EXTRACTION EFFICIENCY

Extraction ratio, or the **extraction efficiency** (EE), η_{EE}

$$\eta_{EE} = \frac{\text{Photons emitted externally from the device}}{\text{Photons generated internally by recombination}}$$

$$P_o = \eta_{EE} P_{o(\text{int})} = h\upsilon \eta_{EE} \eta_{IQE} (I/e)$$

External Quantum Efficiency

External quantum efficiency (EQE) η_{EQE} of an LED represents the efficiency of conversion from electrical quanta, *i.e.* electrons, that flow in the LED to optical quanta, *i.e.* photons, that are emitted into the outside world.

Actual optical power emitted to the ambient = Radiant flux = P_o
(Φ_e is also used)

$P_o/h\upsilon$ is the number of emitted photons per second

I/e is the number of electrons flowing into the LED

$$\eta_{EQE} = \frac{P_o / h\upsilon}{I/e}$$

POWER CONVERSION EFFICIENCY

Power conversion efficiency (PCE)
Power efficiency
η_{PCE}

Efficiency of conversion from the input of electrical power to the output of optical power

$$\eta_{PCE} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_o}{IV} \approx \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

LED BRIGHTNESS

Luminous flux Φ_υ is a measure of *visual* **brightness**, in lumens (lm), and is defined by

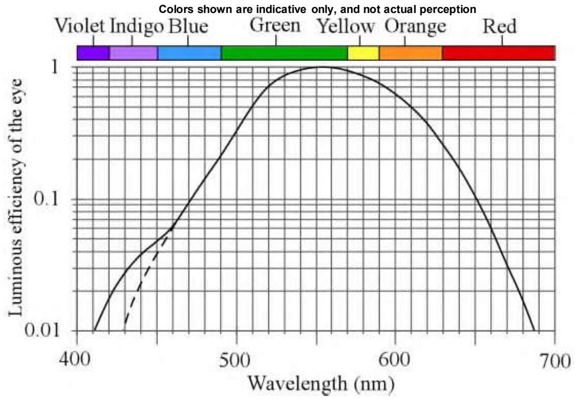
$$\Phi_\upsilon = P_o \times (683 \text{ lm W}^{-1}) \times V(\lambda)$$

$V(\lambda)$ = **relative luminous efficiency** or the relative sensitivity of an average light-adapted (photopic) eye, which depends on the wavelength

$V(\lambda)$ = **luminosity function** and the **visibility function**

$V(\lambda)$ is a Gaussian-like function with a peak of unity at 555

The luminous efficiency of the eye



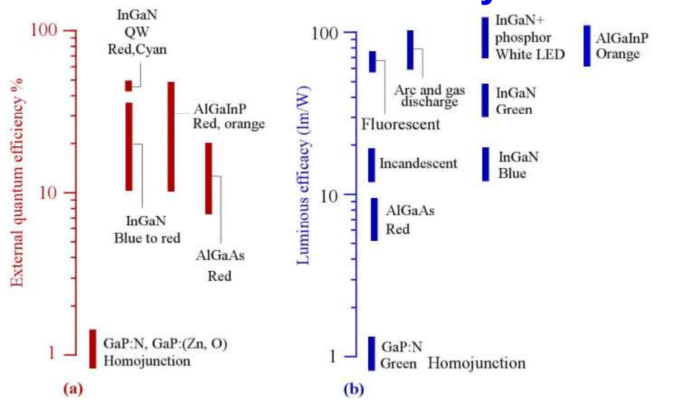
The luminous efficiency $V(\lambda)$ of the light-adapted (photopic) eye as a function of wavelength. The solid curve is the Judd-Vos modification of the CIE 1924 photopic photosensitivity curve of the eye. The dashed line shows the modified region of the original CIE 1924 curve to account for its deficiency in the blue-violet region. (The vertical axis is logarithmic)

LED BRIGHTNESS AND EFFICACY

Luminous efficacy

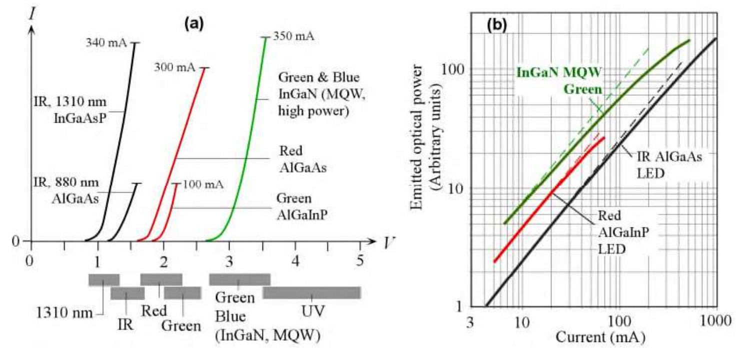
$$\eta_{\mathrm{LE}} = \frac{\Phi_v}{IV}$$

Luminous Efficacy



Typical (a) external quantum efficiency and (b) luminous efficacy of various selected LEDs, and how they stand against other light sources such as the fluorescent tube, arc and gas discharge lamps and the incandescent lamp.

LED Characteristics: *I* vs. *V*



(a) Current-Voltage characteristics of a few LEDS emitting at different wavelengths from the IR to blue. (b) Log-log plot of the emitted optical output power vs. the dc current for three commercial devices emitting at IR (890 nm), Red and Green. The vertical scale is in arbitrary unit and the curves have been shifted to show the dependence of P_o on I. The ideal linear behavior $P_o \propto I$ is also shown.

EXAMPLE: LED brightness LED brightness

Consider two LEDs, one red, with an optical output power (radiant flux) of 10 mW, emitting at 650 nm, and the other, a weaker 5 mW green LED, emitting at 532 nm. Find the luminous flux emitted by each LED.

Solution

For the **red LED**, at $\lambda = 650$ nm, Figure 3.41 gives $V \approx 0.10$ so that from Eq. (3.14.8)

$\Phi_\upsilon = P_o \times (683 \text{ lm W}^{-1}) \times V$

$= (10\times10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.10) =$ **0.68 lm**

For the **green LED**, $\lambda = 532$ nm, Figure 3.41 gives $V \approx 0.87$ so that from Eq. (3.14.8)

$\Phi_\upsilon = P_o \times (683 \text{ lm W}^{-1}) \times V$

$= (5\times10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.87) =$ **3.0 lm**

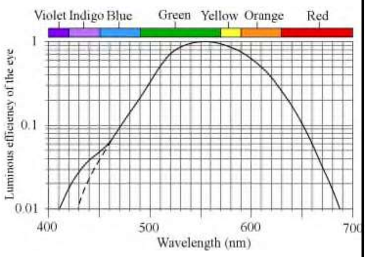
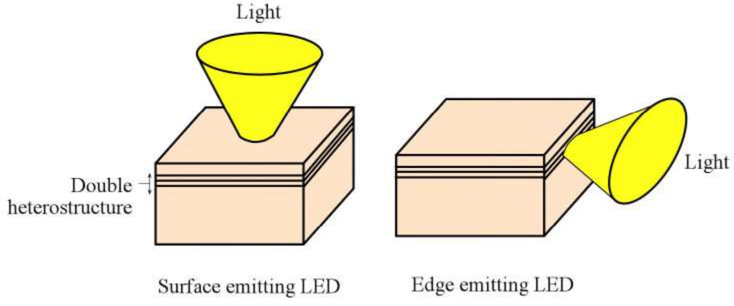


Figure 3.41

Clearly the **green LED** at half the power is 4 times brighter than the **red LED**.

LED TYPES



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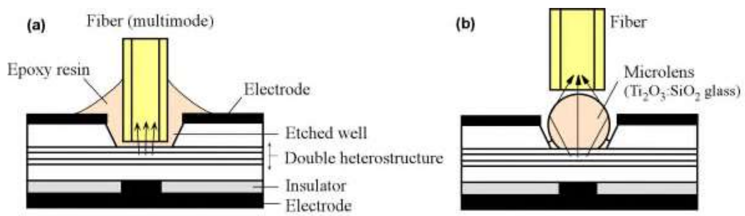
SLED



Coupling of light from LEDs into optical fibers. (a) Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure. (b) A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.

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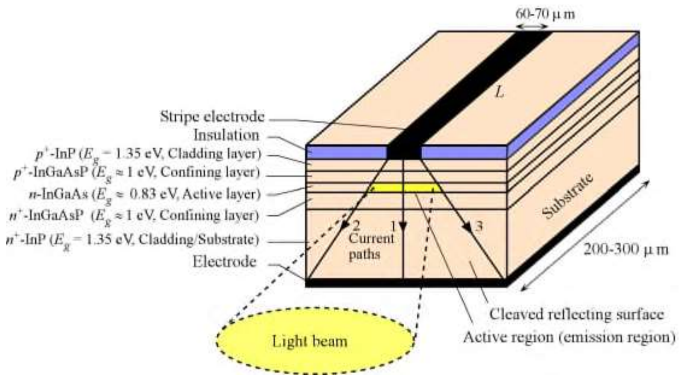
ELED



Schematic illustration of the structure of a double heterojunction stripe contact edge emitting LED. (Upper case notation for a wider bandgap semiconductor is not used as there are several layers with different bandgaps.)

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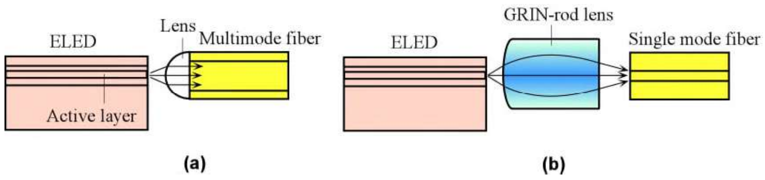
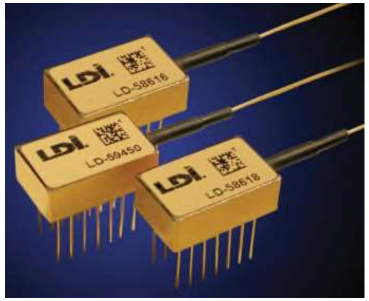
ELED Coupling into Fibers



Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.

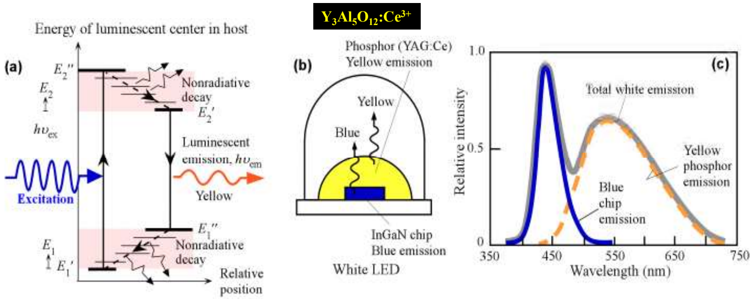
Pigtailed LEDs



InGaAsP 1300nm LED emitters, each pigtailed to an optical fiber for use in ruggedized optical communication modems and lower speed data / analog transmission systems. (Courtesy of OSI Laser Diode, Inc)

White LEDS

$Y_3Al_5O_{12}:Ce^{3+}$



(a) A simplified energy diagram to explain the principle of photoluminescence. The activator is pumped from E_1' to E_2''. It decays nonradiatively down to E_2'. The transition from E_2' down to E_1'. (b) Schematic structure of a blue chip yellow phosphor white LED (c) The spectral distribution of light emitted by a white LED. Blue luminescence is emitted by GaInN chip and "yellow" phosphorescence is produced by phosphor. The combined spectrum looks "white". (Note: Orange used for yellow as yellow does not show well.)

White LEDS

Photoluminescence is the emission of light by a material, called a **phosphor**, that has been first excited by light of higher frequency. Higher energy photons are first absorbed, and then lower energy photons are emitted.

Typically the emission of light occurs from certain dopants, impurities or even defects, called luminescent or **luminescence centers**, purposefully introduced into a **host matrix**, which may be a crystal or glass.

White LEDS

The luminescent center is also called an **activator**. Many phosphors are based on activators doped into a host matrix.

$\mathbf{Eu^{3+}}$ (europium ion) in a $\mathbf{Y_2O_3}$ (yttrium oxide, called yttria) matrix is a widely used modern phosphor. When excited by UV radiation, it provides an efficient luminescence emission in the red (around 613 nm). It is used as the red-emitting phosphor in color TV tubes and in modern tricolor fluorescent lamps.

Another important phosphor is $\mathbf{Ce^{3+}}$ in $\mathbf{Y_3Al_5O_{12}}$ **(YAG)**, written as $\mathbf{Y_3Al_5O_{12}{:}Ce^{3+}}$, which is used in white LEDs. $\mathbf{YAG{:}Ce^{3+}}$ can absorb blue radiation, and emit yellow light.

White LEDS

(Photo by SK)

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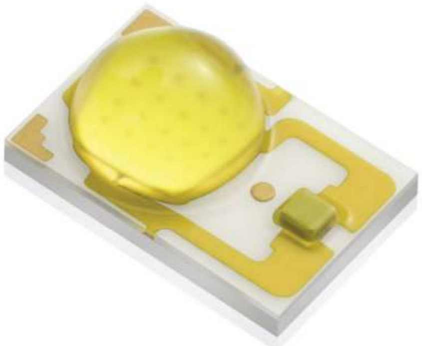
White LEDS



LUXEON Rebel ES white emitting LED (Courtesy of Philips Lumileds)

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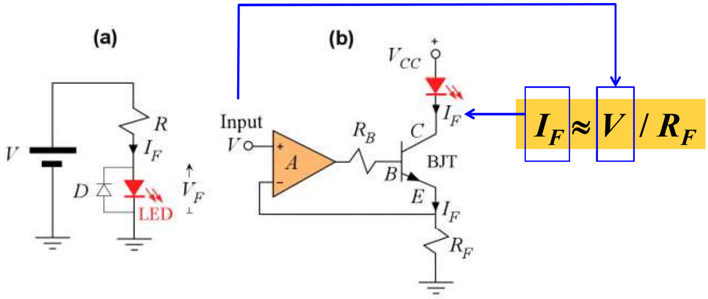
LED Electronics: Analog



(a) The simplest circuit to drive an LED involves connecting it to a voltage supply (*V*) through a resistor *R*. (b) Bipolar junction transistors are well suited for supplying a constant current. Using an IC and negative feedback, the current is linearly controlled by *V*. (c) There are various commercial LED driver modules that can be easily configured to drive a number of LEDs in parallel and/or series. The example has a module driving 4 LEDs, has a dimmer (*R*) and an on/off switch.

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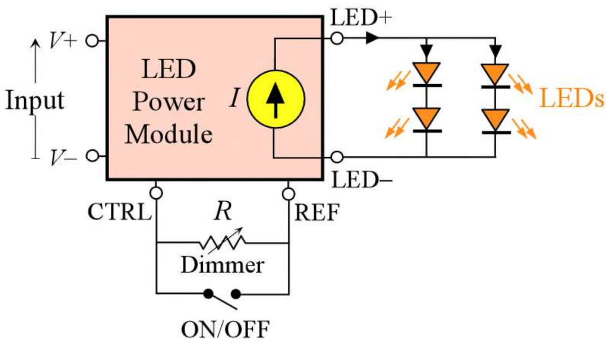
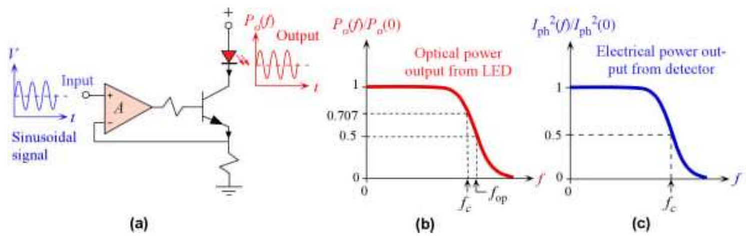
LED Electronics: Drive Modules



There are various commercial LED driver modules that can be easily configured to drive a number of LEDs in parallel and/or series. The example has a module driving 4 LEDs, has a dimmer (R) and an on/off switch.

LED Electronics



$$P_o(\omega)/P_o(0) = 1/\sqrt{[1+(\omega\tau)^2]}$$

τ = Net minority carrier recombination time

$$1/\tau = 1/\tau_r + 1/\tau_{nr}$$

(a) Sinusoidal modulation of an LED. (b) The frequency response where f_c is the cut-off frequency at which $P_o(f)/P_o(0)$ is 0.707. (c) The electrical power output from the detector as a function of frequency. At f_c, $[I_{ph}(f)/I_{ph}(0)]^2$ is 0.5. However, it is 0.707 at a lower frequency f'_c.

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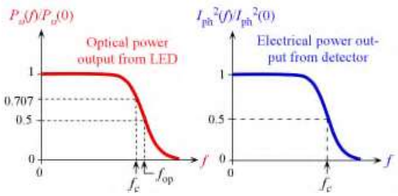
LED Electronics



$$P_o(\omega)/P_o(0) = 1/\sqrt{[1+(\omega\tau)^2]}$$

$$f_{\text{op}} = \frac{\sqrt{3}}{2\pi\tau}$$

Optical Bandwidth

$$f = f_{\text{op}} \Longrightarrow P_o(f_{\text{op}})/P_o(0) = 1/2$$

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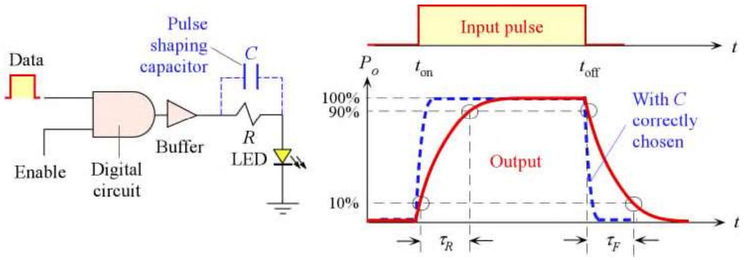
LED Electronics: Digital



$$\tau_R = \tau_F = 2.2\tau \qquad 1/\tau = 1/\tau_r + 1/\tau_{nr}$$

A LED in a digital circuit is turned on and off by a logic gate, assumed to have a buffered output as shown, to avoid being loaded. A BJT can be used after the logic gate to drive the LED as well (not shown). Definitions of rise and fall times are shown in the light output pulse.

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