Final Exam - Solutions, Spring Semester 2005

ECSE-6961, *Light-emitting diodes and solid-state lighting*

1. (a) Explain the effect of temperature change on the performance characteristics of (i) LED-based white sources, and (ii) phosphor-based white LED sources.
   (b) Discuss the significance of the temperature effect for any application of your choice.

   a)
      (i) Temperature affects the peak wavelength, spectral line-width, and output power of LEDs. In an LED based white light source, this can result in change in the color coordinates, color temperature, color rendering index, luminous efficiency.
      (ii) In a phosphor based white light sources the above effect is not as prominent due to weak temperature dependence and the very broad emission spectrum of phosphors.

   b) In case of LED-based white light sources used in residential lighting the color temperature, color rendering index, and efficiency of the source will change as the season (hot summer, cold winter) or even time of the day changes (warm day cold night).

2. Give three methods each to
   (a) Increase light extraction.
   (b) Increase internal quantum efficiency.
   (c) Decrease the forward voltage of an LED.

   a)
      1. Double heterostructure
      2. Shaping of LED dies
      3. Transparent contacts
      4. Transparent substrate
      5. High refractive index epoxy
      6. Textured surfaces

   b)
      1. Double heterostructure
      2. Low or no doping in active region
      3. Lattice matching of layers
      4. Carrier blocking layers

   c)
      1. Lower contact resistance
      2. Lower bulk (confinement layer) resistance
      3. Minimizing non-adiabatic carrier injection

3. (a) What is thermal runaway?
   (b) What is the advantage of a high cavity quality factor Q? How can one obtain a high Q?
   (c) State three differences between a laser and an LED.
   (d) What is the minimum flicker method?
   (e) What is the significance of the circadian rhythm?
   (f) What is the "green gap"?
   (g) Are semiconductors with a large Urbach tail preferable over semiconductors with a small Urbach tail?

   a) As temperature increases, efficiency decreases (non-radiative recombination increases), diode temperature increases …
   b) High Q reflects narrower spectral line width and hence a purer color. One way to increase the Q is to increase cavity length.
   c) Coherent light, stimulated emission, narrow line-width, polarized light, high optical power density.
   d) Minimum flicker method is a classic method for luminance comparison and determination of $V(\lambda)$. The stimulus is a light-emitting small circular area, alternatingly illuminated (with a frequency of 15 Hz) with the standard color and the comparison color. Since the hue-fusion frequency is lower than 15 Hz, the hues fuse. However, the brightness-fusion frequency is higher than 15 Hz and thus if the two colors differ in brightness, then there will be a visible flicker. The human subject's task is to adjust the target color until the flicker is minimal.
   e) Circadian rhythm is the wake-sleep rhythm of human beings which is synchronized by light.
   f) Wavelengths corresponding to green color (~ 555 nm) lie around the center of the range of visible wavelengths (~ 380 nm to 780 nm). There is a lack of *efficient* green LEDs. The efficiency increases as the emission wavelength moves away from green on either side. This creates a "green gap" of available efficient visible-spectrum LEDs.
   g) No.

4. (a) Can you obtain a color with (x, y) chromaticity coordinates (0.3, 0.4) if you have two LEDs with (x, y) chromaticity coordinates (0.1, 0.1) and (0.7, 0.3)?
   (b) Can you obtain a color with (x, y) chromaticity coordinates (0.2, 0.5) if you have three LEDs with (x, y) chromaticity coordinates (0.2, 0.1), (0.6, 0.3), and (0.3, 0.5)?
   (c) Can you obtain a color with (x, y) chromaticity coordinates (0.4, 0.6) if you have two LEDs with (x, y) chromaticity coordinates (0.1, 0.1) and (0.25, 0.35)?

   c) No.
   d) No.
   e) No.

5. Consider a two LED light source with the following parameters:
Source 1: $\lambda = 460$ nm, $P_{electrical} = 50$ mW, $\eta_{external} = 50\%$, and $V_f = 4.0$ V
Source 2: $\lambda = 580$ nm, $P_{electrical} = 50$ mW, $\eta_{external} = 30\%$, and $V_f = 3.0$ V
Calculate the following quantities:
(a) η_{power}.
(b) Luminous efficiency.
(c) Show the location of the resultant color on the (x, y) chromaticity coordinate system.

a) $\eta_{power} = \dfrac{\eta_{power,460} + \eta_{power,580}}{2} = \dfrac{\eta_{ext,460}\left(\dfrac{hc/\lambda}{eV_f}\right) + \eta_{ext,580}\left(\dfrac{hc/\lambda}{eV_f}\right)}{2} = \dfrac{33.7 + 21.4}{2} =$ 27.55%

b) Luminous Efficiency $= \dfrac{\Phi_{lum}}{IV} = \dfrac{\dfrac{683}{IV} \times \left((P_{460} \times V_{460}) + (P_{580} \times V_{580}) \right)}{2} = 70.5$ lm/W

c) See attachment.

6. Consider a 1 km long multimode step-index fiber with a core index of 1.45 and a cladding index of 1.4. Assume that the fiber input comes from either an LED emitting at 800 nm or an LED emitting at 1300 nm. Assume that both the LEDs have a spectral linewidth of 25 nm.
(a) Calculate the modal and material dispersion (pulse broadening) for each case.
(b) What limits the maximum bit rate at each wavelength?
(c) Explain the result obtained in (b).

a) Critical angle, $\theta_c = \cos^{-1}\left(\dfrac{n_2}{n_1}\right) = 15°$

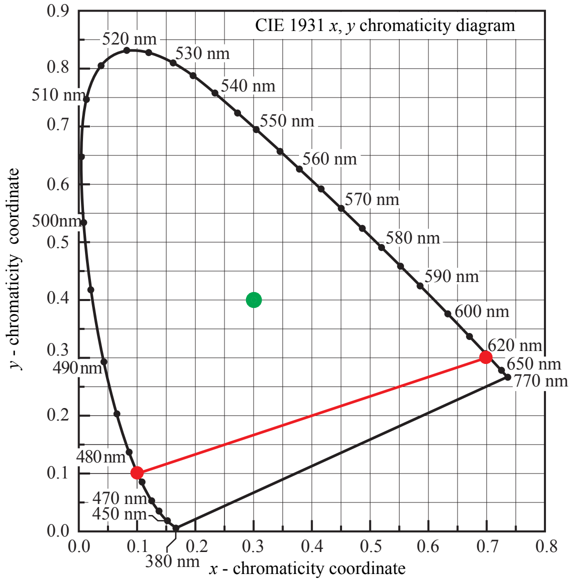
Modal dispersion (800nm) $= \dfrac{n_1}{c}\left(\dfrac{1}{\cos\theta_c} - 1\right) = 0.17$ ns/m

Material dispersion (800nm) = – 80 ps/(km nm)

Modal dispersion (1300nm) $= \dfrac{n_1}{c}\left(\dfrac{1}{\cos\theta_c} - 1\right) = 0.17$ ns/m

Material dispersion (1300nm) = 0 ps/(km nm)

b) The modal dispersion limits the maximum bit rate at the wavelengths 800 nm and 1300 nm.
c) Modal/material dispersion gives the time delay between the slowest and the fastest mode/color in an optical fiber. The larger time delay of the two restricts the maximum bit rate at which data can be transferred.


CIE 1931 x, y chromaticity diagram
520 nm
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550 nm
560 nm
570 nm
580 nm
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770 nm
510 nm
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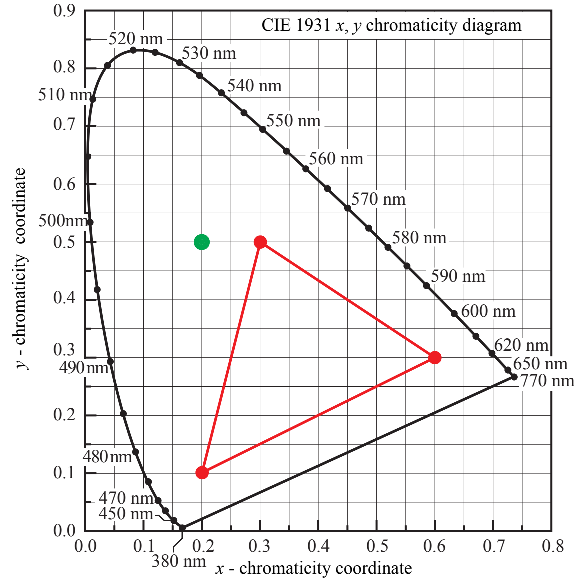
490nm
480nm
470 nm
450 nm
380 nm
x - chromaticity coordinate
y - chromaticity coordinate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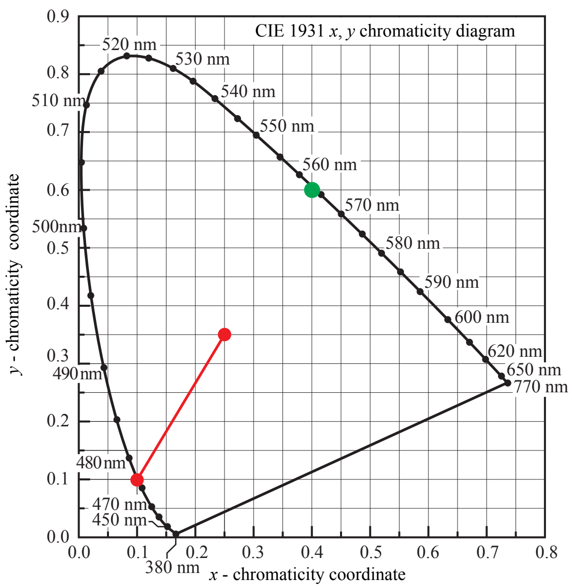
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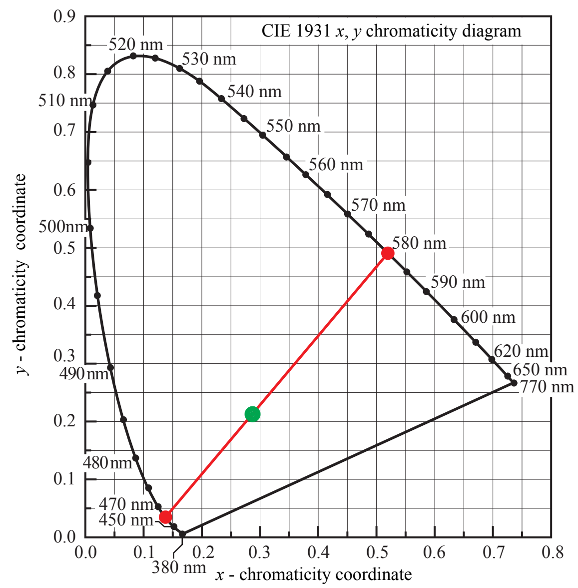
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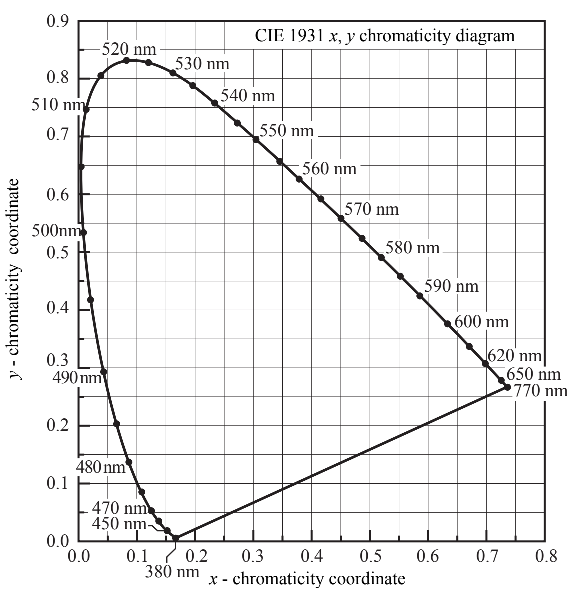
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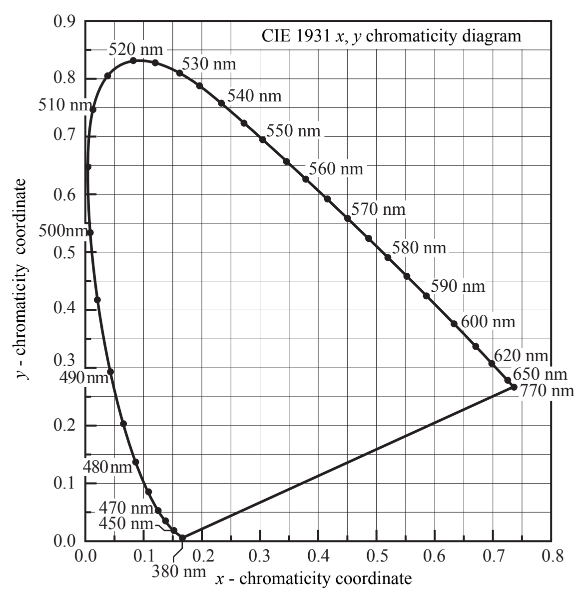
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