14
3x10^16
3x10^18
3x10^20
3x10^22
Frequency (s^-1)
Radio Waves
TV
Microwaves
Infrared Radiation
Ultraviolet Radiation
X-Rays
Gamma Rays
Cosmic Rays
Wavelength (m)
10^1
10^-1
10^-3
10^-5
10^-7
10^-9
10^-11
10^-13
10^-15
Increasing Wavelength

Basic Optical Phenomena

Refraction governed by Snell's law defining the relationship between incident and transmitted rays at the interface of two media

$n_1 \sin(\varphi_1) = n_2 \sin(\varphi_2)$ Eq. 1 (n_1 and n_2 are indices of refraction

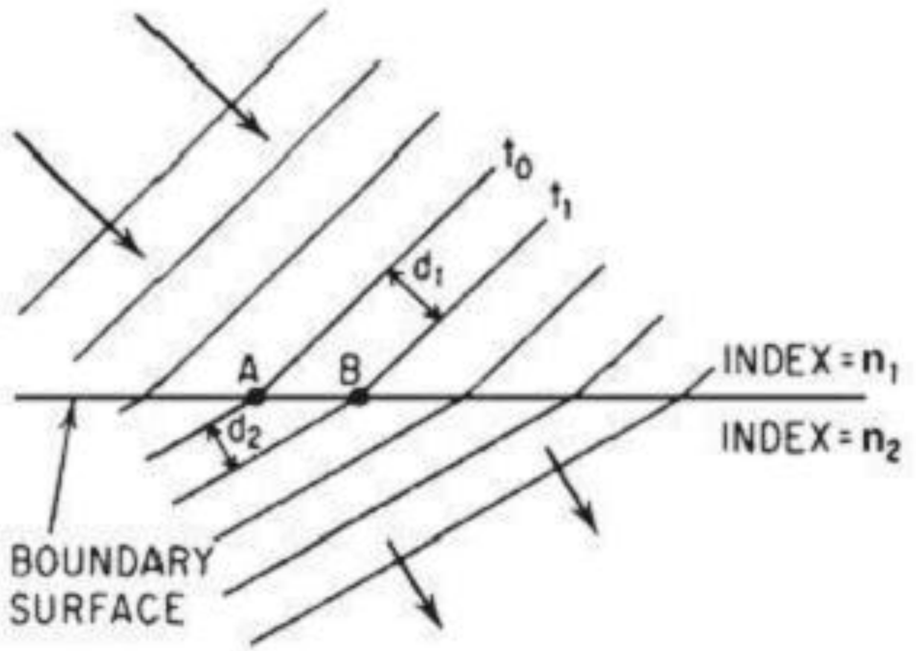


Figure 1.4 A plane wave front passing through the boundary between two media of differing indices of refraction ($n_2 > n_1$).

Review of optical phenomena that might be used in microsensors

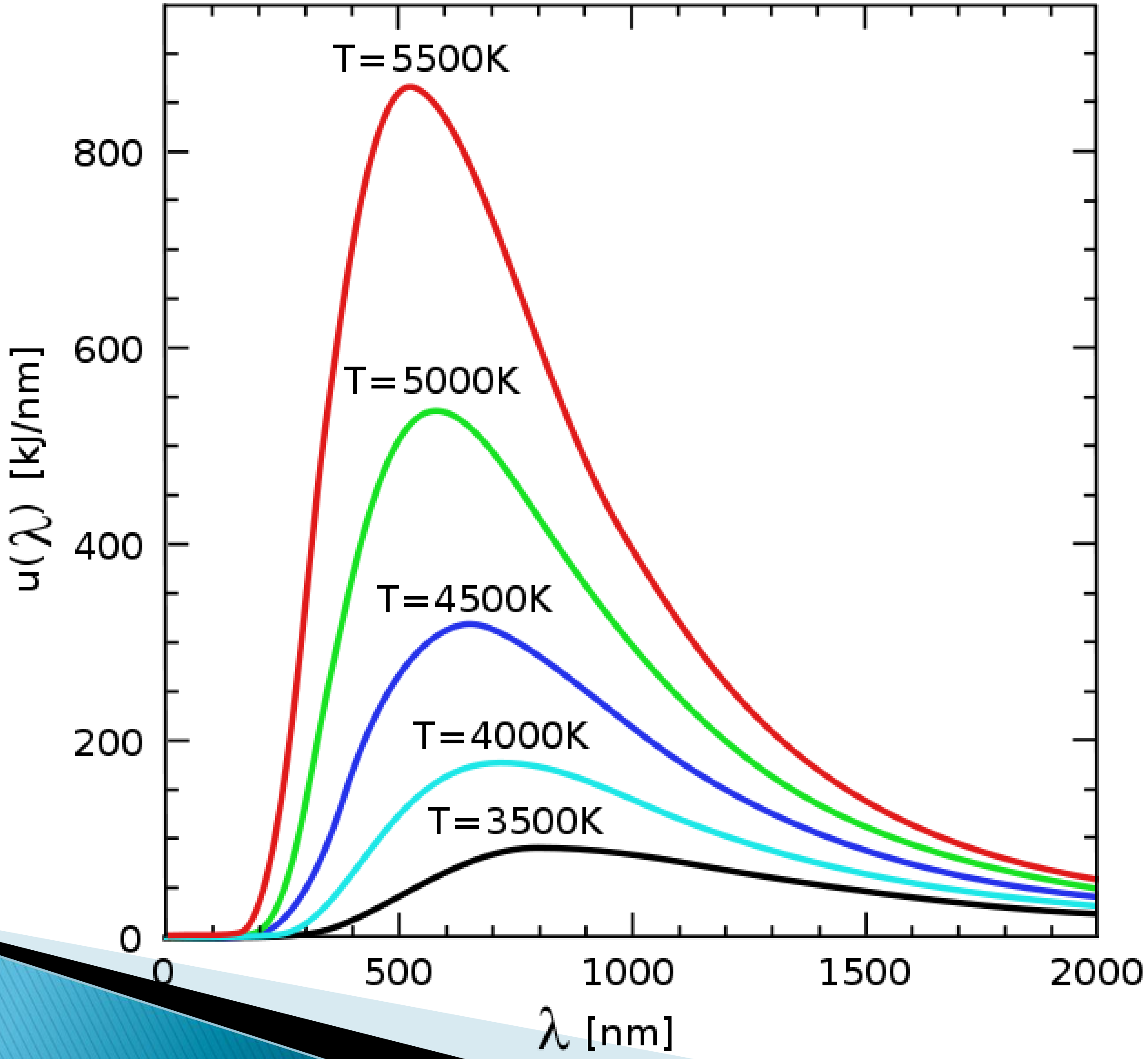
Name of effect	Description
Photovoltaic	A voltage is generated by incident radiation at the juction of two dissimilar materials
Photomagnetoelectric	An electrical field is generated by both a magnetic field and incident radiation
Photoconductivity	Electrical conductivity is increased due to incident radiation
Photoelectric	Electrons and holes are generated and separated in a junction area by incident radiation
Photodielectric	The change of a dielectric constant due to incident radiation
Laser	Energy is generated by an optical resonance cavity
Photoluminescence	Radiant energy is emitted by incident radiation with shorter wavelength
Radioluminescence	Visible radiant energy is emitted by incident x- rays or gamma rays
Radiation heating	The increase of temperature of a material by incident radiation

Divergence

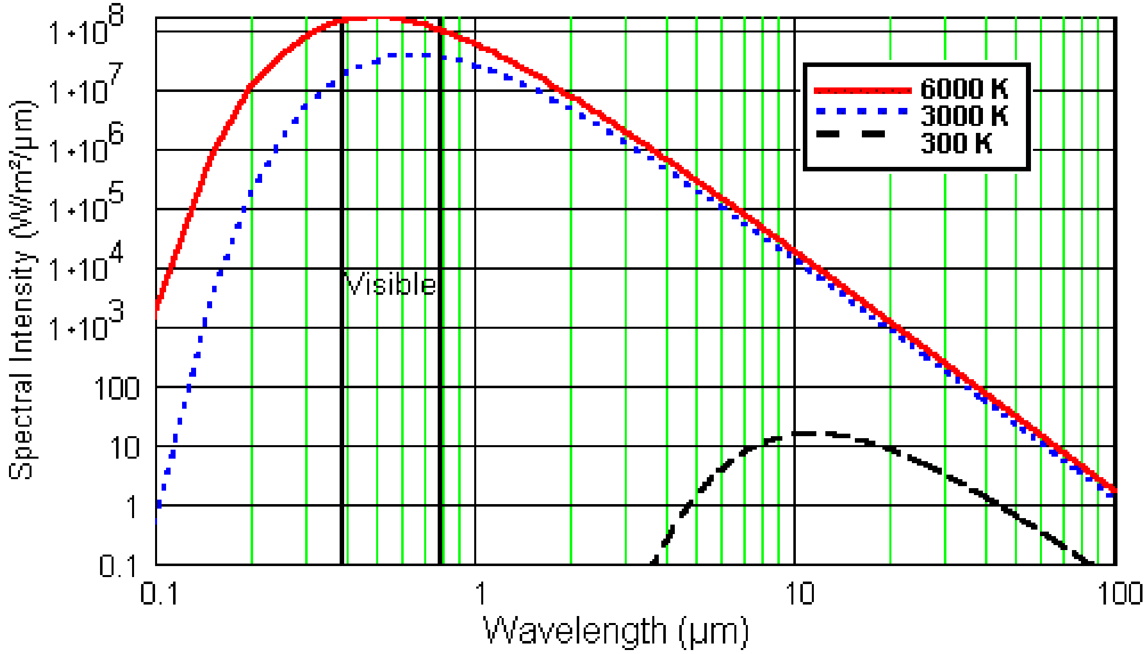
- Beam Divergence of an electromagnetic beam is an angular measure of the increase in beam diameter or radius with distance from the optical aperture or antenna aperture from which the electromagnetic beam emerges
- The divergence of a beam can be calculated if one knows the beam diameter at two separate points (D_i, D_f), and the distance (l) these points. The beam divergence, Θ, is given by

$$\Theta = 2\arctan\left(\frac{D_f - D_i}{2l}\right).$$

Thermal Radiation of Sources

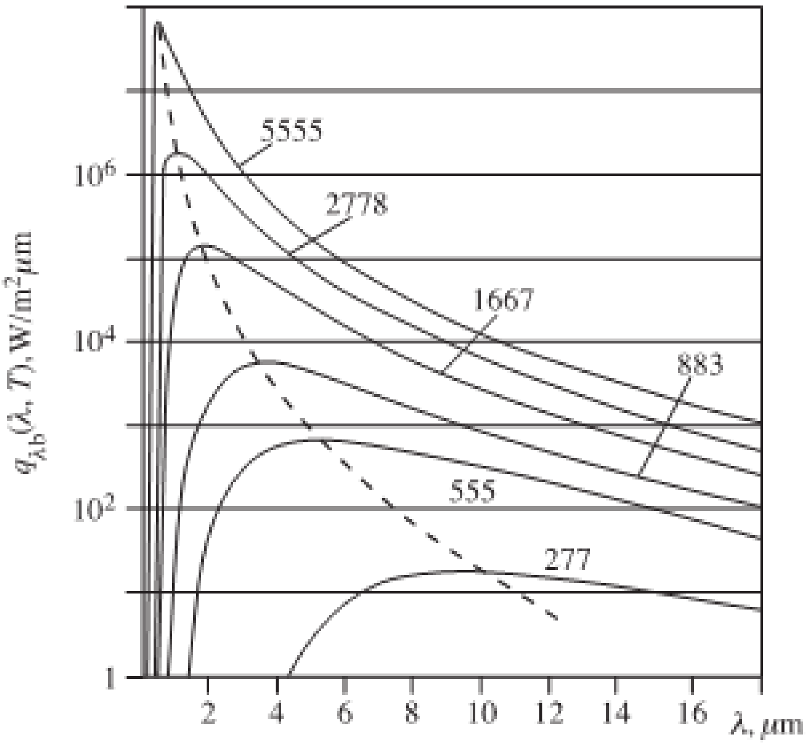


EM Radiation Spectrum of Sources



Spectral content of a source is described by a curve of how is distributed in a function of wavelength

Thermal Radiation



Application of Wien's Law to human body emission results in a peak wavelength of

$$\lambda_p(\mu m) = \frac{2900}{T}$$

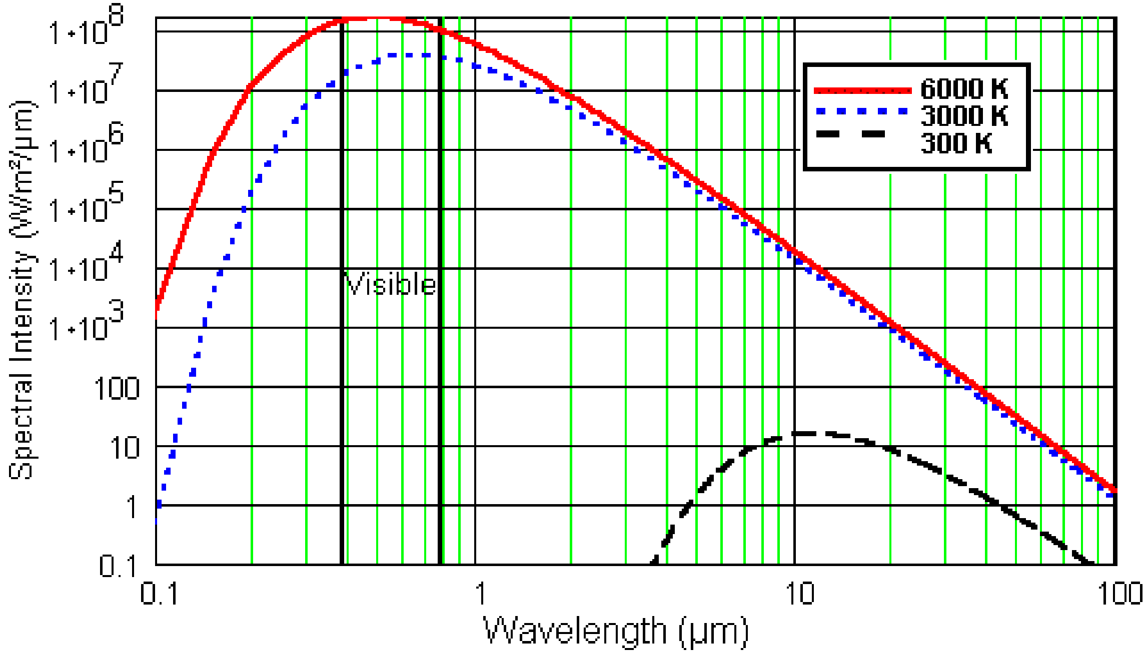
$$\lambda_{\text{peak}} = \frac{2.898 \times 10^6 \text{ K} \cdot \text{nm}}{305 \text{ K}} = 9500 \text{ nm}.$$

$$F(\lambda) = \frac{2\pi h c^2}{\lambda^5\left(\exp\left(\frac{hc}{k\lambda T}\right) - 1\right)}$$

Stefan–Boltzmann law

- **Stefan–Boltzmann law**
- The Stefan–Boltzmann law states that the power emitted per unit area of the surface of a black body is directly proportional to the fourth power of its absolute temperature:
- where P is the total power radiated per unit area, T is the absolute temperature and $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant.

Thermal Radiation



Human Radiation

The net power radiated is the difference between the power emitted and the power absorbed:

$$P_{\text{net}} = P_{\text{emit}} - P_{\text{absorb}}.$$

Applying the Stefan-Boltzmann law,

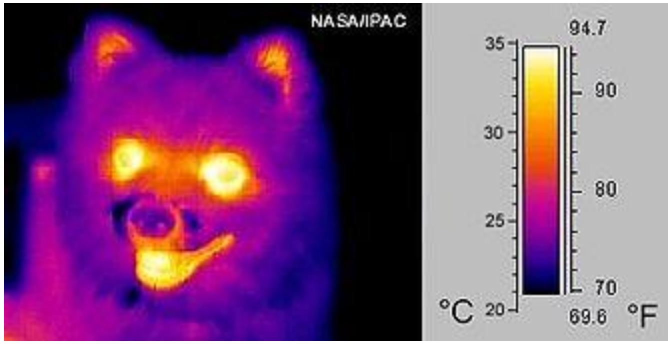
$$P_{\text{net}} = A\sigma\varepsilon \left(T^4 - T_0^4\right) .$$

The total surface area of an adult is about 2 m^2, and the mid- and far-infrared emissivity of skin and most clothing is near unity, as it is for most nonmetallic surfaces. Skin temperature is about 33 °C, but clothing reduces the surface temperature to about 28 °C when the ambient temperature is 20°C. Hence, the net radiative heat loss is about

$$P_{\text{net}} = 100\ \text{W}.$$

Infrared Camera

- **infrared camera** is a device that forms an image using infrared radiation, similar to a common camera that forms an image using visible light. Instead of the 450–750 nanometer range of the visible light camera, infrared cameras operate in wavelengths as long as 14,000 nm (14 μm).



IR imaging

Much of a person's energy is radiated away in the form ofinfrared light. Some materials are transparent in the infrared, while opaque to visible light, as is the plastic bag in this infrared image (bottom). Other materials are transparent to visible light, while opaque or reflective in the infrared, noticeable by darkness of the man's glasses.

Types of Light Sources

- Incandescence

- Luminescence
  - –Neon

  - –Fluorescent

- LEDs

- LASERS

Incadescence

- **Incandescence** is the emission of light from a hot body as a result of its temperature.

- An **incandescent light bulb** is an electric light which produces light with a filament wire heated to a high temperature by an electric current passing through it, until it glows. The hot filament is protected from oxidation with a glass bulb that is filled with inert gas. In a halogen lamp, filament evaporation is prevented by a chemical process that redeposits metal vapor onto the filament, extending its life.

- Sunlight is the incandescence of the "white hot" surface of the sun.

Neon Light

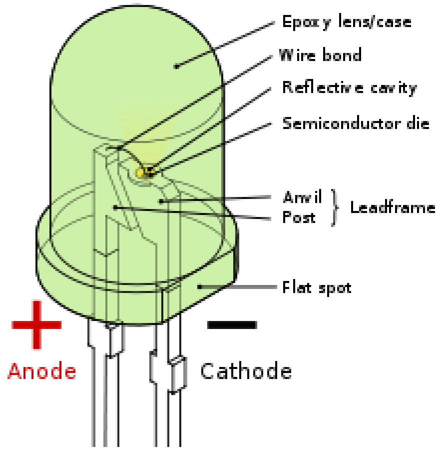
- The idea behind a **neon light** is simple. Inside the glass tube there is a gas like neon, argon or krypton at low pressure. At both ends of the tube there are metal electrodes. When you apply a high voltage to the electrodes, the neon gas ionizes, and electrons flow through the gas. These electrons excite the neon atoms and cause them to emit light that we can see. Neon emits red light when energized in this way. Other gases emit other colors.

Fluorescent light

- A **fluorescent light** works on a similar idea but it has an extra step. Inside a fluorescent light is low-pressure mercury vapor. When ionized, mercury vapor emits ultraviolet light. Therefore, the inside of a fluorescent light is coated with a **phosphor**. A phosphor is a substance that can accept energy in one form and emit the energy in the form of visible light. In a fluorescent lamp, the phosphor accepts the energy of ultraviolet photons and emits visible photons.
- he light we see from a fluorescent tube is the light given off by the phosphor that coats the inside of the tube (the phosphor **fluoresces** when energized, hence the name). The light of a neon tube is the colored light that the neon atoms give off directly.

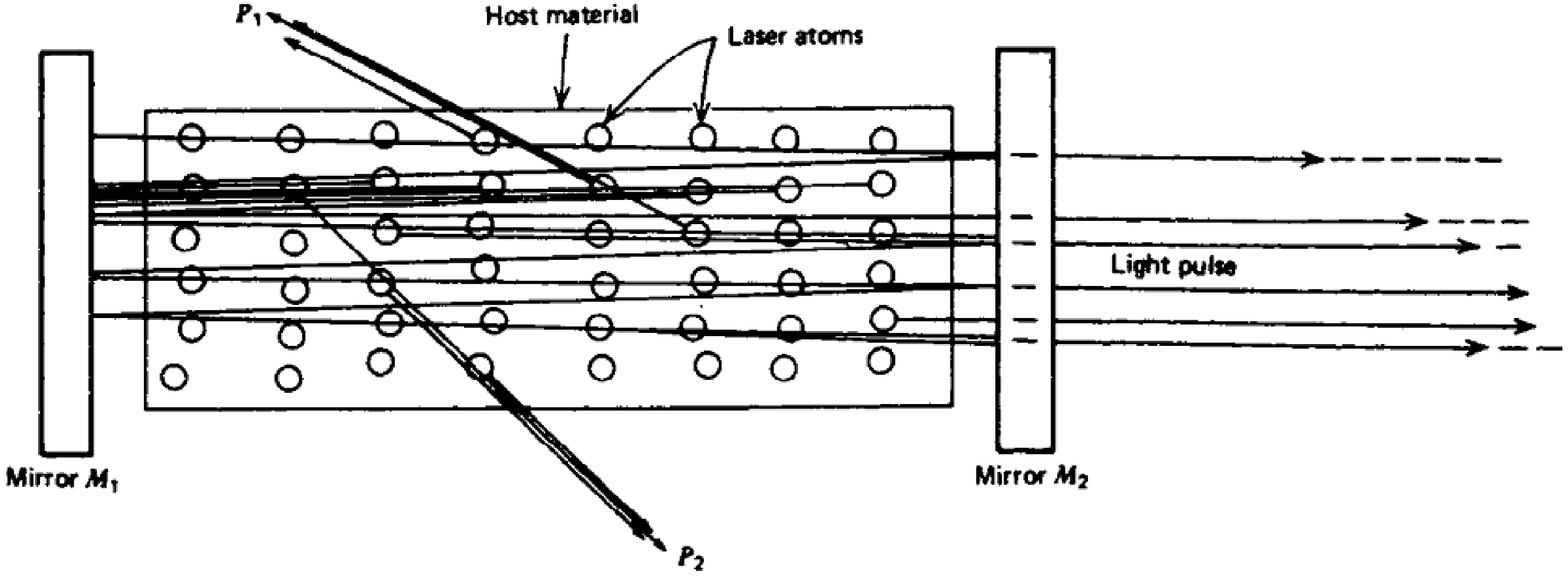
LEDs

- A **light-emitting diode** (**LED**) is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for other lighting. Appearing as practical electronic components in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible, ultraviolet, and infrared wavelengths, with very high brightness.
- When a light-emitting diode is forward-biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. An LED is often small in area (less than 1 mm^2), and integrated optical components may be used to shape its radiation pattern.
- LEDs present many advantages over incandescent light sources including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. LEDs powerful enough for room lighting are relatively expensive and require more precise current and heat management than compact fluorescent lamp sources of comparable output.

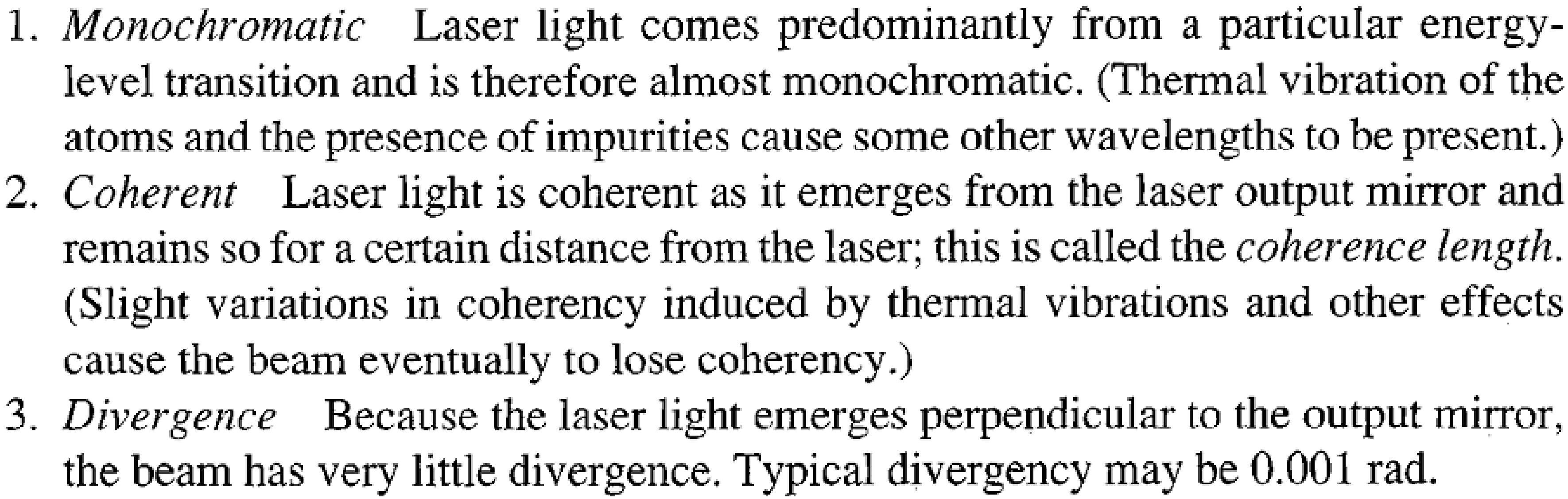


Lasers

Stimulation Emission The basic operation of the laser depends on a principle formulated by Albert Einstein regarding the emission of radiation by excited atoms. He found that if several atoms in a material are excited to the same level and one of the atoms emits its radiation before the others, then the passage of this radiation by such excited atoms can also stimulate them to de-excite. It is significant that when stimulated to de-excite, the emitted radiation will be *inphase* and *in the same direction* as the stimulating radiation.

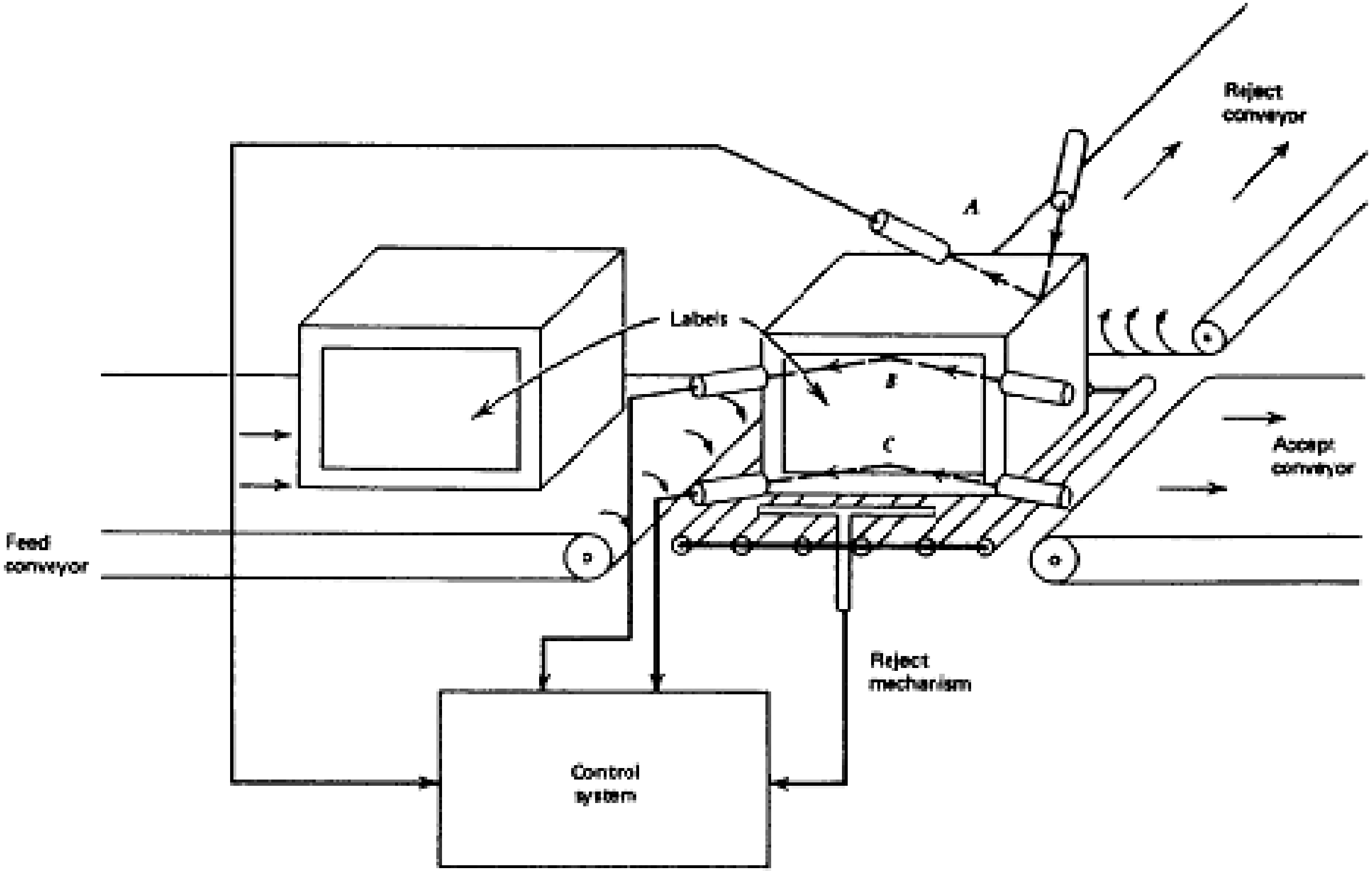


Properties of Lasers

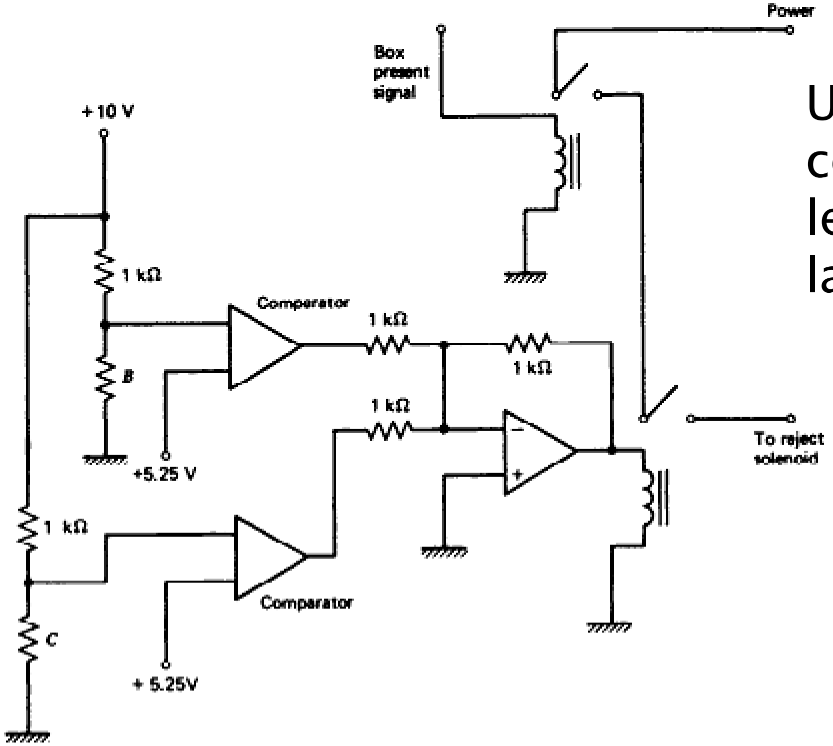


1. *Monochromatic* Laser light comes predominantly from a particular energy-level transition and is therefore almost monochromatic. (Thermal vibration of the atoms and the presence of impurities cause some other wavelengths to be present.)
2. *Coherent* Laser light is coherent as it emerges from the laser output mirror and remains so for a certain distance from the laser; this is called the *coherence length*. (Slight variations in coherency induced by thermal vibrations and other effects cause the beam eventually to lose coherency.)
3. *Divergence* Because the laser light emerges perpendicular to the output mirror, the beam has very little divergence. Typical divergency may be 0.001 rad.

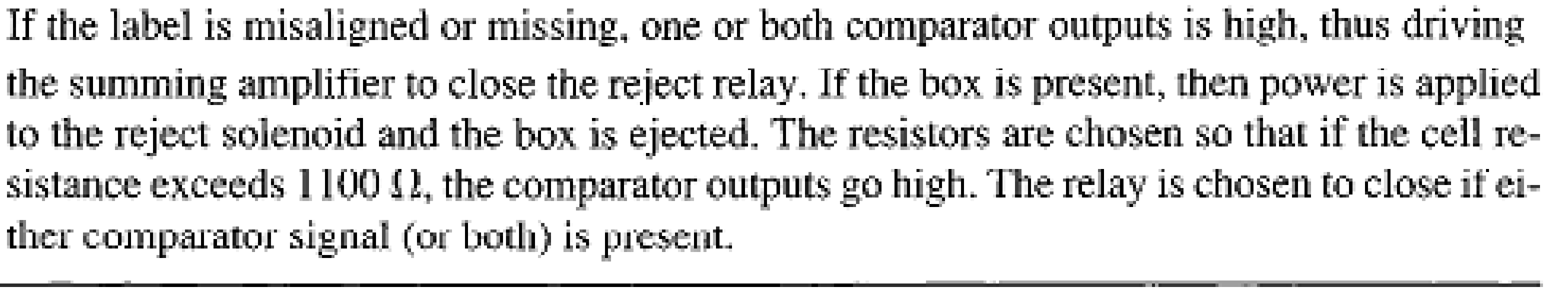
Application-Label Inspection



Solution



Using CdS cells as detectors .If both cells have resistance 1000±100Ω or less the label is considered OK. No label produces 2000Ω



If the label is misaligned or missing, one or both comparator outputs is high, thus driving the summing amplifier to close the reject relay. If the box is present, then power is applied to the reject solenoid and the box is ejected. The resistors are chosen so that if the cell resistance exceeds 1100 Ω, the comparator outputs go high. The relay is chosen to close if either comparator signal (or both) is present.

Photodetectors

- Photoconductive Detectors
-
- Photovoltaic Detectors

- Photodiode Detectors

- Photoemissive Detectors

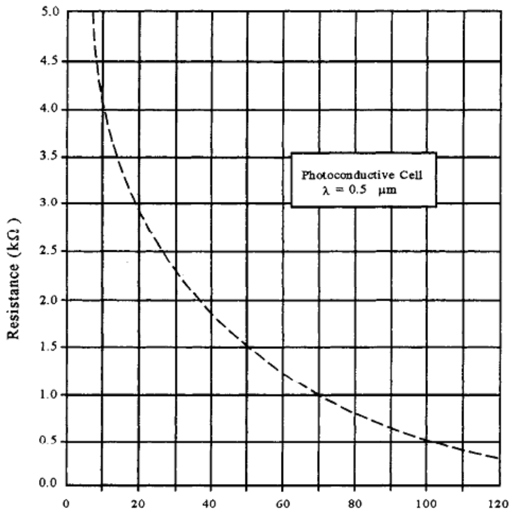
Photoconductive Detectors

One of the most common photodetectors is based on the change in *conductivity* of a semiconductor material with radiation *intensity*. The change in conductivity appears as a change in *resistance*, so that these devices also are called *photoresistive* cells. Because resistance is the parameter used as the transduced variable, we describe the device from the point of view of *resistance changes* versus *light intensity*.

Cell Structure Two common photoconductive semiconductor materials are cadmium sulfide (CdS), with a band gap of 2.42 eV, and cadmium selenide (CdSe), with a 1.74-eV gap. Because of these large gap energies, both materials have a very high resistivity at room temperature. This gives bulk samples a resistance much too large for practical

Photoconductor characteristics

Photoconductor	Time Constant	Spectral Band
CdS	~100 ms	0.47 to 0.71 μm
CdSe	~10 ms	0.6 to 0.77 μm
PbS	~400 μs	1 to 3 μm
PbSe	~10 μs	1.5 to 4 μm



Example

A CdS cell has a dark resistance of 100 kΩ and a resistance in a light beam of 30 kΩ. The cell time constant is 72 ms. Devise a system to trigger a 3-V comparator within 10 ms of the beam interruption.

$$R(t) = R_1 + (R_f - R_i)[1 - e^{-t/\tau}]$$

$$R(10\text{ ms}) = 30\text{ k} + 70\text{ k}\,(0.1296) = 39.077\text{ k}\Omega$$

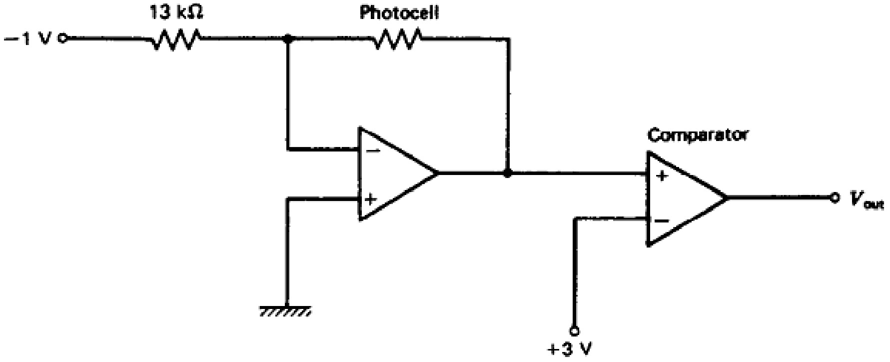
so that we must have a +3-V signal to the comparator when the cell resistance is 39.077

$$V_{\text{out}} = -\left(\frac{R_2}{R_1}\right)(-1\text{ V}) = \frac{R_2}{R_1}$$

when $R_2 = 39.077$ kΩ; we make $V_{\text{out}} = 3$ V so that

$$R_2 = 39.077\text{ k}\Omega$$

$$R_1 \simeq \mathbf{13\text{ k}\Omega}$$

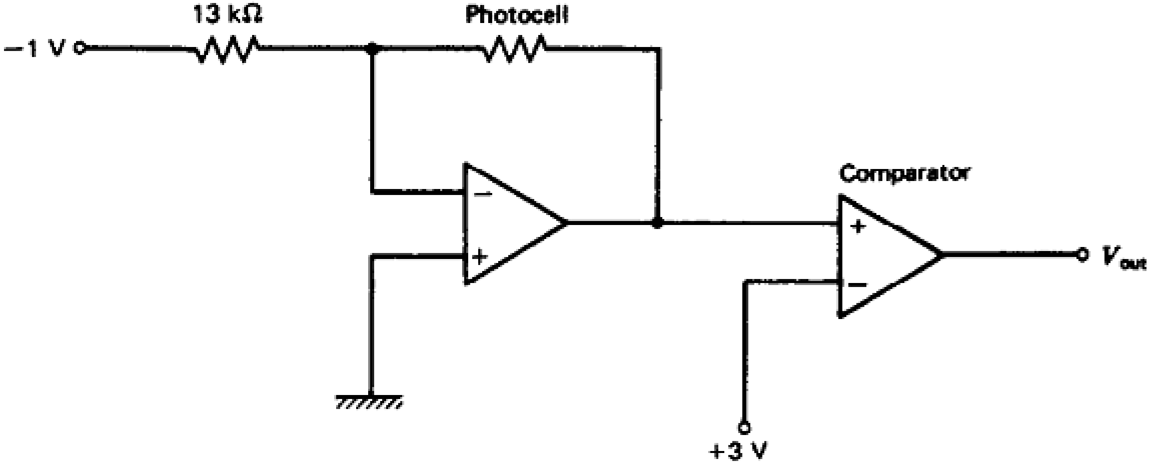


$$V_{\text{out}} = -\left(\frac{R_2}{R_1}\right)(-1\text{ V}) = \frac{R_2}{R_1}$$

when $R_2 = 39.077\text{ k}\Omega$; we make $V_{\text{out}} = 3\text{ V}$ so that

$$R_2 = 39.077\text{ k}\Omega$$
$$R_1 \simeq \mathbf{13\text{ k}\Omega}$$

which ensures that the comparator will trigger at 10 ms from beam interruption. To see that the comparator will *not* trigger with the beam present, set $R_2 = 30\text{ k}\Omega$ and the amplifier output is

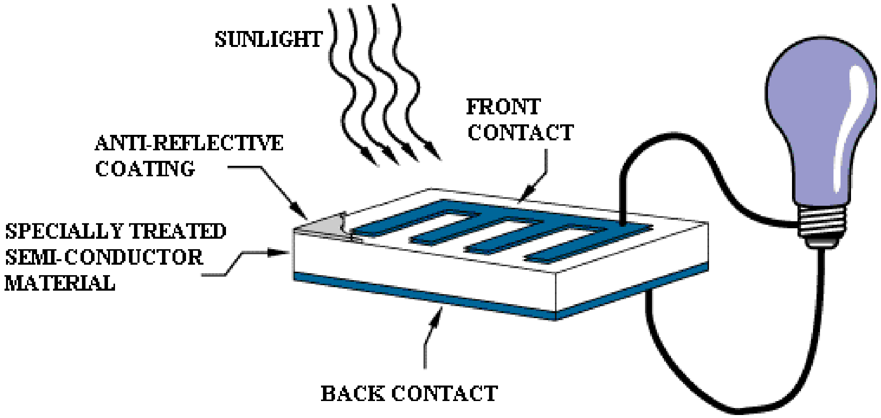


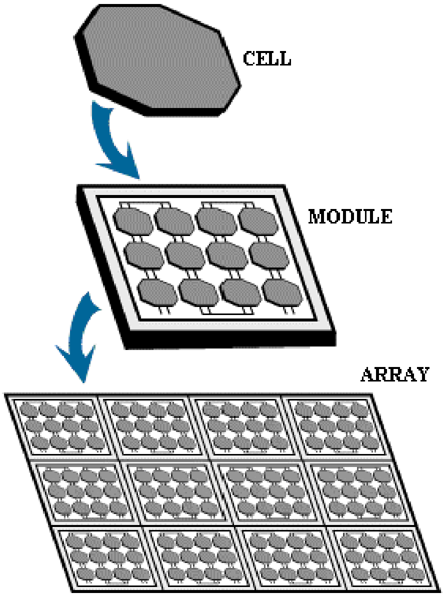
$$V_{\text{out}} = \frac{-30\text{ k}\Omega}{13\text{ k}\Omega}(-1\text{ V})$$
$$V_{\text{out}} = 2.3\text{ V}$$

which is insufficient to trigger the comparator.

PHOTOVOLTAIC EFFECT

Total global capacity roughly 64 GW



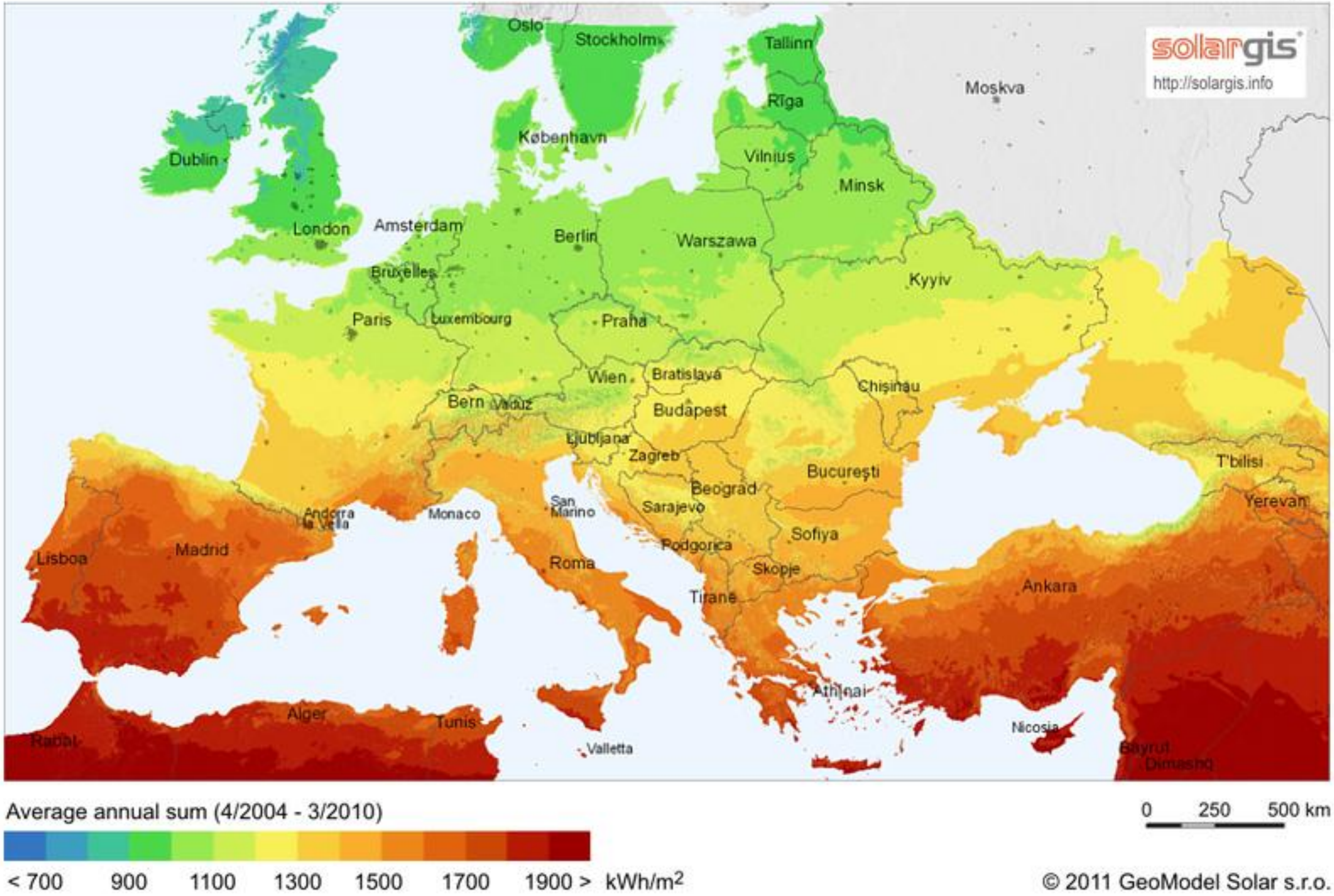


Photovoltaics is the direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When these free electrons are captured, an electric current results that can be used as electricity.

The term photovoltaic denotes the unbiased operating mode of a photodiode in which current through the device is entirely due to the transduced light energy.

Global horizontal irradiation

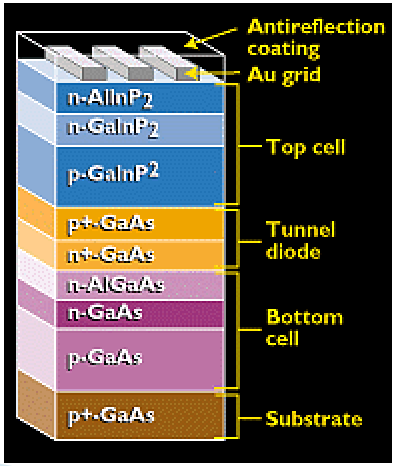
Europe



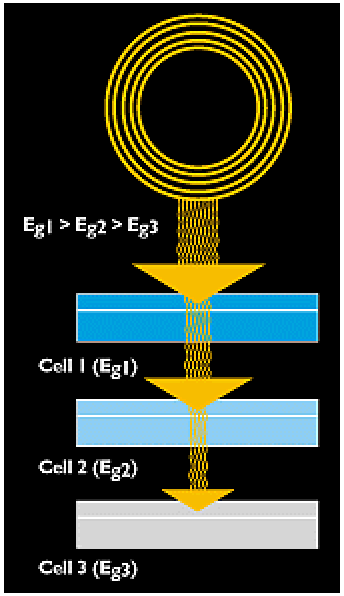
© 2011 GeoModel Solar s.r.o.

PV…

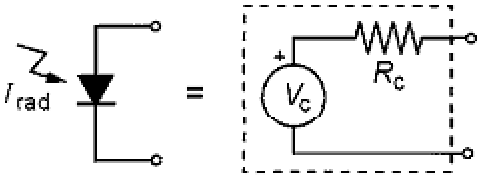
- Today's most common PV devices use a single junction, or interface, to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used



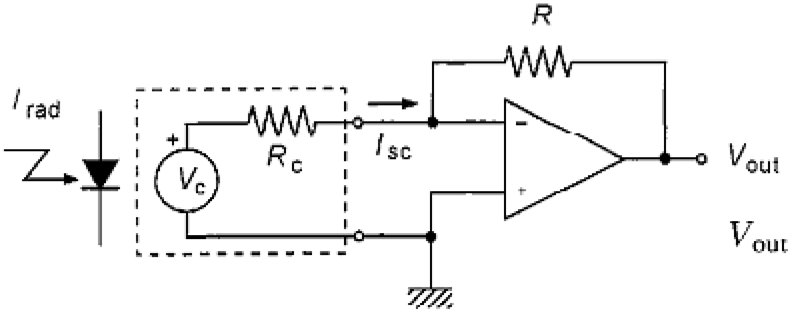
efficiencies of around 35%



Equivalent Circuit to Photovoltaic

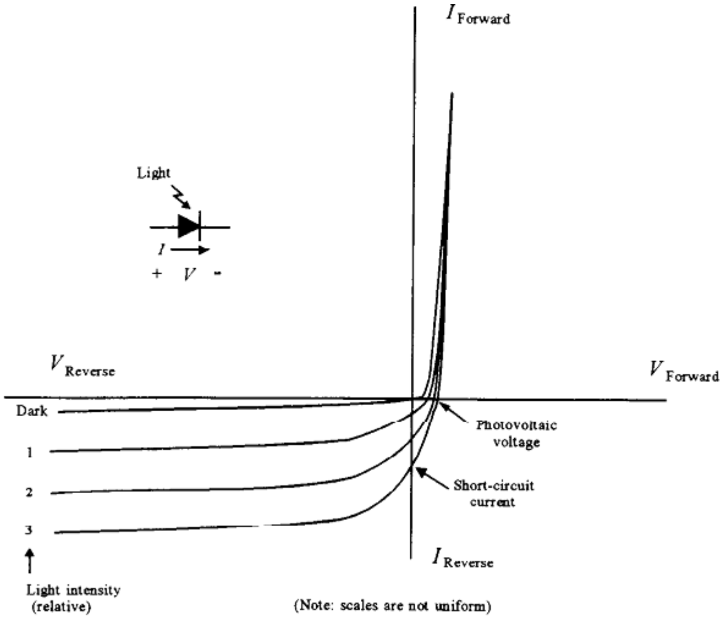


$$V_c \approx V_0 \log_e(1 + I_R)$$



$$V_{out} = -RI_{SC}$$

where V_c = open-circuit cell voltage
V_0 = constant, dependent on cell material
I_R = light intensity



(Note: scales are not uniform)

A photovoltaic cell is to be used with radiation of intensity from 5 to 12 mW/cm^2. Measurements show that its unloaded output voltage ranges from 0.22 to 0.41 V over this intensity while it delivers current from 0.5 to 1.7 mA into a 100-Ω load.

a. Find the range of short-circuit current.

b. Develop signal conditioning to provide a linear voltage from 0.5 to 1.2 V as the intensity varies from 5 to 12 mW/cm^2.

a. To find the short-circuit current, we need to find the cell resistance at the given intensities. This can be done by noting that the load current delivered into a 100-Ω load is given by

$$I_L = \frac{V_c}{100 + R_c}$$

where V_c is the cell open-circuit voltage and R_c is the cell internal resistance. Solving for the resistance, we find

$$R_c = (V_c - 100 I_L)/I_L$$

So at 5 mW/m^2 we find

$$R_c = (0.22 - 0.05)/0.0005 = 340\ \Omega$$

and at 12 mW/cm^2,

$$R_c = (0.42 - 0.17)/0.0017 = 147\ \Omega$$

Now the short-circuit current is given by $I_{SC} = V_c/R_c$, so

$$I_{SC}(5\ \text{mW/cm}^2) = 0.22/340 = 065\ \text{mA}$$

$$I_{SC}(12\ \text{mW/cm}^2) = 0.42/147 = 2.86\ \text{mA}$$

$$V_{\text{out}} = mI_{SC} + V_0$$

Then, to find m and V_0, we form two equations from the given facts:

$$1.2 = 0.00286m + V_0$$

$$0.5 = 0.00065m + V_0$$

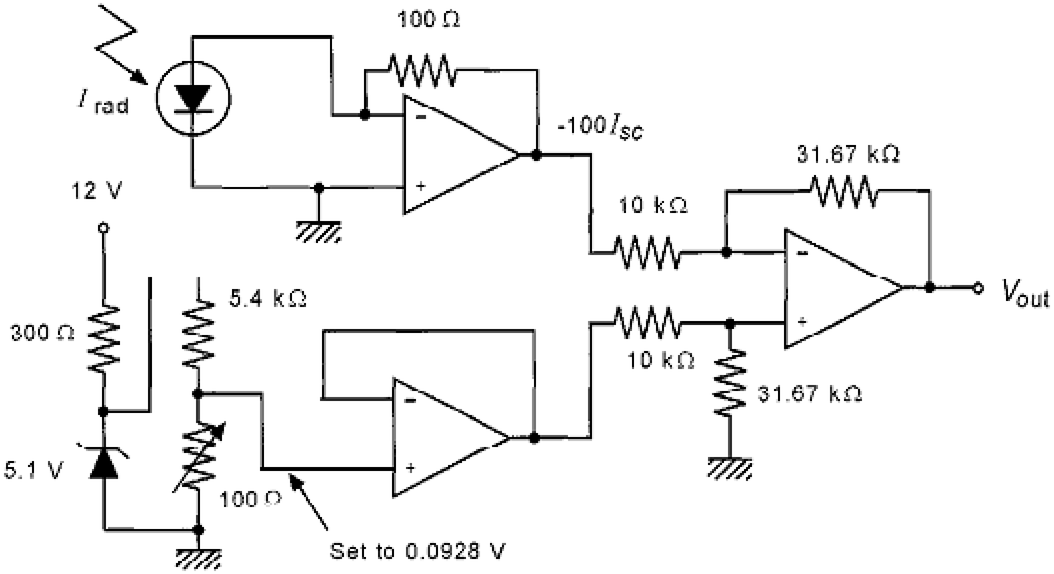
$$V_{\text{out}} = 316.7I_{SC} + 0.294$$

For the first stage, let's use a 100-Ω feedback resistor:

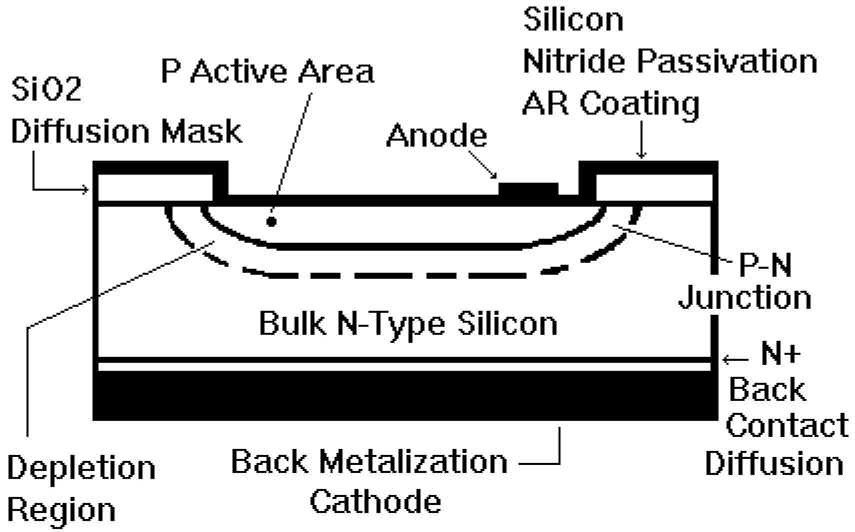
$$V_{\text{out}} = 3.167(100I_{SC}) + 0.294$$

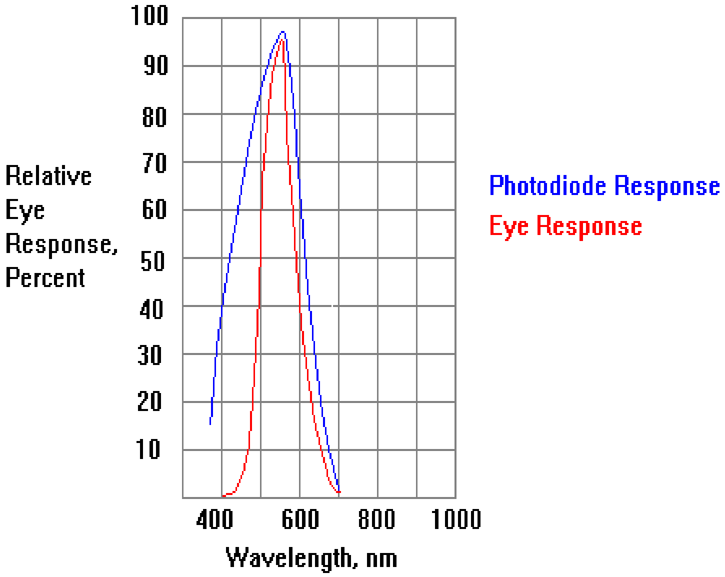
What remains can be provided by a differential amplifier, since

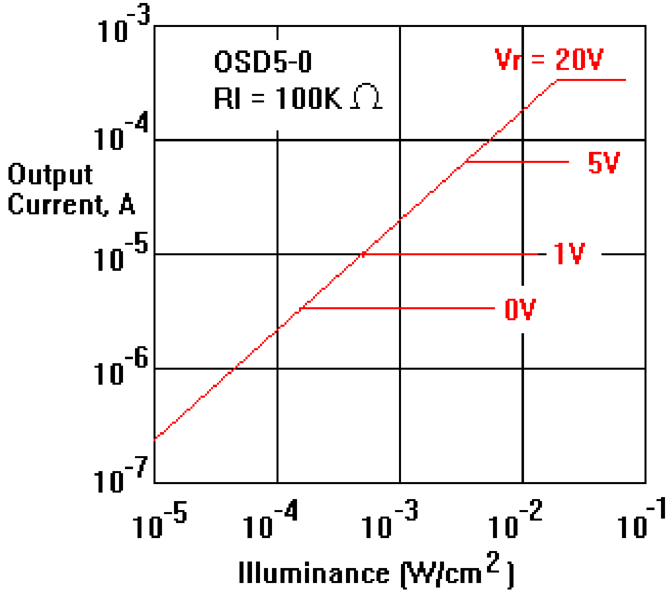
$$V_{\text{out}} = 3.167(100I_{SC} + 0.0928)$$

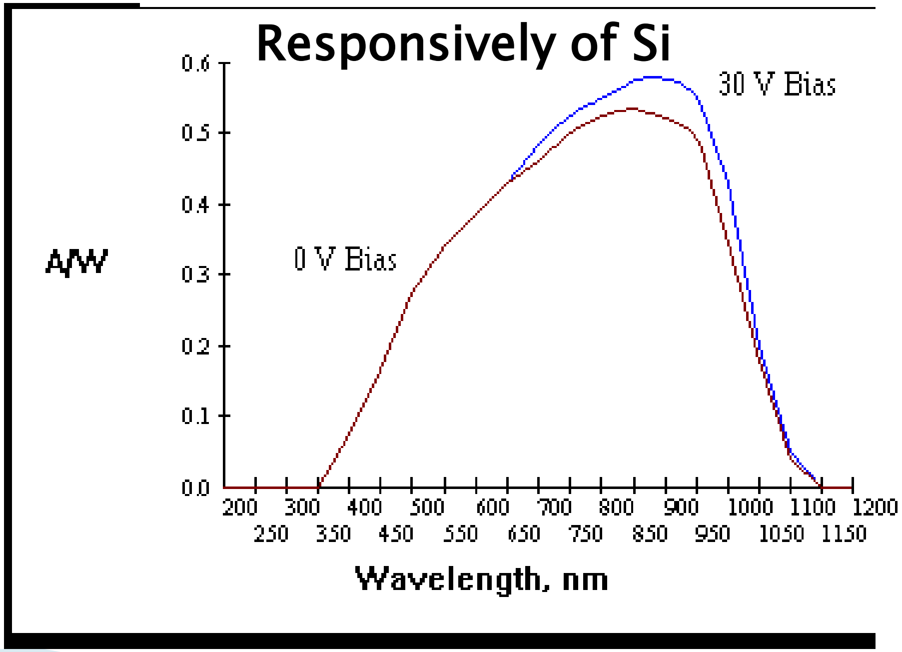


Photodiode

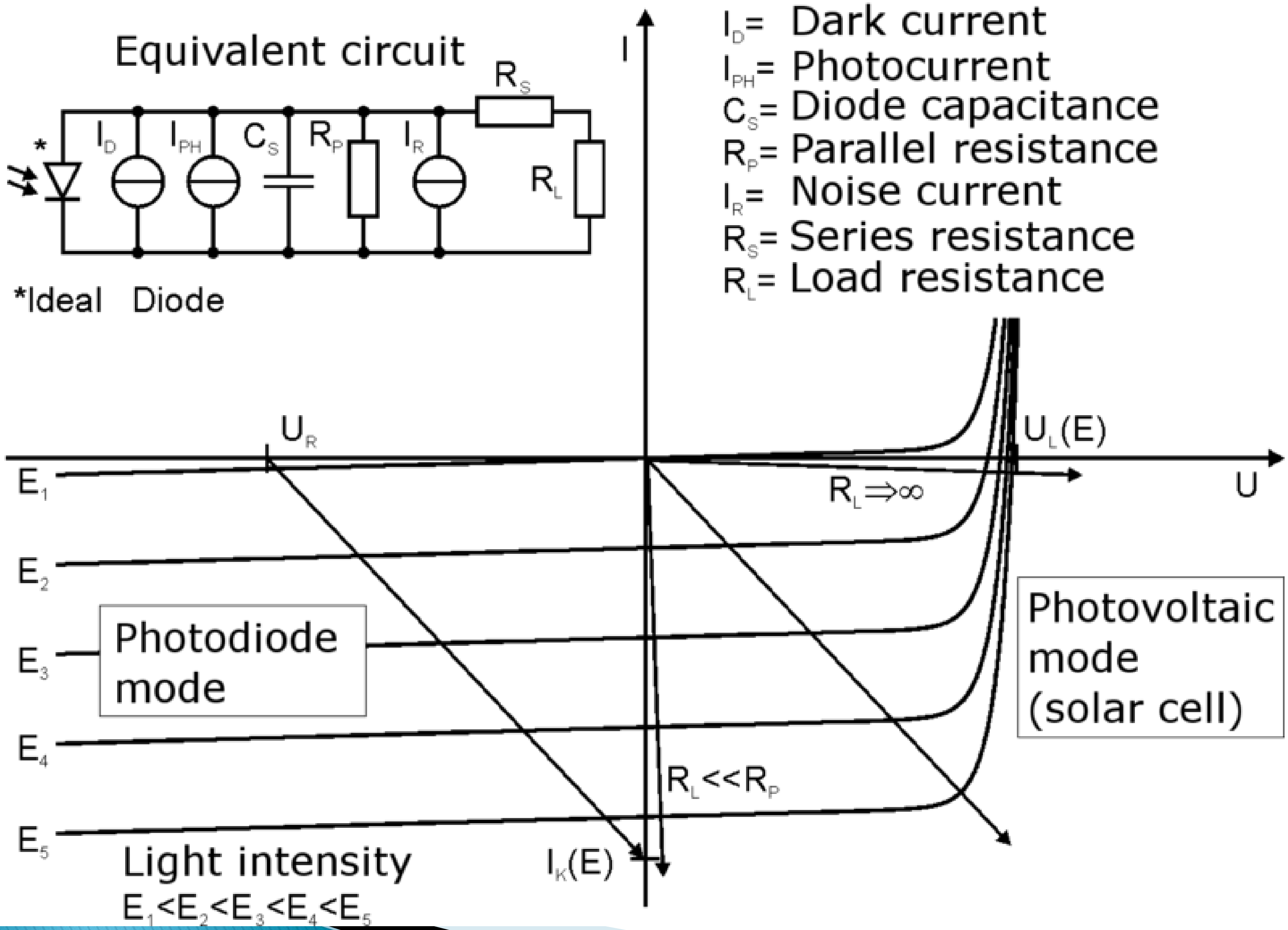






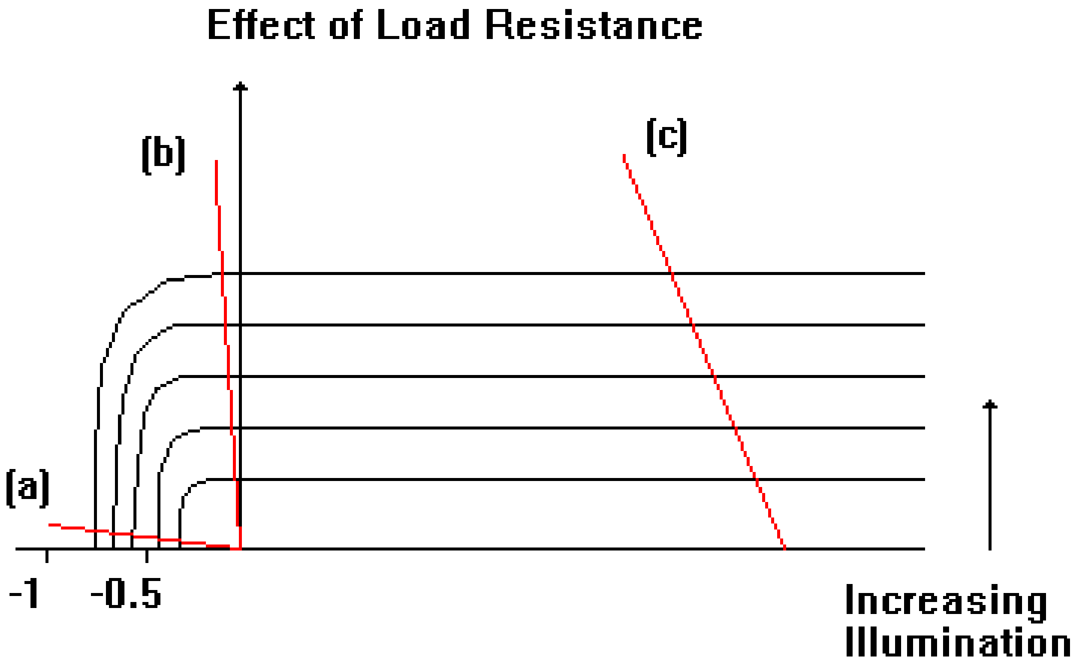

Responsively of Si

Photodiode Operation

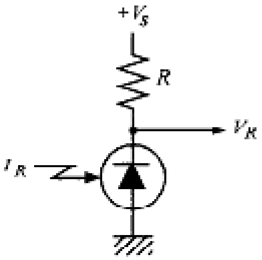


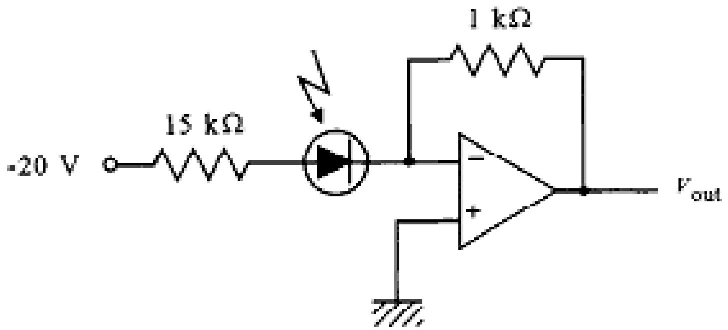
I_D = Dark current
I_{PH} = Photocurrent
C_S = Diode capacitance
R_P = Parallel resistance
I_R = Noise current
R_S = Series resistance
R_L = Load resistance

Photodiode Operation

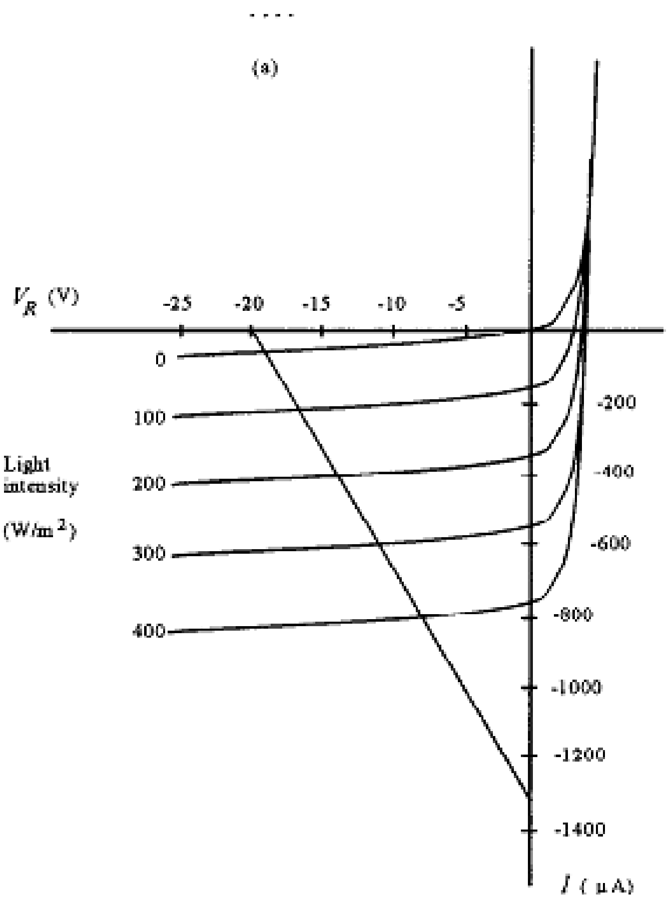


Examples





What range of output will result from light intensities from 100-400W/m2



(b)

$$1000(200\ \mu\text{A}) = 0.2\ \text{V to } 1000(800\ \mu\text{A}) = 0.8\ \text{V}$$

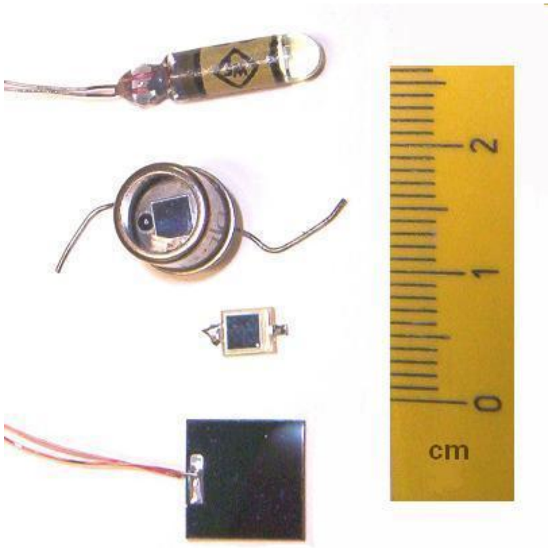
Photodiode Polarity

- IMPORTANT: Normal biased operation of most PD calls for negative biasing the active area of the device which is the anode or positive biasing the backside of the device, which is the cathode.

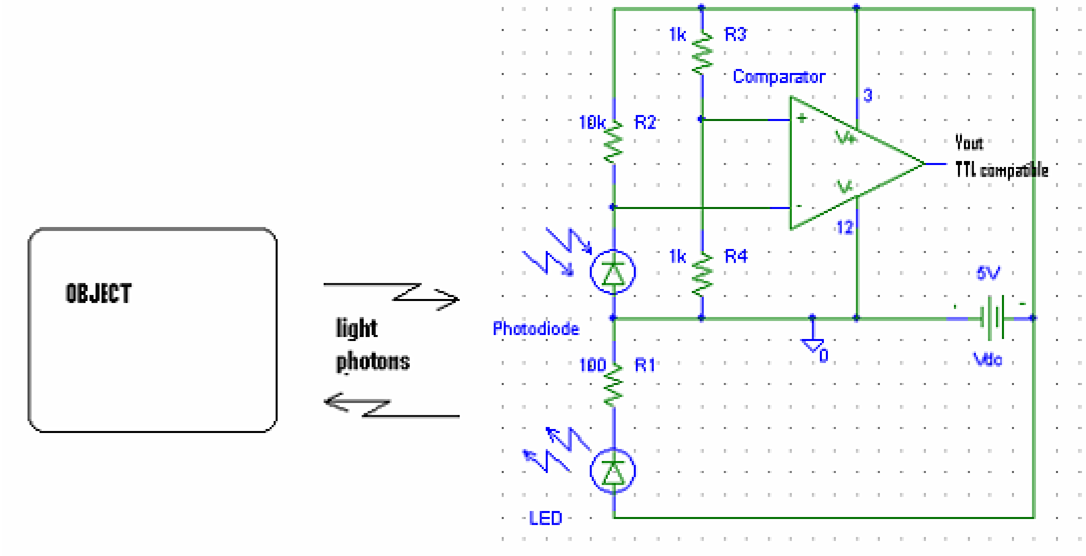
Fundamentally a photodiode is a current generator. The junction capacitance of the photodiode depends on the depletion layer depth and hence bias voltage. The value of the shunt resistance is usually high (megohms). The series resistance is low.

Quantum Efficiency

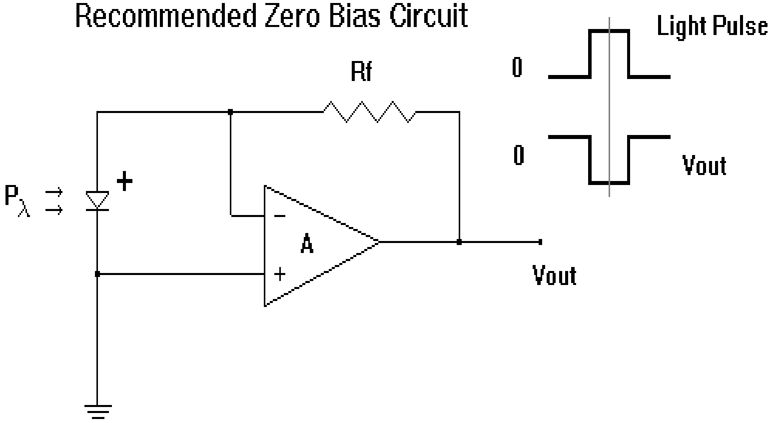
$$Q.E.[\%] = \frac{1.24 \times 10^5 \, R[A/W]}{\lambda \, [nm]}$$



Equivalent Operating Circuits



Recommended Zero Bias Circuit



Negative Bias Circuit