Light

Definition: wave or particle of electromagnetic energy.

Consider photon character of electromagnetic energy.

Photon energy, $E = \frac{ch}{\lambda}$,

where $c = 2.99792458 \times 10^9 \frac{\mathrm{m}}{\mathrm{s}}$, $h = 6.6260755 \times 10^{-34}\,\mathrm{J\,s}$, and λ is the particle wavelength.

Effect of Photon

Type of effect depends upon photon energy, …
… which is proportional to its frequency.

Amount of effect depends upon number of photons.

Our Concerns

Need to measure photon energy and "amount."

Therefore, need to know effect of photons on materials.

Useful Photons

When a photon strikes an atom, …
… it might cause an electron to change energy levels.

Energy level changes to be considered:

- Valence to conduction in a semiconductor.
- Bound-to-an-atom to free-of-the-atom.

Optical Units

Two Types of Units

- *Radiometric units.*
  Based on actual photon energies.
- *Photometric units.*
  Based on human perception.

Examples of When Used

Radiometric units might be used …
… find out how much an item would be warmed by light.

Photometric units might be used …
… for designing room lighting.

Radiometric Units

Consider a light source.

Radiant Energy, Q, total energy.

Could be found by totaling energy of each photon over a specified period of time.

Popular units: erg, joule, kilowatt-hour.

This unit is not usually used to measure light.

Radiant Flux, $\Phi = \frac{dQ}{dt}$, total power.

Total amount of light being radiated from a source per unit time, t.

Popular units: erg/second, watt (sometimes called light-watt).

Irradiance, $E = \frac{d\Phi}{dA}$, flux density.

Amount of light per unit area, A.

Popular unit: watt per square meter.

Radiant Intensity, $I = \frac{d\Phi}{d\omega}$.

Amount of light per unit solid angle, ω.

Popular unit: watt per steradian.

Steradian

Not-very-familiar-unit: steradian, a unit of solid angle.

Abbreviation for this pseudo dimension: sr.

Consider a sphere of radius 1.

Paint a circle on the sphere of area 1.

The circle would subtend one *steradian* of solid angle.

The entire surface of a sphere (of any radius) is 4π steradians.

Example

A light source radiates uniformly in all directions. Its radiant flux is $\Phi = 1\,\mathrm{W}$. Find the radiant intensity and irradiance at a distance of $1\,\mathrm{m}$ and $3.048\,\mathrm{m}$.

At $1\,\mathrm{m}$: $E = \frac{1\,\mathrm{W}}{4\pi(1\,\mathrm{m})^2} = 79.6\frac{\mathrm{mW}}{\mathrm{m}^2}$ (irradiance).

and $I = \frac{1\,\mathrm{W}}{4\pi\,\mathrm{sr}} = 79.6\frac{\mathrm{mW}}{\mathrm{sr}}$ (radiant intensity).

At $3.048\,\mathrm{m}$: $E = \frac{1\,\mathrm{W}}{4\pi(3.048\,\mathrm{m})^2} = 8.56\frac{\mathrm{mW}}{\mathrm{m}^2}$ (irradiance).

and $I = \frac{1\,\mathrm{W}}{4\pi\,\mathrm{sr}} = 79.6\frac{\mathrm{mW}}{\mathrm{sr}}$ (radiant intensity).

Note that radiant intensity is independent of distance.

Wavelengths Considered

On symbols representing light quantities, sometimes need to specify wavelengths (spectrum) being considered.

Two standard ways to do that:

- A subscript indicates that the quantity is measured only at the wavelength indicated by subscript.

  For example, Φ_λ indicates radiant flux at wavelength λ.

- A symbol in the form $X(\lambda)$ indicates a function of wavelength.

  For example, $I(\lambda) = \dfrac{2\pi c^2 h}{\lambda^5(e^{ch/(k\lambda T)} - 1)}$.

In many cases, the wavelengths being considered will be understood ...

... and so is not shown in the symbol.

One special case is the wavelengths perceived by humans.

Human vision has different sensitivities at different wavelengths.

Our eyes are sensitive to yellow light, but are less sensitive to red light.

We cannot see ultraviolet, infrared, radio waves, gamma rays, etc.

Wavelengths $[400\,\mathrm{nm}, 800\,\mathrm{nm}]$ are visible to humans.

Photometric measures take these sensitivities into account.

A standard function, $K(\lambda)$, gives the sensitivity of the human eye at wavelength λ.

Photometric Units

Symbols will be the same, subscript v indicates photometric, subscript e indicates radiometric.

Luminous Energy, $Q_v = \int_{380\,\mathrm{nm}}^{760\,\mathrm{nm}} K(\lambda) Q_e(\lambda) d\lambda$, total energy seen.

Total amount of perceivable energy.

Popular unit: lumen-hour.

This unit is not usually used.

Luminous Flux, $\Phi = \dfrac{dQ_v}{dt}$.

Total amount of perceivable light emitted.

Popular unit: lumen (lm).

Used, for example, to rate light bulb brightness.

Illuminance, $E = \dfrac{d\Phi}{dA}$, flux density.

Amount of perceivable light per unit area, A.

Popular unit: lux (lx), footcandle (lumen per square foot).

Used, for example, to rate camcorder sensitivity.

Luminous Intensity, $I = \dfrac{d\Phi}{d\omega}$.

Amount of perceivable light per unit solid angle, ω.

Popular unit: candela (cd).

Conversion

To convert from radiometric to photometric one would need the wavelength distribution and the function, $K(\lambda)$.

This is too much trouble in some cases, so...

A wavelength of $\lambda = 555\,\mathrm{nm}$ is used for a common conversion.

Then $680\,\mathrm{lm} = 1\,\mathrm{W}$.

The same factor can be used for the other measures discussed.

Example

A light source radiates uniformly in all directions. Its radiant flux is $\Phi_{e\,555\,\mathrm{nm}} = 1\,\mathrm{W}$. *Find the luminous flux, illuminance, and luminous intensity at a distance of* $1\,\mathrm{m}$ *and* $3.048\,\mathrm{m}$.

Luminous flux, $\Phi_v = \Phi_e 680 = 680\,\mathrm{lm}$.

At $1\,\mathrm{m}$: $E = \dfrac{680\,\mathrm{lm}}{4\pi(1\,\mathrm{m})^2} = 54\,\mathrm{lx}$ (illuminance).

and $I = \dfrac{680\,\mathrm{lm}}{4\pi} = 54\,\mathrm{cd}$ (luminous intensity).

At $3.048\,\mathrm{m}$: $E = \dfrac{680\,\mathrm{lm}}{4\pi(3.048\,\mathrm{m})^2} = 5.8\,\mathrm{lx}$ (illuminance).

and $I = \dfrac{680\,\mathrm{lm}}{4\pi} = 54\,\mathrm{cd}$ (luminous intensity).

Note that luminous intensity is independent of distance.

Light Transducers

Basic Types

- *Photodiode.*
  Reverse-biased PN junction of diode exposed to light.

  Photons create carrier pairs, ...
  ... which form a current.

- *Vacuum-Tube Photocell.*
  Two separated plates in an evacuated tube.

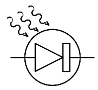
  Photons strike plate, freeing electrons, forming a current.

Composite Types

- *Phototransistor.*
  A photodiode and a transistor fabricated together.

- *Photomultiplier Tube.*
  A vacuum-tube photocell ...
  ... with a *very* effective current amplifier.

Photodiode

Symbol: 

Construction: a diode with junction exposed to light.

Principle of Operation

During operation, diode is reverse biased.

In this state the depletion region. . .
. . . an area normally without charge carriers. . .
. . . is large.

Constructed so that light falls on depletion region.

A photon striking the depletion region . . .
. . . might excite an electron . . .
. . . into the conduction band.

The liberated electron and hole form part of the current.

A few carrier pairs also generated by heat, these form a *dark current.*

Model Function

$H_{t1}(x) = xK_s$,

Typically, $K_s = 3 \frac{\mu\mathrm{A\,cm}^2}{\mathrm{mW}}$.

Peak Wavelength Sensitivity For Selected Types

Silicon, 850 nm.

Gallium Arsenide, 1500 nm.

Germanium, 2000 nm.

Desirable Characteristic

- Linear response.

Undesirable Characteristic

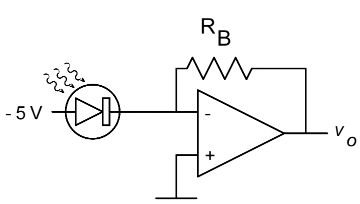
- Capacitance limits speed.
(Capacitance higher at higher bias voltages.)

Photodiode Example Problem

Design a circuit to convert process variable $x \in [0\,\mathrm{W}, 10\,\mathrm{W}]$, *the radiant flux of a light source which radiates uniformly in all directions, to a voltage,* $H(x) = x\frac{\mathrm{V}}{\mathrm{W}}$. *Use a photodiode placed at distance* $r = 1\,\mathrm{cm}$ *from the light source. The photodiode response is* $H_{t1}(E) = EK_s$, *where* $K_s = 3\frac{\mu\mathrm{A\,cm}^2}{\mathrm{mW}}$.

Solution

Because the photodiode acts as a current source, the following circuit would do:



The derivation:

The process variable is radiant flux from the light source.

The photodiode reads irradiance.

Therefore there is a transformation between the process variable and the transducer input. Call the function $H_p(x)$.

By definition of irradiance and the setup for this problem:

$$H_p(x) = \frac{x}{4\pi r^2}.$$

Continuing in the usual way:

$$H(x) = H_c(H_{t1}(H_p(x))) \qquad \text{Let } z = H_{t1}(H_p(x)) = \frac{x}{4\pi r^2}K_s.$$

$$\text{Then } x = \frac{z4\pi r^2}{K_s} \quad \text{and} \quad H_c(z) = H\left(\frac{z4\pi r^2}{K_s}\right) = \frac{z4\pi r^2}{K_s\,\mathrm{W}}\,\mathrm{V}$$

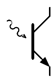
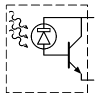
Thus z, a current, should be converted to a voltage.

Use inverting amplifier as current-to-voltage converter.

Current-to-voltage converter response, $H_c(i_A) = R_B i_A$.

Thus, $\boxed{R_B = \frac{4\pi r^2}{K_s\,\mathrm{W}}\,\mathrm{V} = 4.189\,\mathrm{k}\Omega.}$

Phototransistor

Symbols:  and 

Construction: a diode with junction exposed to light connected to a transistor, as shown in second symbol.

Principle of Operation

Photodiode converts irradiance to current.

Current is amplified by transistor.

Desirable Characteristic

- Greater sensitivity than a photodiode.

Undesirable Characteristic

- Not as linear as a photodiode.

Used to detect the presence of light, rather than measure it.

Model Function

$H_{t2}(x) = xK_s$, typically, $K_s = 300\frac{\mu\text{A cm}^2}{\text{mW}}$.

The only difference in the model is the constant.

However, the model error here will be higher.

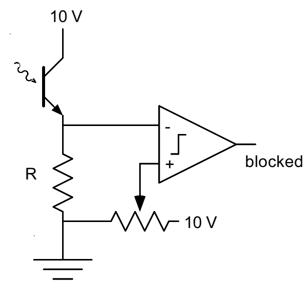
Phototransistor Example

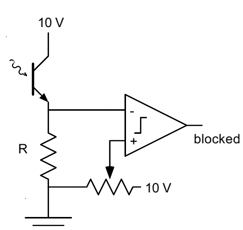
A system is to detect an object between two points using a beam of light. The system should have an output, called `blocked`*, which is TTL logic 1 when the beam is broken and logic 0 when the beam is not broken. The beam will produce a spot of light of irradiance* $\approx 25\frac{\text{mW}}{\text{cm}^2}$ *at the phototransistor. Include a sensitivity adjustment to adjust for ambient light conditions.*

Solution

Convert light to voltage.

Use digital comparator to generate output.





Choose phototransistor with response, $H_{t2}(x) = xK_s$, where $K_s = 300\frac{\mu\text{A cm}^2}{\text{mW}}$.

Suppose a 10 V supply is convenient.

Design circuit so that an irradiance of $25\frac{\text{mW}}{\text{cm}^2}$ will produce a voltage of 7 V at the comparator input.

That is, $H_c\left(H_{t2}\left(25\frac{\text{mW}}{\text{cm}^2}\right)\right) = 7\,\text{V}$.

(Because of model error, calibration error, and possible variations in the physical system, the voltage when the beam is broken can be higher or lower than expected. A choice of 7 V gives a safety margin, 10 V would not.)

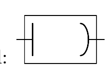
For this circuit, $H_c(i_A) = i_A R$.

Thus, $H_c(H_{t2}(x)) = xK_sR = v_-$.

Solving $R = \frac{v_-}{K_s x}$.

Substituting, $v_- = 7\,\text{V}$ and $x = 25\frac{\text{mW}}{\text{cm}^2}$, $\boxed{R = 933\,\Omega.}$

Vacuum-Tube Photodiode

Symbol: 

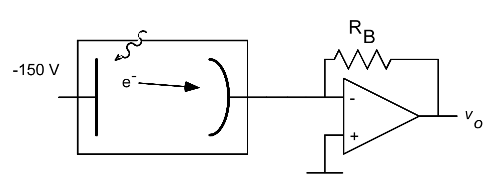
Construction:

Two plates in an evacuated tube, one plate exposed to light.

Each plate connected to a lead.

The plate exposed to light is called the *cathode* . . .
. . . the other plate called the *anode*.

Principle of Operation



Plates biased so that, as one should expect, . . .
. . . the cathode is negative and the anode is positive.

Bias $\approx 150\,\text{V}$.

Photons strike plate. Energy imparted can free some electrons.

Electric field between plates propel electrons to anode . . .
. . . forming the current.

History

Experiment using a similar device, conducted around 1900, contributed to the development of quantum mechanics.

Model Function

$H_{t1}(x) = xK_s$, where K_s is a constant.

Is it a coincidence that this function is the same as the photodiode?

Undesirable Characteristic

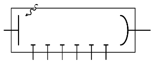
- Bulky and delicate.
- Requires a high bias voltage.

Desirable Characteristic

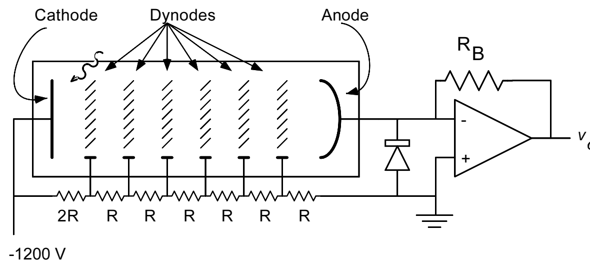
- Fast.

Vacuum-tube photodiodes are obsolete . . .
. . . however a similar device is far from obsolete.

Photomultiplier

Symbol: 

Construction:



At least three plates in an evacuated tube, one plate exposed to light.

Each plate connected to a lead.

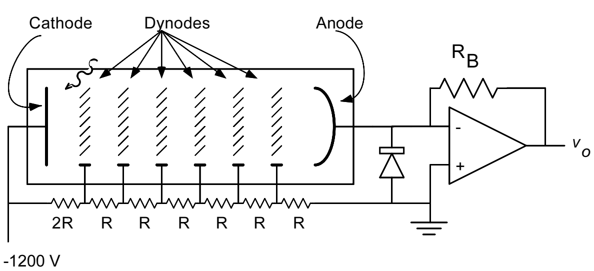
The plate exposed to light called the *cathode*, one plate called the *anode*, and the rest are called *dynodes*.

Dynodes are placed between cathode and anode, and are ordered. (That is, one dynode is closest to the cathode, one is second closest, and so on.)

The closest dynode is called the *first dynode*, the second-closest dynode is called the *second dynode*, and so on.

Symbol n will denote the number of dynodes.

Principle of Operation



Plates typically biased so that the . . .

. . . first dynode is 300 V more positive than the cathode. . .

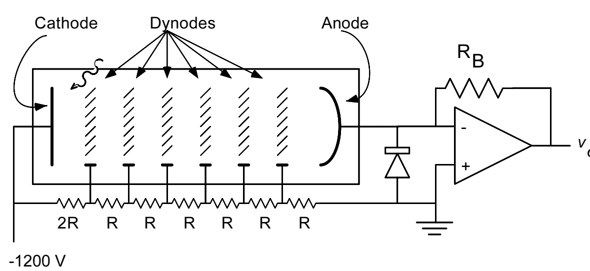
. . . the second dynode is 150 V more positive than the first dynode. . .

⋮

. . . and the anode is 150 V more positive than the last dynode.

(Do not allow children to play around these devices.)

Principle of Operation



Consider a photon striking the cathode.

Suppose an electron is ejected (this happens frequently enough).

The electric field accelerates the electron toward the first dynode.

The field increases the electron energy so that when it strikes the first dynode, it frees $A_s > 1$ electrons.

These electrons are accelerated toward the second dynode.

They strike the second dynode freeing a total of A_s^2 electrons.

These accelerate towards the third dynode. . .

⋮

. . . finally, A_s^n electrons strike the anode.

There is nothing more positive than the anode so the electrons eventually pass through the anode lead, as part of the current.

Model Function

$H_{t1}(x) = xA_s^n K_s$,

where K_s is a constant, A_s is the anode gain, and n is the number of anodes.

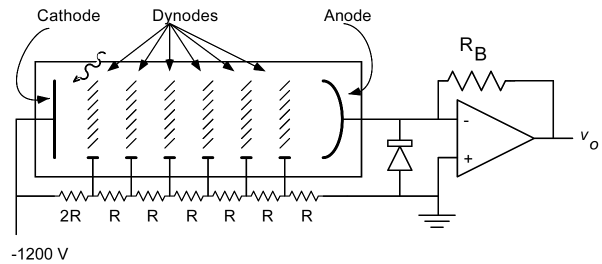
Desirable Characteristic

- Very sensitive. Can detect individual photons.

Undesirable Characteristic

- Bulky and delicate.
- Requires a very high bias voltage.

Typical Conditioning Circuit



Bias to dynodes provided by a ladder of resistors, sometimes called a *bleeder circuit*.

Current into dynodes should be small compared to current through resistors.

Anode lead is connected to a current to voltage converter.

Diode at anode protects op-amp from overload.

Since photomultipliers are usually used to measure very faint light, there is a chance that someone might "open the door" while they are in use.

Photomultiplier Example

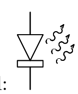
A photomultiplier is to produce a current of at least $1\,\mathrm{mA}$ *when exposed to light of irradiance* $1.44\times10^{-7}\frac{\mathrm{W}}{\mathrm{cm}^2}$. *Suppose each dynode has a gain of* $A_s = 3.50$ *and the cathode has a sensitivity* $K_s = 1.00\frac{\mu\mathrm{A\,cm}^2}{\mathrm{W}}$. *How many dynodes would be necessary to detect the light?*

In other words, solve $H_{t1}\left(1.44\times10^{-7}\frac{\mathrm{W}}{\mathrm{cm}^2}\right) = 1\,\mathrm{mA}$ for n.

$H_{t1}(x) = xA_s^n K_s = i$,

$n = \lceil \log_{A_s}(i/(K_s x)) \rceil = \lceil 18.089 \rceil = 19.$

Light Emitting Diodes

Symbol: 

Construction: semiconductor diode with a rather complicated PN junction. (Don't ask, won't test.)

Principle of Operation

LEDs operated in forward-bias mode.

There is $\approx 2\,\mathrm{V}$ drop across LED.

Charge carriers sometimes recombine in depletion region.

Energy drop, by design, is within range of energy of photon of desired color.

Typical Circuit

Placed in series with either a current source or resistor.

Desirable Characteristic

- Lower Power.
- High (On/Off) Speed.

Undesirable Characteristic

- Limited Colors.
- Limited Brightness.