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Lesson 4: Optoelectronic Devices

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V 2.3

Introduction

- As their name suggests, these devices combine electronics and optics.
- They are typically semiconductor devices.
- Their operation is based on wave theory and quantum mechanics (photoelectric effect).
- They can be divided into three categories:
  - Light-Emitting Devices.
  - Light-Receiving Devices.
  - Light-Emitting and Light-Receiving Devices (Optocouplers).

Physical Principle

- A semiconductor has a conduction band and a valence band.
- Between them lies a forbidden energy gap, whose width is expressed in terms of energy (E_g).
- When an electron "falls" from the conduction band to the valence band, it releases the energy corresponding to the difference between the two bands.
- According to quantum theory: $E_g = h*\nu$.
  - h: Planck's constant.
  - ν: Frequency of the emitted radiation.
- If the frequency of the emitted radiation lies within the visible spectrum, light is emitted.
- The reverse process is also possible: incident light can excite electrons in the valence band, providing them with enough energy to cross the forbidden energy gap and "jump" into the conduction band, thereby increasing the conductivity of the semiconductor.

Light-Emitting Devices

Among semiconductor devices, those capable of emitting light belong to the diode family:

- LEDs (Light-Emitting Diodes).
- LASER Diodes (not covered in this course).

As previously discussed, the key requirement is that the band-gap energy correspond to radiation within the optical spectrum.

This depends on the semiconductor material used, which also determines the color of the emitted light.

LEDs can be driven using:

- DC (Direct Current).
    - Series Connection
    - Parallel Connection
- Pulse-Width Modulation (PWM).
- AC (Alternate Current).

LEDs (I)

Materials

Compound	Color	Wave-length
Gallium Arsenide (GaAs)	Infrared	940 nm
Aluminum Gallium Arsenide (AlGaAs)	Red and Infrared	890 nm
Gallium Arsenide Phosphide (GaAsP)	Red, Orange and Yellow	630 nm
Gallium Phosphide (GaP)	Green	555 nm
Gallium Nitride (GaN)	Green	525 nm
Indium Gallium Nitride (InGaN)	Blue	450 nm
Silicon Carbide (SiC)	Blue	480 nm

V_f

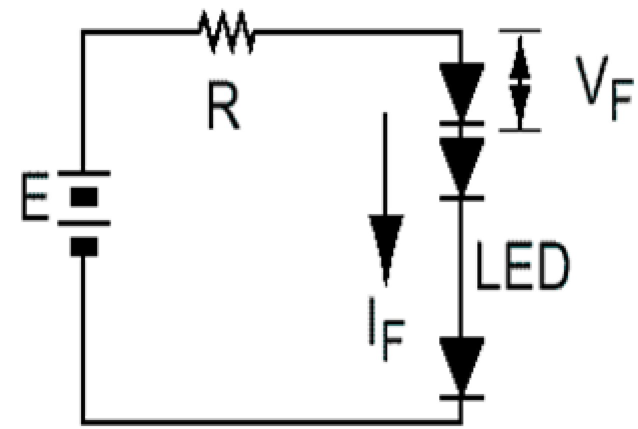
Red = 1.6V
High-Brightness Red = 1.9V
Yellow = 1.7V a 2V
Green = 2.4V
Orange = 2.4V
Bright White = 3.4V
Blue = 3.4V
Blue 430 nm = 4.6V

$$\lambda(m) = \frac{c}{f} \approx \frac{3 \times 10^8\, {}^{m}/_{s}}{f\,(Hz)}$$

For white LEDs, color temperature is used to describe the perceived shade of the emitted white light (Warm White 2700K-3500K, natural 4000K-4500K, Daylight 5000K-6000K, Cool White 6000K-7000K).

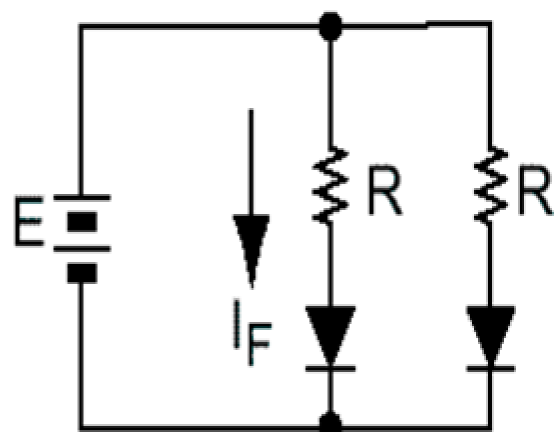
LEDs (II)

Series Drive



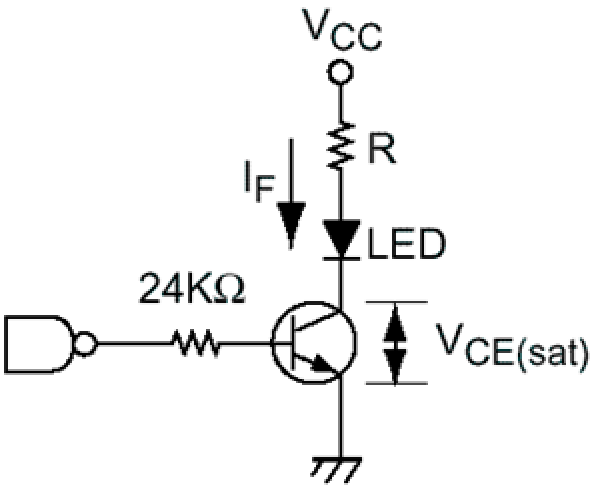
$$I_F = \frac{E - n\,V_F}{R}$$

Parallel Drive



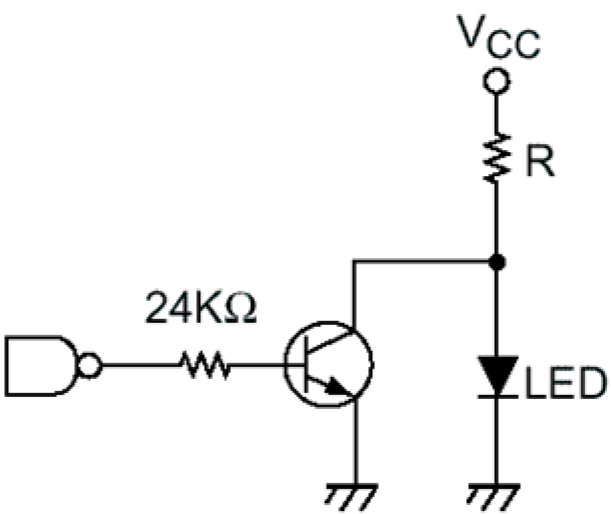
$$I_F = \frac{E - V_F}{R}$$

LEDs (III): digital drive



$$I_F = \frac{V_{CC} - (V_{CE(sat)} + V_F)}{R}$$

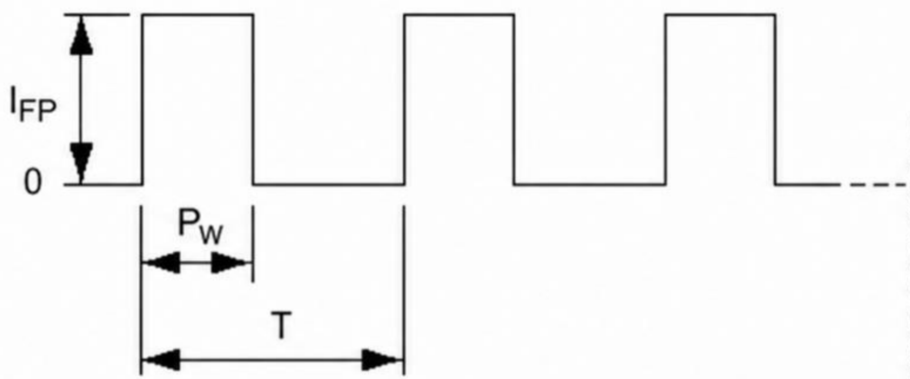
LED activated when the NAND gate output is HIGH. If the NAND gate is ON, the LED is ON



$$I_F = \frac{V_{CC} - V_F}{R}$$

LED activated when the NAND gate output is LOW. If the NAND gate is OFF, the LED is ON.

LEDs (IV): PWM Drive

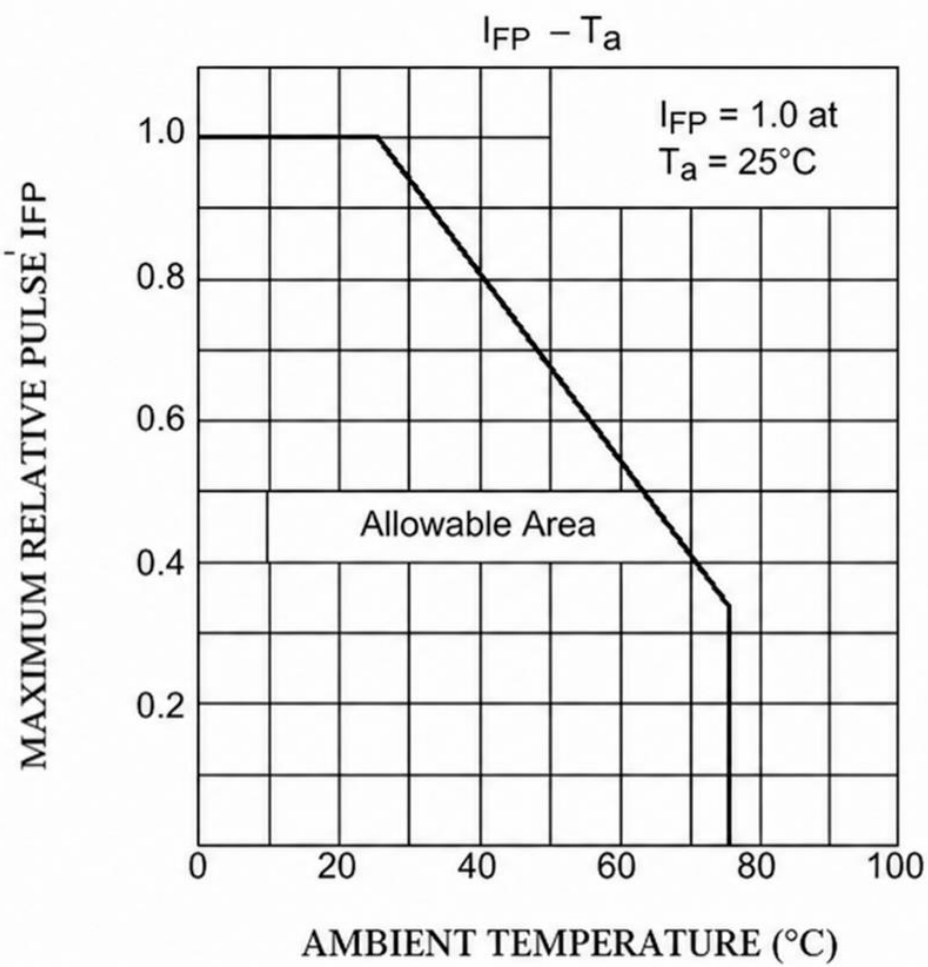


I_{FP} MAXIMUM ALLOWABLE PULSE

P_W : PULSE WIDTH

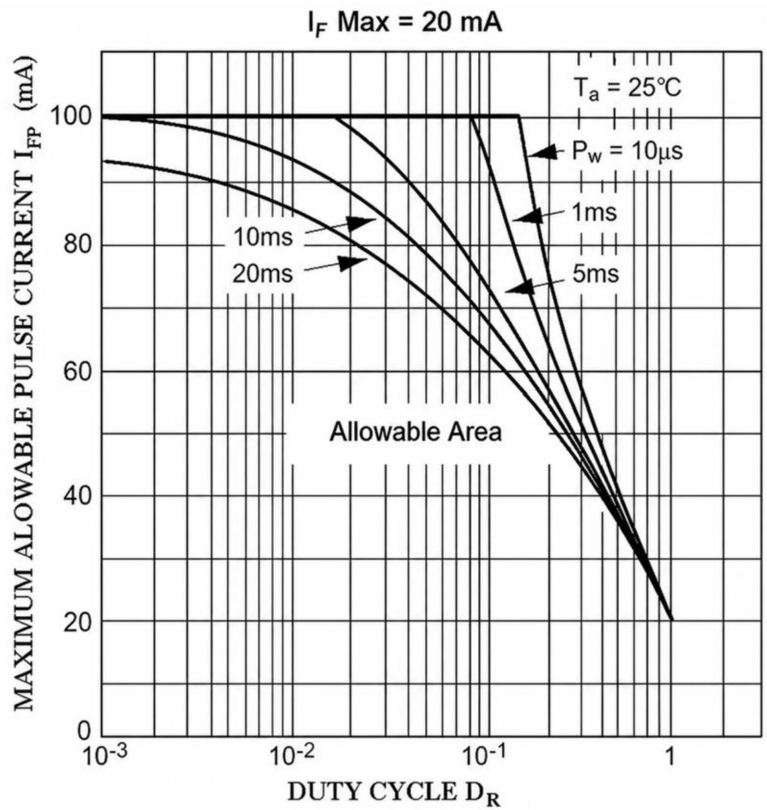
T : SIGNAL PERIOD

D_R : DUTY CYCLE $\left(=\frac{P_W}{T}\right)$



EFFECT OF AMBIENT TEMPERATURE ON APPLIED PULSE PEAK

LEDs (V): PWM Drive

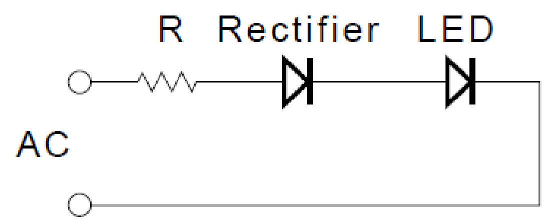


Advantages:

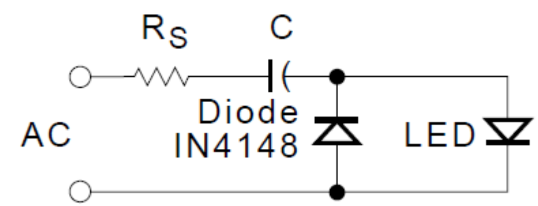
- Allows brightness control without introducing additional dissipative losses.
- The current remains constant during each pulse, so the chromaticity coordinates remain unchanged regardless of brightness.

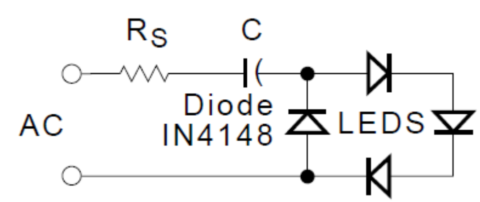
LEDs (VI): AC Drive

- Current Limiting Using a Power Resistor:
  - High power losses in R.



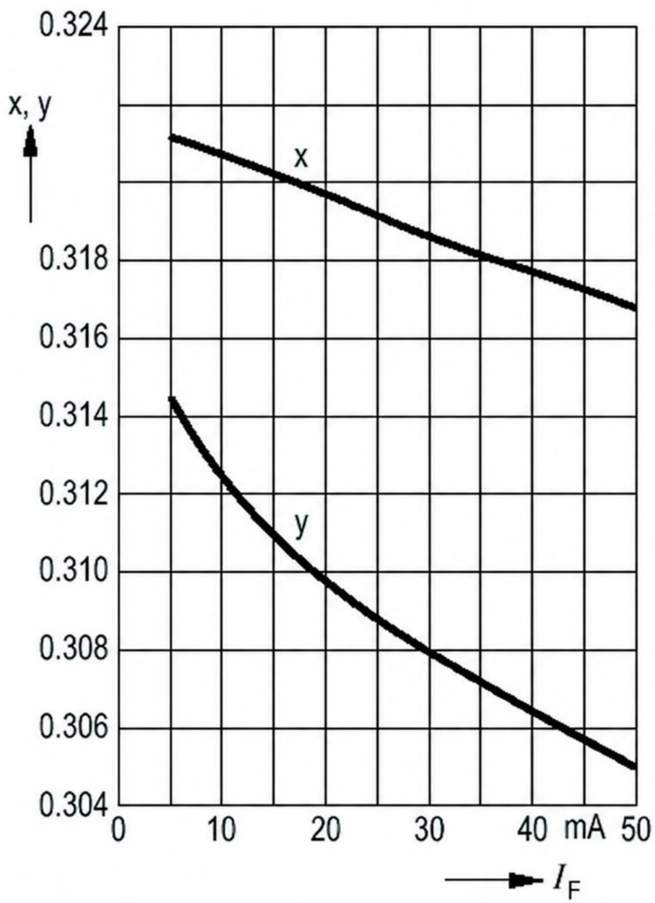
- Current Limiting Using a Capacitor:
  - Rs limits switching transients during turn-on and turn-off. Its value is not critical; 100 Ω, for example, is a suitable value.
  - The antiparallel diode conducts during the negative half-cycle. It can be replaced by another LED. In this configuration, the two LEDs conduct alternately and provide mutual reverse-voltage protection.
  - C limits the current through the LED.
  - Several LEDs can be connected in series.





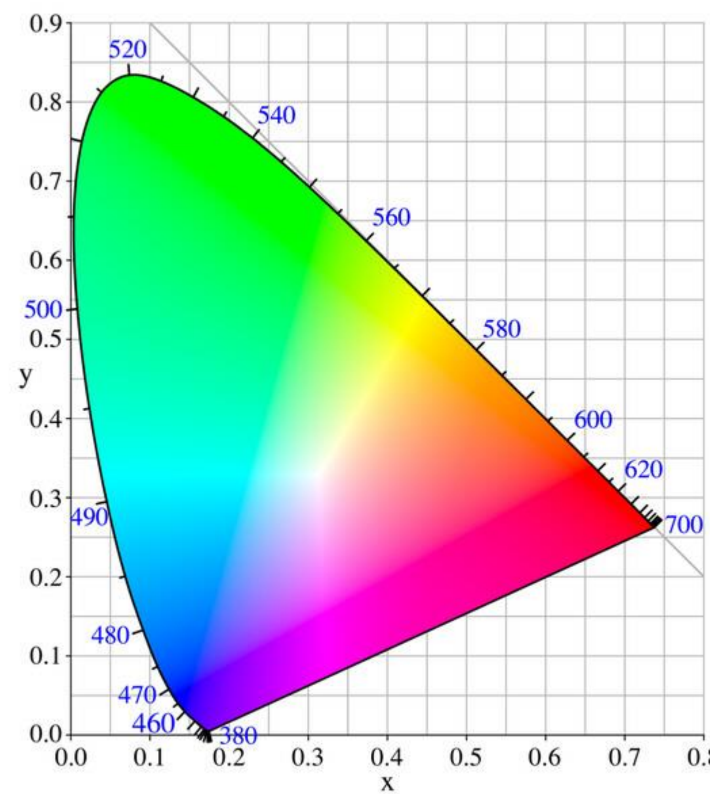
$$I_{LED} \approx \frac{V_{AC}/X_c}{2} = \frac{V_{AC} \cdot \omega C}{2} = \frac{230 \cdot 2\pi \cdot 50 \cdot C}{2} = 36128C => C = \frac{I_{LED}}{36128} F$$

LEDs (VII): Color Dependence



CHROMATICITY COORDINATE CHANGES AS A FUNCTION OF x, y = $f(I_F)$ FOR THE LED'S FORWARD CURRENT.

T_A = 25 °C



White color x=0.33 y=0.33

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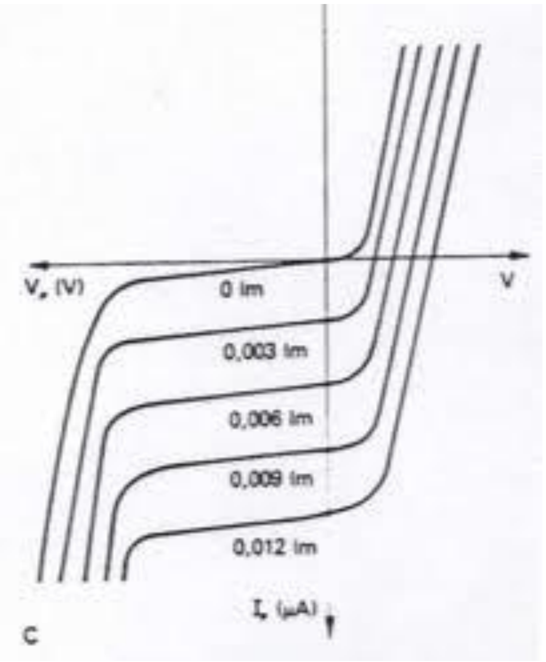
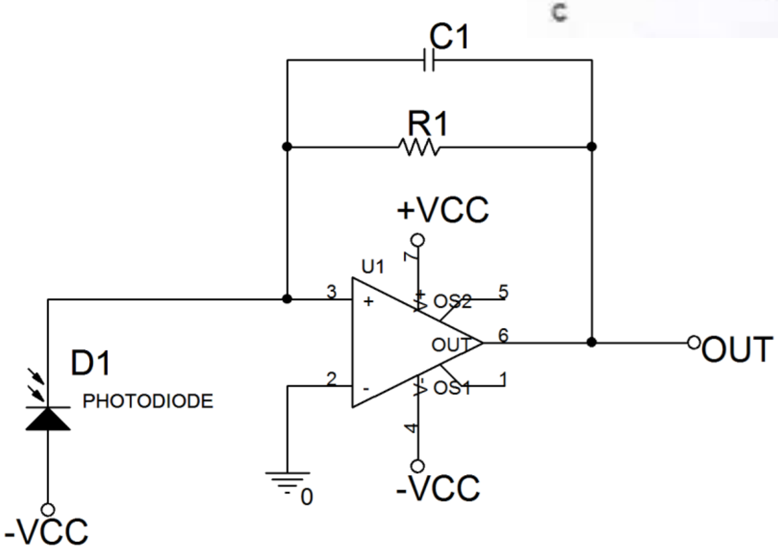
Light Detectors – Photodiode

- A photodiode converts the received optical energy into electron–hole pairs.
- The electron–hole pairs that contribute to current conduction are generated in the depletion region.
- To enhance this effect, an undoped intrinsic region (I) is introduced, increasing the width of the depletion region and forming what is known as a PIN photodiode.



Curiosity: All diodes are photosensitive to some extent, but conventional diodes are much less efficient as photodetectors because of their construction and semiconductor material

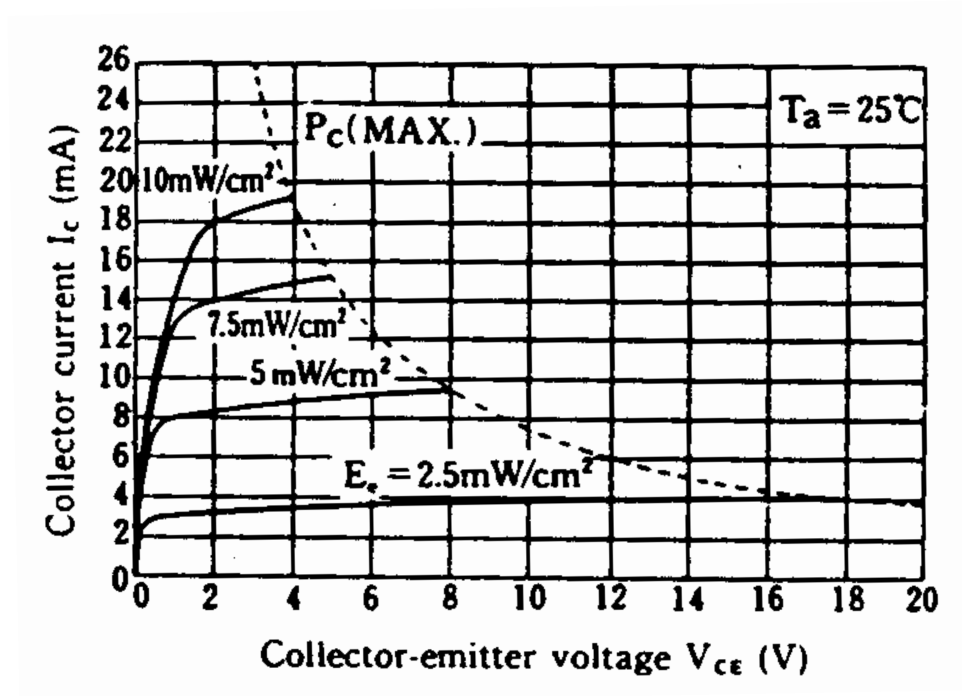


Other Light Detectors

Based on the same principle, other components change their conduction state depending on the incident light energy:

- Photoresistors
- Phototransistors (Bipolar, Darlington, FET, etc.).
- Photothyristors
- Phototriacs

Smart Application of a Phototransistor: Coin Size Detector in a Vending Machine
https://www.youtube.com/shorts/Mjt4sChq7Ys



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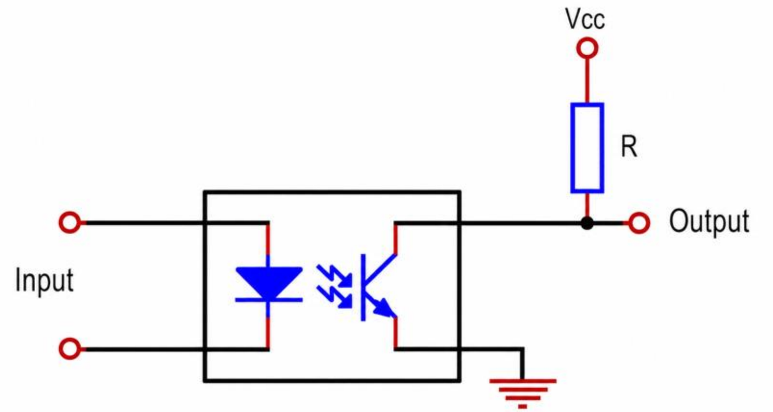
Optocouplers (I): Definition

- These devices combine the two phenomena described above: they include both a light emitter and a light detector.
- They convert an electrical input signal into light (LED) and then convert it back into an electrical signal (photodiode, phototransistor, etc.).
- Their main purpose is to provide galvanic isolation between the input and output circuits.
- An important field of application is power electronics, where optocouplers isolate the power stage from the control circuitry in order to protect the latter.

Optocouplers (II): Parameters

- Main Operating Parameters:
  - Current Transfer Ratio (CTR).
  - Input-to-Output Isolation:
    - Isolation Voltage.
    - Isolation Resistance.
    - Isolation Capacitance.
  - Response Speed: t_{pHL}, t_{pLH}.
  - Common-Mode Rejection (CMR):
    - Common-Mode Transient Immunity (CMTI).
    - Common-Mode Rejection Ratio (CMRR).



Typical circuit with optocoupler

Optocouplers (III): CTR

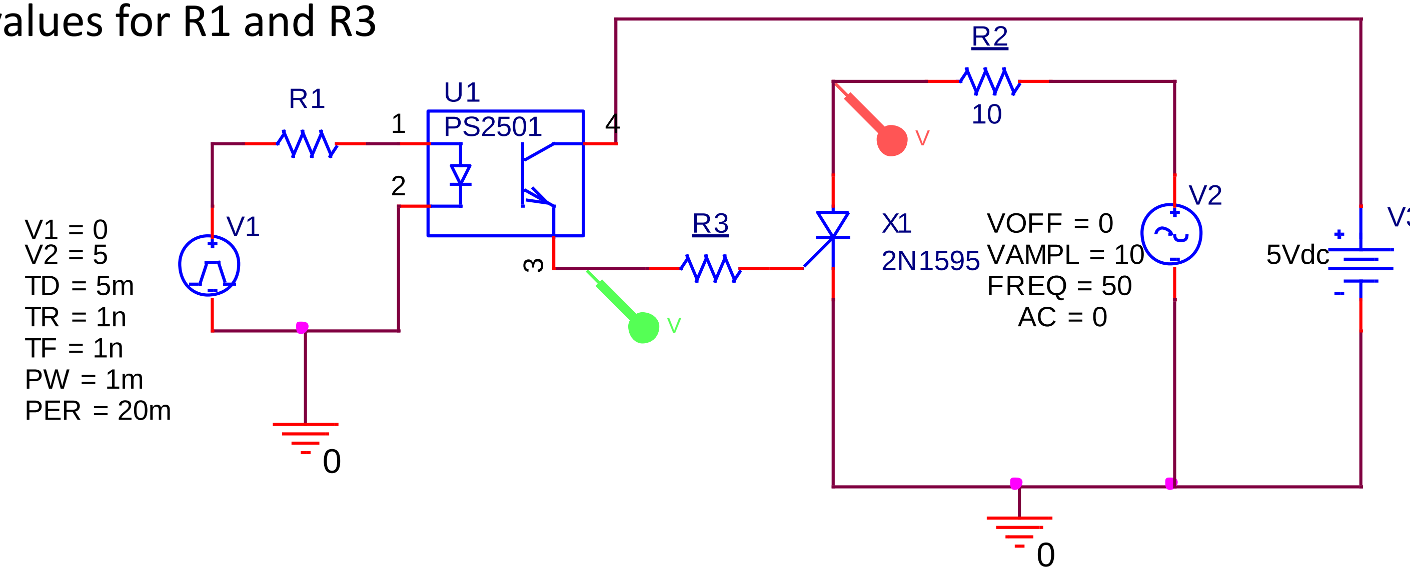
- Current Transfer Ratio:
  - The current transfer ratio reflects the efficiency of the device.
  - It is defined as the ratio between a change in output current and the corresponding change in input current that caused it.
  - It is usually expressed as a %.
  - Typical values for a phototransistor optocoupler range from 10% to 50%. For a photodarlington optocoupler, the CTR can reach 2000%

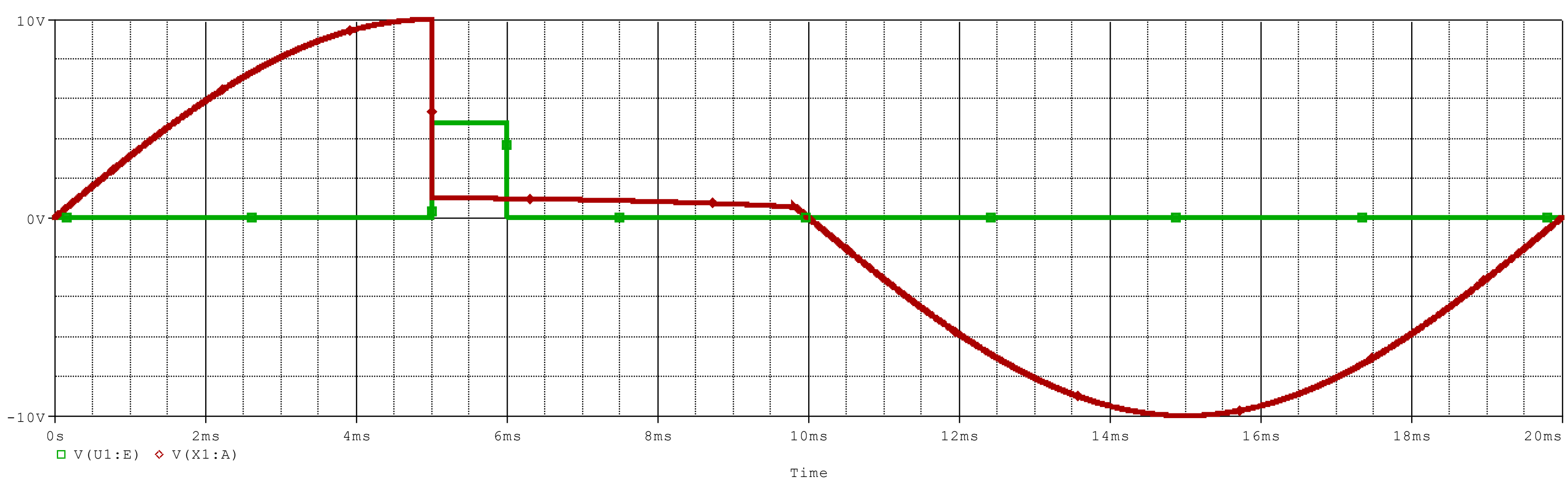
Optocouplers (III): Common-Mode Rejection

- Common-Mode Transient Immunity:
  - Maximum allowable rate of rise or fall of the common-mode signal.
  - It is expressed in V/µs.
  - The maximum allowable amplitude of the common-mode signal is also usually specified.
  - This parameter is mainly relevant to digital devices.
- Common-Mode Rejection Ratio:
  - Ratio of differential-mode gain to common-mode gain.
  - It is expressed in decibels (dB).
  - This parameter is mainly relevant to analog devices.

Optocouplers (IV): Proposed Exercise

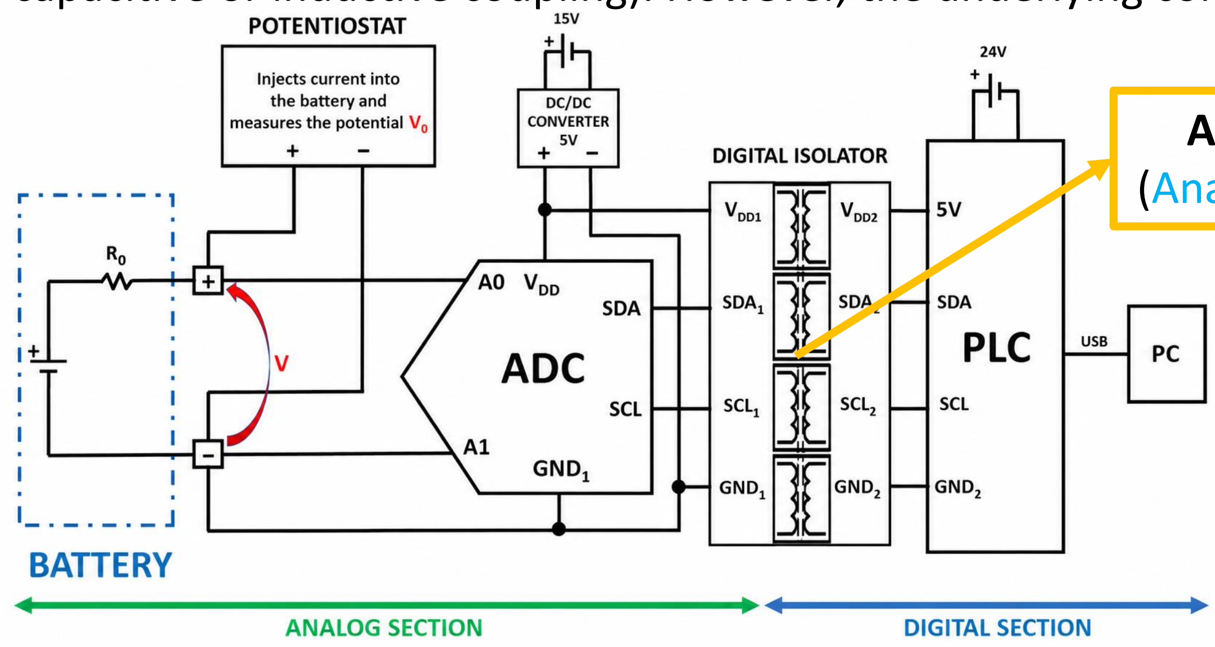
Calculate suitable values for R1 and R3





Digital Isolators

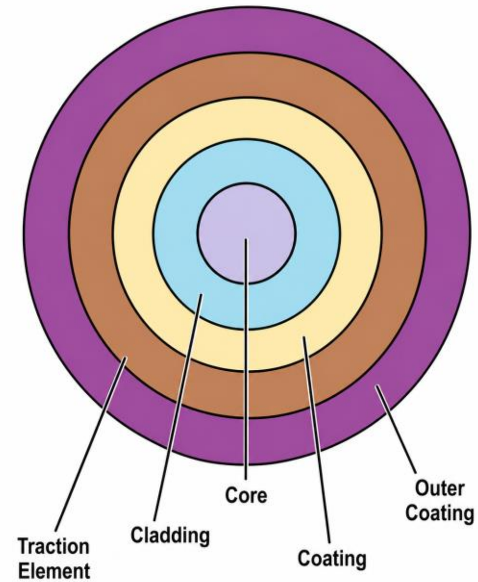
- Galvanic isolation is critical when high measurement accuracy is required, for example when using ADCs with I^2C communication and microvolt-level resolution
- The analog and digital sections must be isolated from each other to break ground loops. In other words, galvanic isolation is required.
- These devices are known as digital isolators. Modern devices generally do not use optocouplers, but instead rely on proprietary isolation technologies (typically based on capacitive or inductive coupling). However, the underlying concept is similar.

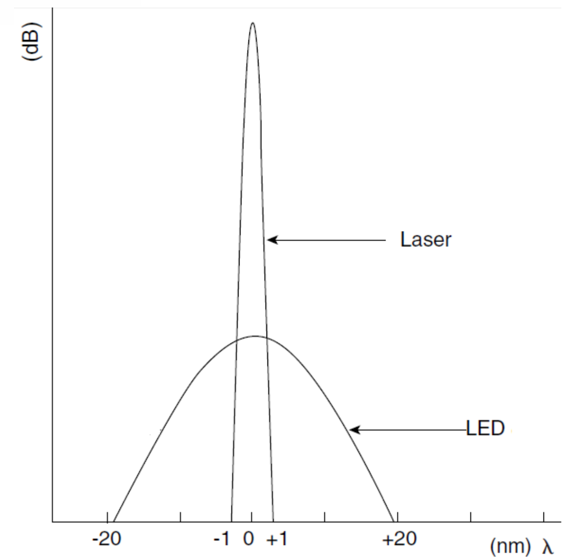


ADuM1250
(Analog Devices)

Fiber Optics (I): Definition

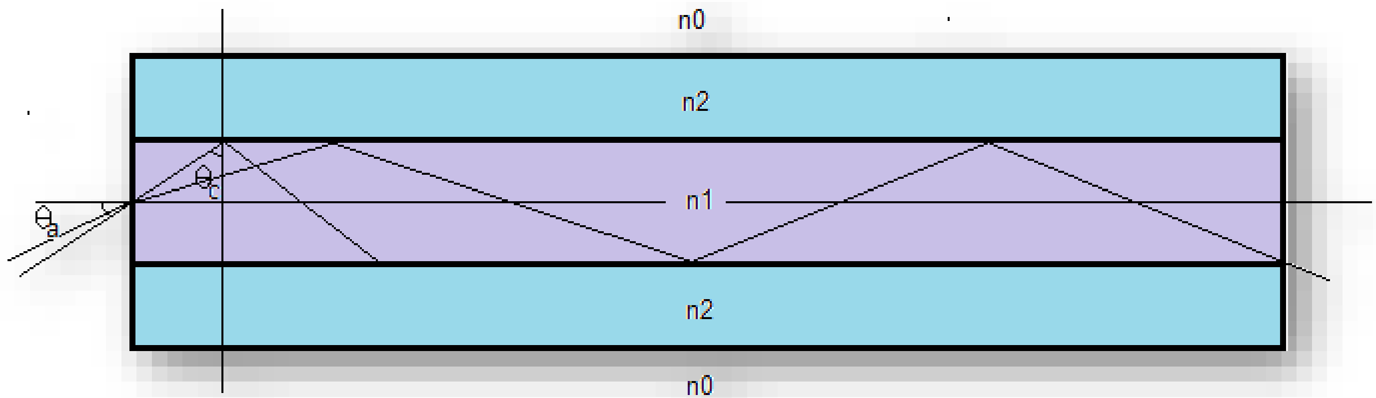
- An optical fiber is a type of cable in which conventional electrical conductors are replaced by materials capable of transmitting light.
- The light is generated by a light-emitting device: an LED or a laser.
- Fiber-optic cables consist of a series of layers designed to confine and guide the light within the fiber.





Fiber Optics (II): Propagation

- Light propagation in an optical fiber is based on the phenomenon of total internal reflection.
- Total internal reflection occurs when the angle of incidence is greater than the critical angle.
- $\theta_c = \ arcsin\left(\frac{n2}{n1}\right)$ where n1 >n2.



- The acceptance angle is the maximum angle at which light rays can enter the fiber and still be guided through it.
- The numerical aperture is defined assuming

$NA = n1 \sin\theta_a = \sqrt{(n1)^2 - (n2)^2}$ assuming n0 = 1 (air).

Fiber Optics (III): Attenuation

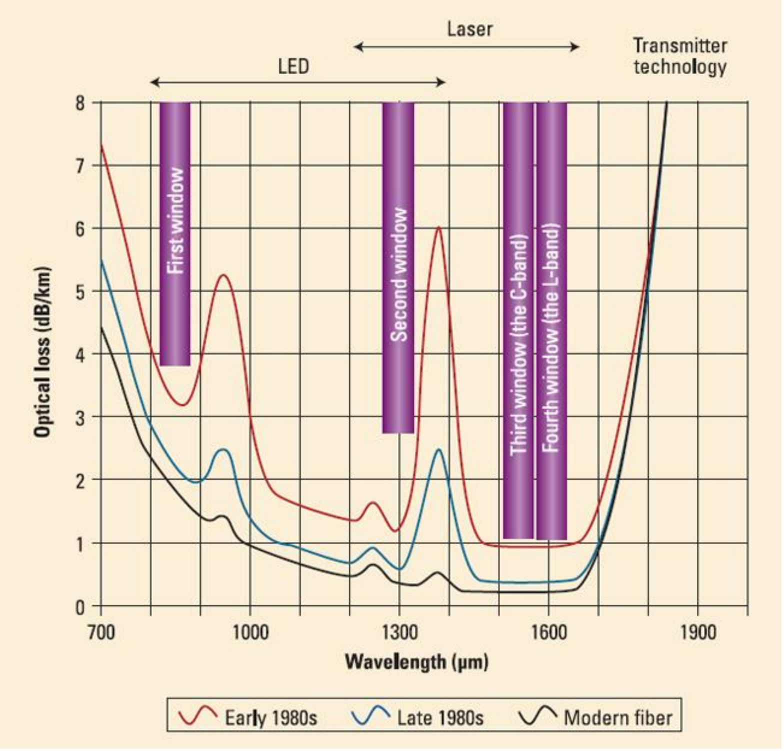
The optical signal is attenuated as it propagates through the fiber:

$$\alpha(dB/km) = \frac{10}{L} log \frac{P_0}{P_L}.$$

This limits the maximum cable length.

Attenuation is caused by several phenomena:

- **Material Absorption**: Caused by imperfections and impurities in the fiber. This gives rise to optical windows: wavelength ranges in which absorption is lower.
- **Heat Dissipation**.
- **Rayleigh Scattering**: Caused by the interaction of light with microscopic variations in the fiber material. Light scattered outside the conditions required for total internal reflection is lost.



Fiber Optics (IV): Dispersion

Dispersion: Pulse broadening that limits the available bandwidth

Modal Dispersion: Different light rays (modes) require different amounts of time to travel through the fiber because they follow different propagation paths.

Chromatic Dispersion: The different spectral components of light propagate at different velocities because the refractive index depends on wavelength → n = n(λ).

Fiber Bandwidth: $B(GHz) = \frac{0.187}{\sigma_{Tot}(ns)}$ $\sigma^2{}_{Tot} = \sigma^2{}_M + \sigma^2{}_C$

Fiber Optics (V): Types of Optical Fiber

- According to the number of propagation modes they support, optical fibers can be classified into two types:
  - Single-Mode Fiber: Supports only one propagation mode. It has a narrow core, so only one mode satisfies the restrictive propagation conditions imposed by its numerical aperture. Since it is not affected by modal dispersion, it provides higher bandwidth. Its attenuation is also lower.
  - Multimode Fiber: supports multiple propagation modes and has a larger core.
- According to the variation of the refractive index within the core, fibers can also be classified as:
  - Step-Index Fiber: The refractive index is constant throughout the core, with an abrupt change at the core–cladding interface. Both single-mode and multimode fibers can use a step-index profile.
  - Graded-Index Fiber: The refractive index varies gradually, decreasing from its maximum value at the center of the core toward the core–cladding interface, where it approaches the refractive index of the cladding. This profile is used in multimode fibers. Its **main advantage** is reduced modal dispersion, since the different propagation paths are partially compensated by differences in propagation velocity. Attenuation is also slightly lower.

Fiber Optics (VI): Commercial Fiber Types

- The same types of optical fiber are commercially available:
  - Single-mode: OS1, OS2.
  - Multimode: OM1, OM2, OM3, OM4, OM5.
- Single-Mode:
  - Core diameter: 8 – 10 µm.
  - Attenuation (dB/km): OS1 (1.0), OS2 (0.4)
  - Same type of fiber: OS1 (interior), Os2 (exterior)
- Multimode:
  - LED-based sources: OM1 y OM2
  - Laser-based sources: OM2, OM3, OM4 y OM5
  - Core diameter 62.5 µm: OM1
  - Core diameter 50 µm: OM2, OM3, OM4 y OM5
  - Bandwidth (MHz*Km): OM1 (200), OM2 (500), OM3 (1500), OM4 (3500), OM5 (3500).

Fiber Optics (VII): Examples

- A typical value for the refractive index of the core is 1.62, while the refractive index of the cladding may be 1.52. For these values, determine: Critical angle; Numerical aperture.

  - $\theta_c = \sin^{-1}\left(\frac{n2}{n1}\right) = \sin^{-1}\left(\frac{1.52}{1.62}\right) = 69.76°$
  - $NA = \sin\theta_a = \sqrt{(n1)^2 - (n2)^2} = \sqrt{1.62^2 - 1.52^2} = 0.56$

- Calculate the bandwidth of a multimode fiber with a modal dispersion of 0.3 ns/km and a chromatic dispersion of 1 ps/(nm·km). The spectral width of the incident light is 10 nm. The fiber length is 2 km.

  - ${\sigma^2}_{Tot} = {\sigma^2}_M + {\sigma^2}_C = (0.3 \times 2)^2 + (0.001 \times 10 \times 2)^2 = 0.3604 \rightarrow \sigma_{Tot} = 0.6003\ ns$
  - $B(GHz) = \frac{0.187}{\sigma_{Tot}(ns)} = \frac{0.187}{0.6003} = 0.3115\ GHz = 311.5\ MHz$

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