

## Chapter 1: The human eye

1. Which diameter has the human iris?

1 mm – 8 mm

2. Which role plays the cornea with respect to the refraction of light?

The cornea provides 2/3 of the eye's focusing power.

Focusing power = 42 D

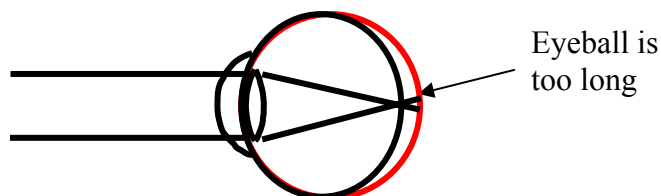
3. Which role plays the lens?

Accommodation of the focusing power to the distance of the observed object.

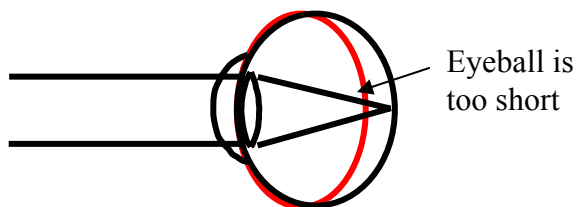
Focusing power = 16 D (not accommodated). Up to +14 D for a young person.

4. Which is the reason for nearsightedness/farsightedness? Use a ray tracing figure for explanation.

Nearsightedness: Eyeball too long or focusing power of cornea too large.



Farsightedness: Eyeball too short or focusing power of cornea too small.



5. What do you understand by old age vision?

Decreasing ability of accommodation of the lens. Near point is beyond approximately 30 cm.

6. What is the light sensitive area within the human eye?

The retina. Color vision (cones) only possible inside the macula. Night vision (rods) predominantly outside the macula.

7. Which role plays the sclera in human vision?

None.

8. What are tears good for?

They moisten and lubricate the cornea. Tears are spread by the eyelids during blinking evenly over the eye. At the same time dust particles are removed from the surface of the cornea. Excess tears travel through a duct directly into the nose.

9. What is the iris good for?

It controls the amount of radiation penetrating into the eye.

10. How fast is the speed of reaction of the human eye on the variation of the light intensity?  
How does the control mechanism work?

The illuminance of the retina controls the diameter of the pupil. The illuminance depends on the luminance [ $\text{lm/sr m}^2$ ] of the observed object. Delay time or speed of reaction amounts to approx. 0.25 s. The diameter of the pupil changes with a velocity of several mm/s. blinking of the lid protects the eye in case of extremely high luminance. Speed of reaction in this case is also approx. 0.25 s.

11. What is the size of the eye?

22 mm deep, 24 mm wide

12. What is the blind spot?

Here, the optic nerve penetrates the retina. No rods or cones are present at that place.

13. What is the macula?

It is a small and highly sensitive part of the retina responsible for detailed central vision. Here the density of cones is highest.

14. How many diopters is the focusing power of the eye?

58 D not accommodated + 14 D for a young person.

15. What is diopter?

Inverse of the focusing length measured in meters.

16. What is the near point/far point?

Near point: Upper limit of accommodation, nearest point which can be focused.

Far point: Lower limit of accommodation, furthest point which can be focused. Infinity, for not nearsighted people.

17. What is accommodation?

Adaptation of the focusing power of the lens to the distance of an observed object.

18. The near point of an 80 years old person is  $d_n = 50$  cm. Its width of accommodation amounts to  $A = -1$  D. Which kind of focusing problem does this person have? Does it need glasses while reading/driving a car? If so, what is the corresponding refracting power of the glasses? Use a ray tracing figure for explanation.

Width of accommodation  $A$  amounts to  $A = -1$  D, where  $A = d_f^{-1} - d_n^{-1}$ . Far point  $d_f = 1$  m. Person suffers from shortsightedness and overlaid old age vision. It needs different glasses for reading (positive refracting power  $B_{near}$ ) and driving a car (negative refracting power  $B_{far}$ ). Car driving: Far point must be infinity:  $d_f^{-1} + B_{far} = 0$ .

$B_{far} = -1$  D.

Reading: Near point must be close to approx. 30 cm.  $d_n^{-1} + B_{near} = 3.33$  D.

$B_{near} = +1.33$  D.

19. You cannot focus objects during diving under water. In case of normal sightedness, which kind of glasses (positive or negative refracting power) would you need for unblurred vision?

The refraction index of water is larger than that of air. Consequently the focusing power of the eye is reduced. Therefore glasses with positive refracting power are needed.

20. You observe the  $a = 5$  mm long and  $b = 1$  mm wide incandescent filament of a light bulb at a distance of  $D = 1$  m. The radiant exitance of the filament is  $M_e = 5$  MW/m<sup>2</sup>. What is the irradiance  $E_e$  on your retina, if your pupil is wide open/closed?

The image size of the filament on the retina is reduced by the ratio  $F$  of the distance of the filament from the eye to the distance of the image from the cornea, which roughly equals the depth of the eye  $D_e = 22$  mm:  $F = D/D_e = 45.45$ . The radiation penetrating into the eye covers a solid angle  $\Omega_A = \pi/4 d^2/D^2$  sr, with  $d = 8$  mm if the pupil is wide open:  $\Omega_A = 0.00005$  sr. Each surface element of the filament emits radiation into a solid angle of  $\Omega = 2\pi$  sr. The incoming radiation flux  $F_e = M_e a b \Omega_A/\Omega$ . The area of the filament image is given by  $A = a b/F^2$ . The irradiation intensity  $E_e$  on the retina amounts to  $E_e = M_e F^2 \Omega_A/\Omega$ .

$$E_e = 82 \text{ kW/m}^2.$$

Remark: The size of the filament is not relevant, only its radiant exitance  $M_e$ . The observation distance  $D$  is also irrelevant, because  $F \sim D$  und  $\Omega_A \sim D^{-2}$  which makes  $E_e$  independent of  $D$ .

A closed pupil does not change the image size, but the solid angle  $\Omega_A$ . It changes with the square of the pupil diameter, in case of the 1mm wide closed pupil by a factor of 1/64. The irradiation intensity is reduced to

$$E_e = 1.3 \text{ kW/m}^2.$$

21. You are driving in your car at night approaching traffic lights. Each of the lights has a diamtere of 20 cm and a luminous intensity of 50 lm/sr. At which distance can you unambiguously identify the color of the traffic lights?

Color vision (pure cone vision) requires a luminance of 30 cd/m<sup>2</sup>. The lights shine with a luminance of  $L_e = 30/0.2^2 \text{ lm/(sr m}^2) = 750 \text{ cd/m}^2$ . Color vision only depends on luminance of a light source. Therefore the color of the lights can be identified at each distance. This is the case because the illuminance on the retina stays constant. Only the image size decreases with

increasing distance. At very large distances the image reaches a minimum size, which is given by the eye's optics. This minimum size amounts to approximately  $10\text{ }\mu\text{m}$ . If the distance of the observed object increases further, the illuminance will decrease and the colours appear darker. The diameter  $d_{\text{image}}$  of the images of the traffic lights result from their diameter  $d$ , the depth of the eye  $b = 22\text{ mm}$ , and the observation distance  $g$  according to  $d_{\text{image}} = d \cdot b/g$ . The distance  $g_{10\mu\text{m}}$ , where the image size equals  $10\text{ }\mu\text{m}$  amounts to  $g_{10\mu\text{m}} = 440\text{ m}$ . With increasing distance the image size stays constant and the illuminance decreases with the square of distance  $g$ . Here the illuminance exceeds the critical illuminance for color vision by a factor of 25. Therefore we can still identify the colors of the traffic lights at a distance of approx. 2.2 km.

## Chapter 2: Light and Color

1. Which are the wavelengths, where the sensitivities for daylight and night vision of the eye have their maximum?

Day: 555 nm, night: 510 nm

2. Do cones or rods see color?

Cones

3. Which is the minimum luminance for pure color vision?

$30\text{ cd/m}^2$

4. What are the color matching functions?

The color matching functions  $\bar{x}, \bar{y}, \bar{z}$  represent the spectral sensitivity of the three different types of cones.

5. What are the color coordinates?

The color coordinates X, Y, Z of a color are convolutions of the spectral intensity of a color and the color matching functions.

6. What are color chromaticity coordinates?

The color chromaticity coordinates x, y, z are the relative parts of the color coordinates X, Y, Z:

$$x = X/(X+Y+Z); y = Y/(X+Y+Z); z = Z/(X+Y+Z)$$

7. Where is monochromatic light located in the chromaticity diagram?

Between 380 nm and 780 nm on the curved boundary line of the area of colors. The straight line between 380 nm and 780 nm consists of colors, which can be mixed by additive color mixing from these two colors.

8. Which wavelength has a color arbitrarily located within the chromaticity diagram?

A spectrum of at least two monochromatic colors is required to display any color. Here the interconnection between the chromaticity coordinates must cross the chromaticity coordinate

of the color. The same color may also be created by an unlimited number of monochromatic colors with distinct intensities. Consequently it is not possible to assign a color unambiguously to one specific spectral distribution.

9. What is the purple line?

The straight line between 380 nm und 780 nm consists of colors, which can be mixed by additive color mixing from these two colors.

10. Explain additive two and three color mixing using the chromaticity diagram.

Two color mixing: All colors on the interconnecting line between the coordinates of the two colors can be created by additive color mixing.

Three color mixing: All colors inside the triangular area limited by the coordinates of the three colors can be mixed.

11. What is additive/subtractive color mixing?

Additive color mixing creates a new color by imaging the light of three different colors on the same area of e.g. a white sheet of paper.

Subtractive color mixing uses white light and one or more color absorbing optical filters to create a color.

12. Which colors uses an ink jet printer?

Yellow, cyan, magenta, black

13. You want to create red color using an ink jet printer. Which print-colors do you use?  
Explanation!

Red color remains if green and blue color is absorbed out of white light. Cyan absorbs the red part of the visible spectrum, green and blue part remains. Yellow absorbs blue, green and red remain. Magenta absorbs green, red and blue remain. Therefore, printing magenta and yellow color on top of each other creates red color.

### Chapter 3: Photometry/Colorimetry

1. What are physical quantities of radiation and irradiation?

They measure the energetic quantities of electromagnetic radiation, without taking into account the eye's sensitivity. Examples are radiant flux or irradiance.

2. What are visual quantities?

The index  $v$  characterizes visual quantities  $X_v$ . Those quantities take into account the eye's sensitivity  $V(\lambda)$  by convolution of  $X_{e\lambda}$  and  $V_\lambda$  according to.

$$X_v = K_m \int_{380nm}^{780nm} V(\lambda) X_{e\lambda} d\lambda$$

with  $K_m = 683 \text{ lm/W}$ .

3. What is 1 Lux, Candela, Lumen?

The illuminance is measured in units Lux,  $\text{lx} = \text{lm/m}^2$ , the luminous intensity in units Candela,  $\text{cd} = \text{lm/sr}$ , and the luminous flux in units Lumen,  $\text{lm}$ .

4. The sensitivity of the eye can be approximated by the following analytical function

$$V(\lambda) = \exp\left[-\left(\frac{\lambda / \text{nm} - 555}{A}\right)^2\right],$$

with  $A = 65$ .

A laser diode creates radiation at a wavelength of 690 nm with an efficiency of 50%. What is the efficacy of the laser?

$$V(690 \text{ nm}) = 0.013, \eta = 0.5, \eta_v = K_m V(690 \text{ nm}) \eta = 4.4 \text{ lm/W}$$

What is the optical efficacy?

The whole radiation is visible (light). Consequently the optical efficacy equals the  $O$  (energetic) efficacy.

$$O = 50\%.$$

What is the visual efficacy?

the visual efficacy  $V_i$  in addition takes into account the eyes sensitivity. It amounts to  $V(690 \text{ nm}) = 0.013$ . The visual efficacy results in  $V_i = 0.013 \cdot 50\%$ .

$$V_i = 0.65\%$$

Calculate the above quantities of a GaN-LED, which converts electrical energy into light at 510 nm with an efficiency of 10%.

$$V(510 \text{ nm}) = 0.62; \eta_v = 42.3 \text{ lm/W}$$

$$O = 10\%$$

$$V_i = 6.2\%$$

Which of the light sources appears brighter if both emit radiation into the same solid angle?

The GaN-LED appears brighter.

Calculate the above quantities of a white light source which creates light of constant spectral power in the visible regime with an electrical efficiency of 100%.

$$\eta_v = K_m \int_{380 \text{ nm}}^{780 \text{ nm}} \eta_\lambda V(\lambda) d\lambda \approx K_m \eta_\lambda \int_{-\infty}^{\infty} \exp\left[-\left(\frac{\lambda / \text{nm} - 555}{65}\right)^2\right] d\lambda$$

with  $\eta_\lambda = \eta / (780 \text{ nm} - 380 \text{ nm}) = 1/400 \text{ nm}$ .

$\int \exp(-a^2 x^2) dx$  can only be solved analytically by integration between  $+\infty$  and  $-\infty$  with the result of

$$\int_{-\infty}^{\infty} \exp(-a^2 x^2) dx = \frac{\sqrt{\pi}}{a}.$$

$$\eta_v = 683 \text{ lm/W} \cdot \frac{1}{400 \text{ nm}} \sqrt{\pi} 65 = 196 \text{ lm/W}$$

5. The color matching functions can be approximated by the following analytical functions

$$\bar{x}(\lambda l) = B_{x1} \exp\left[-\frac{\lambda / nm - 600}{A_{x1}}\right]^2 + B_{x2} \exp\left[-\frac{\lambda / nm - 445}{A_{x2}}\right]^2,$$

$$\bar{y}(\lambda l) = \exp\left[-\frac{\lambda / nm - 555}{A}\right]^2,$$

$$\bar{z}(\lambda l) = B_z \exp\left[-\frac{\lambda / nm - 450}{A_z}\right]^2,$$

with  $B_{x1} = 1.07$ ,  $B_{x2} = 0.35$ ,  $B_z = 1.79$ ,  $A_{x1} = 45$ ,  $A_{x2} = 25$ ,  $A_z = 33$ ,  $A = 65$

Using three monochromatic wavelengths at  $\lambda = 600$  nm,  $\lambda = 555$  nm,  $\lambda = 450$  nm white light can be generated by additive color mixing. What are the intensities of the three colors for white light?

white light:  $X=Y=Z$

$$\begin{aligned} X = & B_{x1} (I_{600nm} + I_{555nm} \exp\left[-\frac{555-600}{A_{x1}}\right]^2 + I_{450nm} \exp\left[-\frac{450-600}{A_{x1}}\right]^2) \\ & + B_{x2} (I_{600nm} \exp\left[-\frac{600-445}{A_{x2}}\right]^2 + I_{555nm} \exp\left[-\frac{555-445}{A_{x2}}\right]^2 + I_{450nm} \exp\left[-\frac{450-445}{A_{x2}}\right]^2) \end{aligned}$$

$$X = B_{x1} (I_{600nm} + 0.37I_{555nm} + 1.5 \times 10^{-5} I_{450nm}) + B_{x2} (2 \times 10^{-17} I_{600nm} + 5.6 \times 10^{-9} I_{555nm} + 0.96I_{450nm})$$

$$X \approx B_{x1} (I_{600nm} + 0.37I_{555nm}) + B_{x2} (+0.96I_{450nm}) \quad (1)$$

$$Y = I_{600nm} \exp\left[-\frac{600-555}{A}\right]^2 + I_{555nm} + I_{450nm} \exp\left[-\frac{450-555}{A}\right]^2$$

$$Y = 0.62I_{600nm} + I_{555nm} + 0.074I_{450nm}$$

$$Y \approx 0.62I_{600nm} + I_{555nm} \quad (2)$$

$$Z = B_z (I_{600nm} \exp\left[-\frac{600-450}{A_z}\right]^2 + I_{555nm} \exp\left[-\frac{555-450}{A_z}\right]^2 + I_{450nm})$$

$$Z = B_z (1.06 \times 10^{-9} I_{600nm} + 4.01 \times 10^{-5} I_{555nm} + I_{450nm})$$

$$Z \approx B_z I_{450nm} \quad (3)$$

$$(2) = (3): B_z I_{450nm} - 0.62I_{600nm} - I_{555nm} = 0$$

$$1.97I_{450nm} - 0.62I_{600nm} - I_{555nm} = 0$$

$$I_{450nm} / I_{555nm} = 0.508 + 0.315I_{600nm} / I_{555nm} \quad (4)$$

$$(1) = (3): (B_z - B_{x2} 0.96)I_{450nm} - B_{x1}I_{600nm} - B_{x1} 0.37I_{555nm} = 0$$

$$1.454I_{450nm} - 1.07I_{600nm} - 0.396I_{555nm} = 0$$

$$3.67I_{450nm} / I_{555nm} = 0.272 + 0.736I_{600nm} / I_{555nm} \quad (5)$$

$$(4) = (5): I_{600nm} / I_{555nm} = 1.336$$

$$(4): I_{450nm} / I_{555nm} = 0.929$$

6. A white sheet of paper on your desk is illuminated by white light. Illuminance is 750 lx. The surface of the paper reflects 70 % of the light equally into the upper hemisphere.

What is the luminous intensity of the sheet of paper? What is illuminance on the retina in your eye if you observe the paper at a distance of 1 m perpendicularly with wide open?

$$E_v = 750 \text{ lm/m}^2$$

$$\text{Luminous intensity } L_v = 0.7 \times 525 / 2\pi \text{ lm/(m}^2\text{sr)} = 83.6 \text{ lm/(m}^2\text{sr)}$$

The image size on the retina is reduced by the ratio of the distance  $D = 1 \text{ m}$  of the object to the eye and the depth  $d_e = 22 \text{ mm}$  of the eye. The demagnification amounts to  $F = 45.45$ . The solid angle  $\Omega_A$  of the incoming light amounts to  $\Omega_A = \pi/4 \cdot d^2/D^2 \text{ sr}$ , with pupil diameter  $d = 8 \text{ mm}$ .  $\Omega_A = 0.00005 \text{ sr}$ . The light flux per surface element of the sheet entering the eye is  $\Phi_v/\text{m}^2 = L_v \Omega_A = 41.8 \times 10^{-4} \text{ lm/m}^2$ . The demagnification increases the illuminance on the retina  $E_{v\text{Retinat}}$  by a factor  $45.5^2$ .

$$E_{v\text{Retinat}} = 8.6 \text{ lm/m}^2.$$

7. You adjust an optical system, which contains a laser emitting visible radiation of wavelength 488 nm with a power of 10 mW, without using safety goggles. You darken the lab for better visibility of the laser beam. You intend to focus the laser beam into a 20  $\mu\text{m}$  wide pin hole. Therefore you directly focus the pinhole with one of your eyes in opposite direction to the spreading laser beam. During turning the adjustment screw of a mirror the laser beam suddenly hits the center of your eye with its full power. The beam diameter is 10 mm. What is the irradiance on your retina if the diameter of the laser beam focus is 5  $\mu\text{m}$ ? What would it have been if you didn't darken the lab?

dark lab: pupil diameter is 8 mm.

Power density (irradiance) of the laser beam on the eye's surface:

$$E_e = \frac{10 \text{ mW}}{\pi (10 \text{ mm})^2 / 4} = 127 \text{ W/m}^2$$

Laser power penetrating the eye is  $(8/10)^2 10 \text{ mW} = 6.4 \text{ mW}$ .

Power density (irradiance) on the retina:

$$E_e = \frac{6.4 \text{ mW}}{\pi (5 \times 5 \mu\text{m})^2 / 4} = 3.26 \times 10^8 \text{ W/m}^2$$

illuminated lab: Pupil diameter is 1 mm.

Power density is reduced by a factor 64:

$$E_e = \frac{6.4 \text{ mW}}{\pi (1 \mu\text{m})^2 / 4} = 5.09 \times 10^6 \text{ W/m}^2$$

## Chapter 4: Incoherent light sources

1. What is black body, grey body, selective body radiation?

Black body:  $\varepsilon=1$

grey body:  $\varepsilon<1$ ,  $\varepsilon=\text{const.}$

selective body:  $\varepsilon<1$ ,  $\varepsilon=\varepsilon(\lambda)$

2. Write down Wien's displacement law?

$$\lambda_{max} T = \text{const.}$$

$$\text{sun: } T = 6000 \text{ K, } \lambda_{max} = 500 \text{ nm}$$

$$\text{const.} \approx 3000 \text{ } \mu\text{mK}$$

3. What is the radiant exitance of the sun's surface?

$$64 \text{ MW/m}^2$$

4. Write down Kirchhoff's law?

$$L_{e\lambda}(\lambda) = a_{\Phi}(\lambda) L_{e\lambda}^{black}(\lambda) \left[ \frac{W}{m^2 sr \mu m} \right].$$

5. Why use incandescent lamps coiled tungsten filaments?

Heat loss via heat conduction at the surface of the filament *gas filled* lamps does not depend on the diameter of the filament, but on the length. A given supply voltage and lamp power results in distinct filament diameter and length. Forming the filament into a coil reduces the effective length and increases the effective diameter, with the consequence of reduced heat loss.

6. What is the optical efficacy of incandescent lamps?

$$15\% - 20\%$$

7. What is the visual efficacy of incandescent lamps?

$$4\% - 5\%$$

8. Why and how do incandescent lamps burn out?

Constant evaporation of tungsten versus the filament length would result in a constant decrease of the filament diameter  $D$ . Electrical resistance  $R$  would increase with  $D^{-2}$ . Electric power consumption  $P=U^2/R$  decrease with square of filament diameter. Emitted radiation power is proportional to area of filament surface and decreases linearly with diameter. Consequently temperature must decrease if filament gets thinner and lifetime of a lamp would be infinity. The production process of tungsten filaments leads to inhomogeneous wire diameter. A small part of the filament with smaller diameter results in a higher power density and consequently in a higher temperature at that place. This increases the evaporation rate and the filament at that place will faster get thinner than the rest of the filament. Because the length of the thinner part is small compared to the total filament length, the total resistance will not change significantly. Consequently the current stays nearly constant. A constant current leads to an increase of the dissipated electrical power which is proportional to the increase of the resistance according to  $P=I^2R$ . The filament temperature will increase at that place (*hot spot*) more and more until it burns out.

9. Why is the glass bulb of an incandescent lamp shaped like a pear?

Incandescent lamps are either evacuated or filled with gas. In both cases the bulb has to withstand pressure from outside (vacuum) or from inside. A sphere is the optimum shape with respect to mechanical stability at a given volume. Taking into account the socket a pear shaped glass bulb is the most stable.

10. Why are tungsten halogen lamps so small? Explain the working principle.

Tungsten halogen lamps are filled with Krypton or Xenon gas. The gas pressure reaches up to 10 bar and reduces the evaporation of the tungsten filament and thus increases the lifetime of the lamp. The risk of explosion makes it necessary to reduce the volume of the bulb as much as possible, if such high gas pressures are used. In addition the wall thickness of the glass bulb has to be increased compared to ordinary incandescent lamps. To avoid blackening of the inner bulb surface by evaporated tungsten, a small amount halogen gas, mostly bromine, is added. Evaporated tungsten and bromine react to form tungsten-bromine. The partial pressure of tungsten-bromine is lower than the vapor pressure of tungsten-bromine at the lowest occurring temperature, which is generally at the inner surface of the glass bulb. Therefore tungsten bromine does not condense at the inner surface of the glass bulb. The incandescent filament decomposes tungsten-bromine into tungsten and bromine atoms, due to its high temperature. Tungsten condenses at the surface of the filament, but, unfortunately, not at the hot spots. Thus the lifetime of the filament is not prolonged. The increase of efficacy or lifetime is the consequence of the high gas pressure.

## Chapter 5: Light emitting diodes

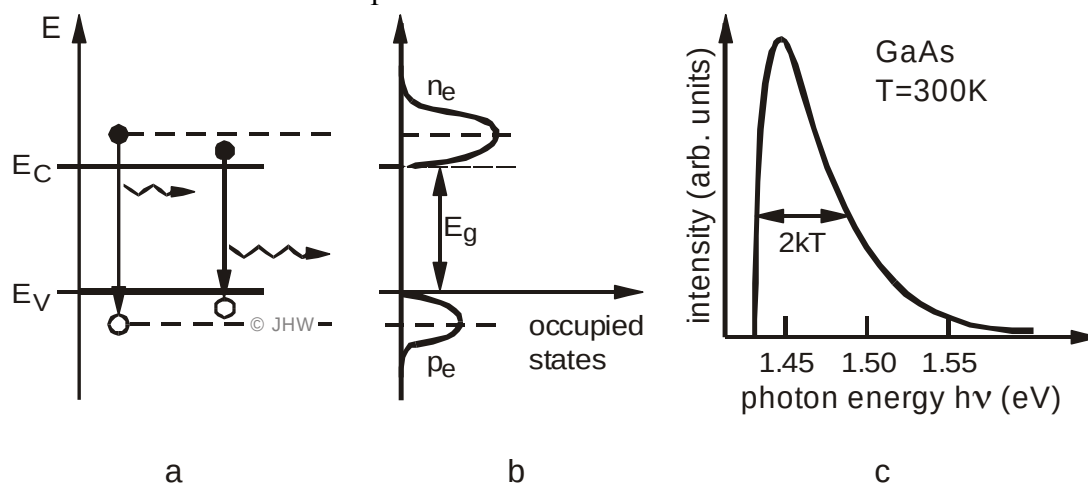
1. What is the band gap  $E_g$  of semiconductors for the generation of light?

$$380 \text{ nm} < \lambda < 780 \text{ nm}, E_g = hc/\lambda, 1.6 \text{ eV} > E_g > 3.26 \text{ eV}$$

2. What is radiating recombination?

Generation of one photon by recombination of one electron and one hole.

3. How does the emission spectrum of an LED look like?



a) Energy of electrons and holes b) occupied states c) Spectrum of an LED.

4. Which are the materials used for LEDs?

direct semiconductors:

a) III-V compounds like GaAs, GaP, InAs, InP, InSb

b) semiconductors on the basis of nitrides like GaN, GaAlN, InN

5. What for do we need blue emitting LEDs?

For illumination and display purposes. Red green and blue light is used to create colors that cover an area inside the chromaticity diagram, which is as large as possible.

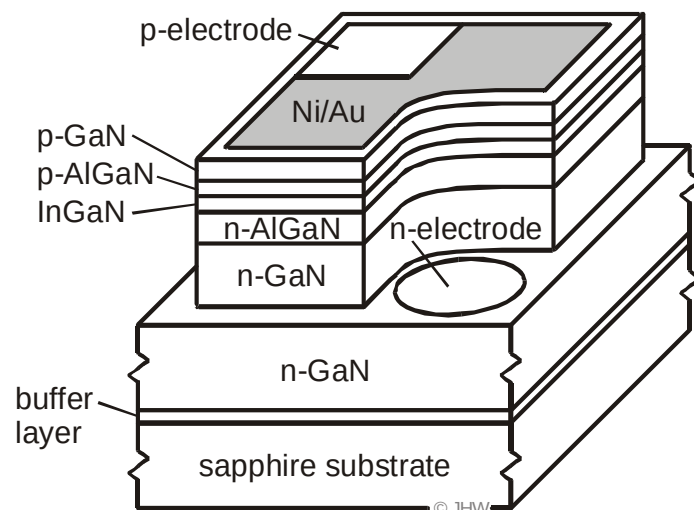
6. Which effects limit the efficacy of an LED?

Total reflection, reflection and reabsorption.

7. Which are the drawbacks of LUCOLEDs?

Currently still too expensive, poor color rendering, caused by low intensity in the green wavelength region..

8. Sketch the structure of an nitride-LED



A thin layer of InGaN sandwiched between two layers of n- and p-type AlGaN provides the optically active zone, where recombination takes place. Insulating sapphire substrates requires p- and n- front contacts. Ni/Au layer is extremely thin and therefore transparent.

9. Which are the relevant types of chemical bonds in organic semiconductors?

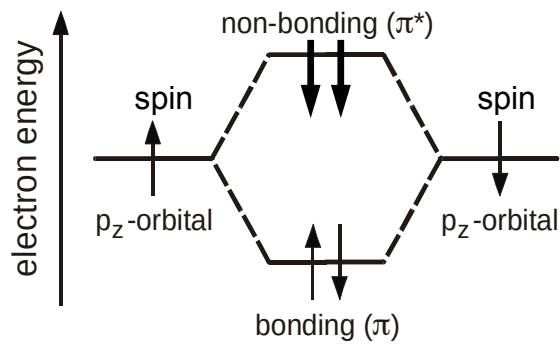
$\sigma$ -bonds and  $\pi$ -bonds. A  $\sigma$ -bond is created by two overlapping  $sp_2$ -orbitals, which are the result of hybridisation of one  $2s$  orbital and two out of three  $2p$ -orbitals of carbon atoms. A  $\pi$ -bond is formed by the two remaining  $2p$ -orbitals.

10. Where do LUMO and HOMO in organic semiconductors come from?

LUMO: Lowest Unoccupied Molecular Orbital. Many of such energy states create the “conduction band” in organic semiconductors.

HOMO: Highest Occupied Molecular Orbital. Many of such energy states create the “valence band” in organic semiconductors.

Energie



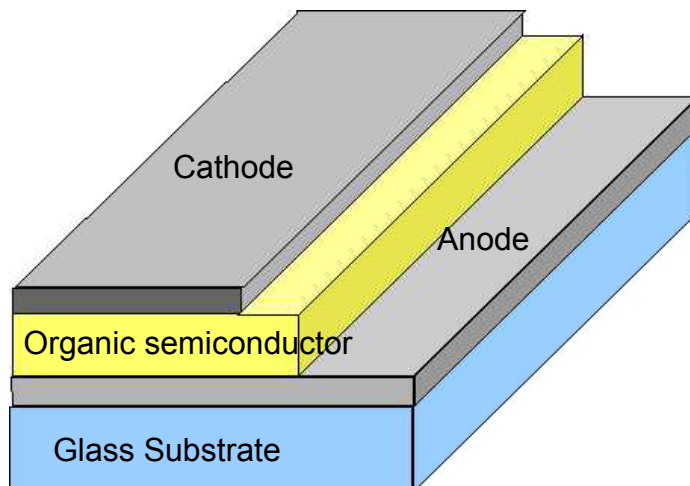
Bonding ( $\pi$ ) and a non-bonding ( $\pi^*$ ) state lead to two energy states within the molecule

11. Which are the optically active materials and materials for the contacts in organic LEDs?  
Sketch the general structure of an OLED.

Anode: Transparent contact (TCO) made of ITO (IndiumZinnOxid)

Organic semiconductor: Polymers, example PPV, or small molecules, example Alq<sub>3</sub>

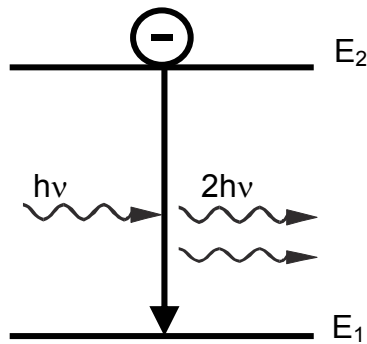
Cathode: metal with low work function, example Ca.



## Chapter 6: Lasers

1. What is stimulated emission?

Photon forces excited atom to emit a photon of same energy (wavelength), phase and direction



Stimulated  
emission

2. On what does the relation between stimulated and spontaneous emission depend? How can it be made as large as possible?

$$\frac{\left. \frac{dN_2}{dt} \right|_{stim}}{\left. \frac{dN_2}{dt} \right|_{sp}} = \frac{\sigma_{12}}{A} \Phi_j$$

$\sigma_{12}$  and  $A$  are material constants. The photon flux density  $\Phi_j$  can be increased by using an optical resonator.

3. Why does a laser require inversion?

Probability for stimulated emission equals that of absorption. Both are proportional to the density of excited/ground states  $N_2/N_1$ . Amplification larger than absorption requires  $N_1 > N_2$ .

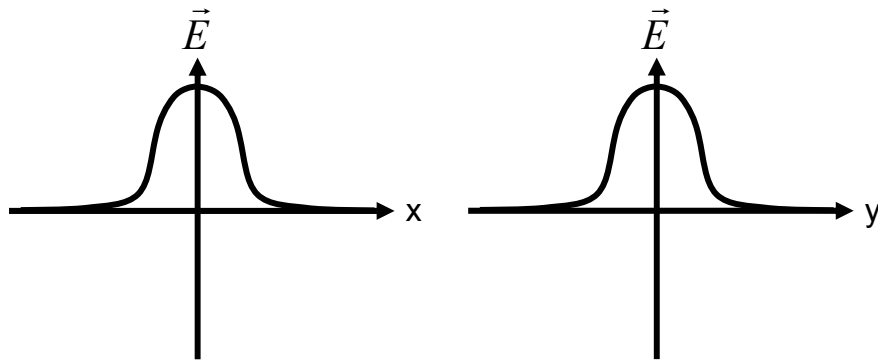
4. Which are the three main components of a laser?

- (1) Energy source, which delivers pump energy
- (2) optically active medium.
- (3) resonator

5. What are laser modes?

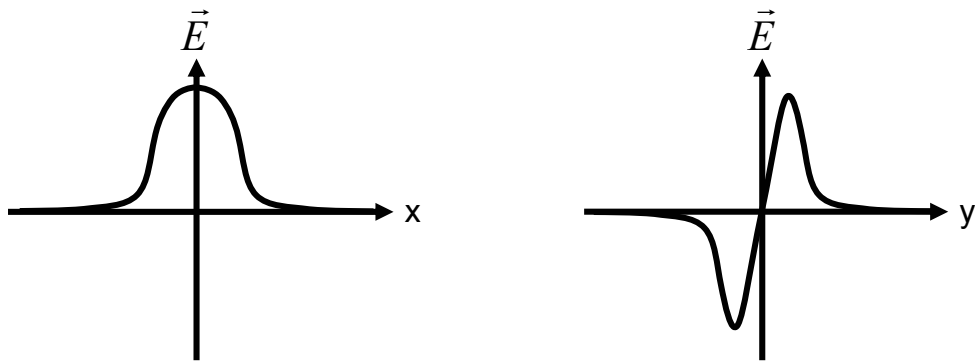
- (a) Transversal laser modes ( $TEM_{mn}$ ) define the intensity distribution of the electromagnetic field perpendicularly (transversal) to the propagation direction. The electric field has a Gaussian distribution, which is modulated by polynomial function of order  $n, m$  in direction  $x, y$ .

$TEM_{00}$ :



TEM<sub>01</sub> results in:

$$\vec{E}(x, y) \propto y e^{-(x^2+y^2)}.$$



- (b) Longitudinal laser modes define the frequency or wavelength of the laser radiation. They result from the second laser condition  $m\lambda/2 = d$ , with the length of the resonator  $d$ . The difference in frequency  $\Delta\nu$  of two subsequent laser modes is given by

$$\Delta\nu = \nu_{m+1} - \nu_m = \frac{c/n_r}{2d}$$

6. Why are at least three energy states necessary in an optically pumped laser?

The probability for stimulated emission equals that of absorption. Both are proportional to the corresponding density of occupied states  $N_1 / N_2$ . If  $N_2 > N_1$ , then more atoms would be excited than during pumping, until  $N_2 > N_1$ .

7. What is a resonator good for in a laser?

It increases the photon flux density  $\Phi_j$  inside the optically active medium and thus increases the number of stimulated emission processes. It selects the frequency or wavelength of the laser radiation. It amplifies only radiation with a wavelength that equals twice the resonator length.

8. How is inversion achieved in a semiconductor laser?

The energy difference between the quasi Fermi levels of electrons and holes must exceed the band gap  $E_g$ . The current through the pn-junction must exceed a so called threshold value, which results from additional absorption losses, mainly absorption by free carriers.

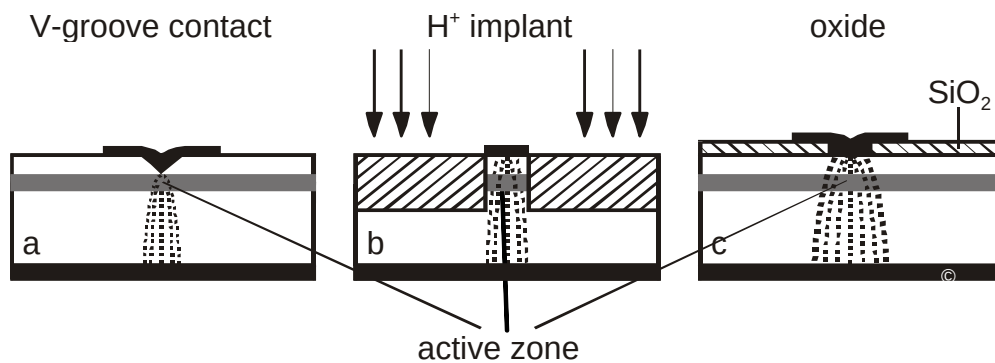
9. What are the lasing conditions in a semiconductor laser?

First lasing condition:  $E_F^n - E_F^p > E_g$

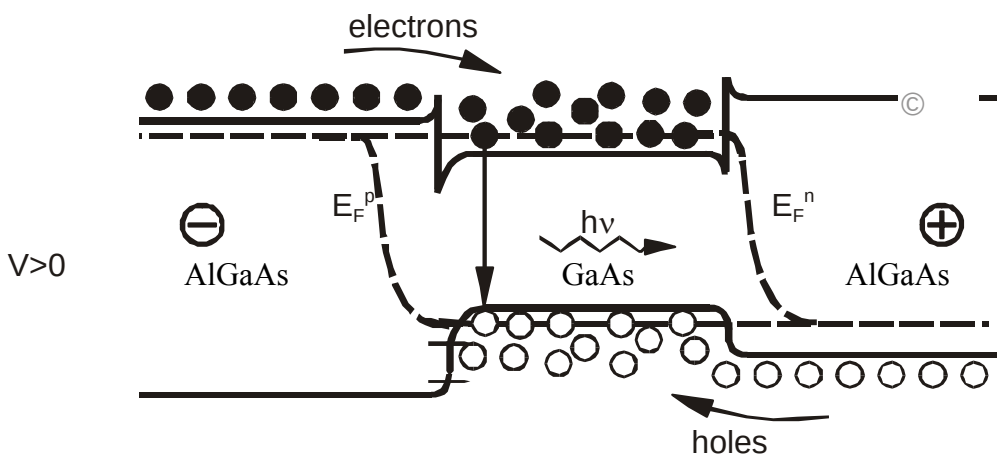
Second lasing condition: Optical resonator defines wavelength of amplified radiation via optical feedback, with the result of standing waves. Thus stimulated emission rate increases and beats the rate of spontaneous emission. Standing waves create locations with high intensity separated by half a wavelength. Here, stimulated emission takes place preferentially.

10. Which kind of semiconductor lasers do you know?

Stripe contact laser:



Double-heterostructure laser:

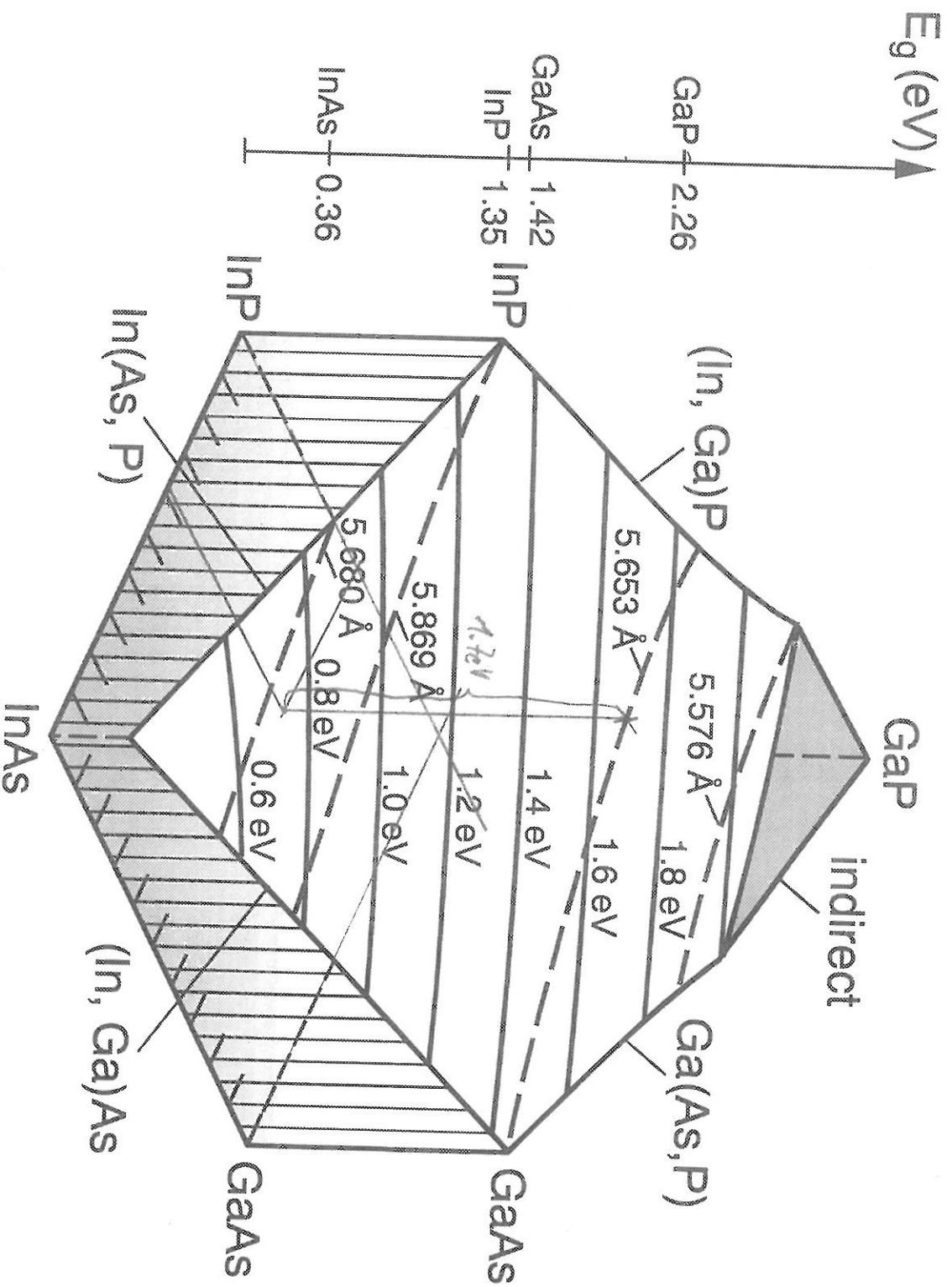


Examination  
Lasers and Light Sources  
09.02.2013  
14:00 – 15:00

1. Color mixing:
  - a) Explain the difference between additive and subtractive color mixing. Which primary colors can be used in both cases? 2
2. A 20 years old person uses eye glasses with a refracting power of -3 D.
  - a) Which kind of focusing problem does this person have? 1
  - b) Calculate the far point of this person without glasses. 1
  - c) Calculate the near point of this person without glasses. 1
3. You mix the light of three monochromatic light sources with wavelengths  $\lambda_1 = 400$  nm,  $\lambda_2 = 500$  nm and  $\lambda_3 = 600$  nm. The light sources have electrical efficiencies  $\eta_1 = 30\%$ ,  $\eta_2 = 15\%$ , and  $\eta_3 = 25\%$ . They are operated at input powers  $P_1 = P_2 = P_3 = 1$  W.
  - a) Calculate the color chromaticity coordinates of the mixed light. Use the attached tabulated color matching functions. 3
  - b) Calculate the combined luminous efficacy of the three light sources. 2
4. Incandescence lamps:  
Explain why the filament of an incandescent lamp burns out? 2
5. Gas discharge lamps:  
Which gas discharge lamp has the best luminous efficacy? Why don't we use them for illuminating our office? 1
6. A semiconductor laser emits radiation at a wavelength  $\lambda = 720$  nm.
  - a) Calculate the corresponding photon energy and the band gap of the semiconductor material. 1
  - b) Which substrate material can be used if the material is grown via epitaxy? 1
  - c) Use the attached figure to estimate its composition. 1
  - d) The active laser material has a refraction index  $n_r = 3.4$ . The distance between the front and back mirror is  $d = 150$   $\mu$ m. Calculate the distance in wavelength units between two neighboring longitudinal laser modes. 2
  - e) Estimate the number of emitted laser modes, when the laser is operated just above its threshold power at a temperature  $T = 45^\circ\text{C}$ . 2

**Total 21**





Quaternary alloys in the system  $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ .

# tabulated CIE color matching functions

| wavelength $\lambda_i$ [nm] | $\bar{x}$ | $\bar{y} = V(\lambda)$ | $\bar{z}$ | wavelength $\lambda_j$ [nm] | $\bar{x}$ | $\bar{y} = V(\lambda)$ | $\bar{z}$ |
|-----------------------------|-----------|------------------------|-----------|-----------------------------|-----------|------------------------|-----------|
| 380                         | 1.37E-03  | 3.90E-05               | 6.45E-03  | 590                         | 1.03E+00  | 7.57E-01               | 1.10E-03  |
| 390                         | 4.24E-03  | 1.20E-04               | 2.01E-02  | 600                         | 1.06E+00  | 6.31E-01               | 8.00E-04  |
| 400                         | 1.43E-02  | 3.96E-04               | 6.79E-02  | 610                         | 1.00E+00  | 5.03E-01               | 3.40E-04  |
| 410                         | 4.35E-02  | 1.21E-03               | 2.07E-01  | 620                         | 8.54E-01  | 3.81E-01               | 1.90E-04  |
| 420                         | 1.34E-01  | 4.00E-03               | 6.46E-01  | 630                         | 6.42E-01  | 2.65E-01               | 5.00E-05  |
| 430                         | 2.84E-01  | 1.16E-02               | 1.39E+00  | 640                         | 4.48E-01  | 1.75E-01               | 2.00E-05  |
| 440                         | 3.48E-01  | 2.30E-02               | 1.75E+00  | 650                         | 2.84E-01  | 1.07E-01               | 0.00E+00  |
| 450                         | 3.36E-01  | 3.80E-02               | 1.77E+00  | 660                         | 1.65E-01  | 6.10E-02               | 0.00E+00  |
| 460                         | 2.91E-01  | 6.00E-02               | 1.67E+00  | 670                         | 8.74E-02  | 3.20E-02               | 0.00E+00  |
| 470                         | 1.95E-01  | 9.10E-02               | 1.29E+00  | 680                         | 4.68E-02  | 1.70E-02               | 0.00E+00  |
| 480                         | 9.56E-02  | 1.39E-01               | 8.13E-01  | 690                         | 2.27E-02  | 8.21E-03               | 0.00E+00  |
| 490                         | 3.20E-02  | 2.08E-01               | 4.65E-01  | 700                         | 1.14E-02  | 4.10E-03               | 0.00E+00  |
| 500                         | 4.90E-03  | 3.23E-01               | 2.72E-01  | 710                         | 5.79E-03  | 2.09E-03               | 0.00E+00  |
| 510                         | 9.30E-03  | 5.03E-01               | 1.58E-01  | 720                         | 2.90E-03  | 1.05E-03               | 0.00E+00  |
| 520                         | 6.33E-02  | 7.10E-01               | 7.82E-02  | 730                         | 1.44E-03  | 5.20E-04               | 0.00E+00  |
| 530                         | 1.66E-01  | 8.62E-01               | 4.22E-02  | 740                         | 6.90E-04  | 2.49E-04               | 0.00E+00  |
| 540                         | 2.90E-01  | 9.54E-01               | 2.03E-02  | 750                         | 3.32E-04  | 1.20E-04               | 0.00E+00  |
| 550                         | 4.33E-01  | 9.95E-01               | 8.75E-03  | 760                         | 1.66E-04  | 6.00E-05               | 0.00E+00  |
| 560                         | 5.95E-01  | 9.95E-01               | 3.90E-03  | 770                         | 8.31E-05  | 3.00E-05               | 0.00E+00  |
| 570                         | 7.62E-01  | 9.52E-01               | 2.10E-03  | 780                         | 4.15E-05  | 1.50E-05               | 0.00E+00  |
| 580                         | 9.16E-01  | 8.70E-01               | 1.65E-03  |                             |           |                        |           |

# Examination Lasers and Light Sources

9.02.2013

①

- 1.) additive color mixing superimposes two or more primary colors to generate the desired color.

primary colors: red, green, blue ①

subtractive color mixing uses a white light source, which contains all colors. Different filters absorb parts of the spectrum of the white light source creating the desired color.

filters: magenta, cyan, yellow

magenta filter absorbs green light

cyan " " red "

yellow " " blue " ①

- 2) a) refracting power of glasses is negative  
⇒ eye length is too long  
⇒ person is nearsighted ①

b)  $D_{\text{glasses}} = -3 \text{ D}$

$$D_F + D_{\text{glasses}} = \frac{1}{\infty}$$

$$\Rightarrow D_F = -D_{\text{glasses}} = 3 \text{ D}$$

$$\Rightarrow \boxed{a_F = \frac{1}{D_F} = 0.33 \text{ m}}$$

①

- c) width of accommodation:

20 y.o. person  $A = 11.1 \text{ D}$

$$A = D_N - D_F \Rightarrow D_N = A + D_F = 14.1 \text{ D}$$

$$\Rightarrow \boxed{a_N = 7.1 \text{ cm}}$$

①

3)

| a)     |  | $\bar{x}$            | $\bar{y}$            | $\bar{z}$            |
|--------|--|----------------------|----------------------|----------------------|
| 400 nm |  | $1.43 \cdot 10^{-2}$ | $3.96 \cdot 10^{-4}$ | $6.79 \cdot 10^{-2}$ |
| 500 nm |  | $4.90 \cdot 10^{-3}$ | $3.23 \cdot 10^{-1}$ | $2.72 \cdot 10^{-1}$ |
| 600 nm |  | 1.06                 | $6.31 \cdot 10^{-1}$ | $8.00 \cdot 10^{-4}$ |

(1)

radiant flux

$$\begin{aligned}\phi_{e,1} &= 0.3 \text{ W} \\ \phi_{e,2} &= 0.15 \text{ W} \\ \phi_{e,3} &= 0.25 \text{ W}\end{aligned}$$

color coordinates

$$X = 0.3 \cdot 1.43 \cdot 10^{-2} + 0.15 \cdot 4.90 \cdot 10^{-3} + 0.25 \cdot 1.06 = 2.70 \cdot 10^{-1}$$

$$Y = 0.3 \cdot 3.96 \cdot 10^{-4} + 0.15 \cdot 3.23 \cdot 10^{-1} + 0.25 \cdot 6.31 \cdot 10^{-1} = 2.06 \cdot 10^{-1}$$

(1)

$$Z = 0.3 \cdot 6.79 \cdot 10^{-2} + 0.15 \cdot 2.72 \cdot 10^{-1} + 0.25 \cdot 8.00 \cdot 10^{-4} = 6.14 \cdot 10^{-2}$$

color chromaticity coordinates

$$\begin{aligned}x &= \frac{X}{X+Y+Z} = 0.502 \\ y &= \frac{Y}{X+Y+Z} = 0.384\end{aligned}$$

(1)

b)

luminous flux:

$$\phi_v = k_m \int_{380 \text{ nm}}^{780 \text{ nm}} \phi_{e,\lambda}(\lambda) \cdot V(\lambda) d\lambda \quad ; \quad k_m = 683 \frac{\text{lm}}{\text{W}}$$

$$= k_m \cdot (0.3 \text{ W} \cdot 3.96 \cdot 10^{-4} + 0.15 \text{ W} \cdot 3.23 \cdot 10^{-1} + 0.25 \text{ W} \cdot 6.31 \cdot 10^{-1}) = 141 \text{ lm}$$

(1)

$$\phi_v = 141 \text{ lm}$$

$$\text{Input power } P_{in} = 3 \text{ W}$$

$$\boxed{\eta_v = \frac{\phi_v}{P_{in}} = 47 \frac{\text{lm}}{\text{W}}} \quad (1)$$

4. homogeneous evaporation along the filament results in an increase of the filaments resistivity  $R$ . This will reduce the input power dissipation according to  $P = \frac{U^2}{R}$  (0.5)

As the emitted radiation power is proportional to the surface area of the filament, which is proportional to its diameter and the input power goes with  $d^2$ , the temperature of the filament will decrease. (0.5) Consequently the evaporation of the filament decreases, leading to a decrease of the evaporation. Therefore, the lifetime should be infinite.

The reason for filament burn out is therefore caused by inhomogeneous evaporation at "hot spots" (0.5) where the temperature is slightly higher than at the rest of the filament.

At a "hot spot" the power dissipation is given by  $P_{hs} = I^2 \cdot R_{hs}$ . As the filament current  $I$  is constant the local power dissipation increases rapidly if the local resistivity in-

Finally the temperature at the hot spot (0.5) reaches the melting temperature of the filament material and the filament burns out.

5. A low pressure sodium vapor lamp has the best luminous efficacy  $\eta_v$  of all gas discharge lamps.

$$\eta_v \approx 200 \frac{\text{lm}}{\text{W}} \quad (0.5)$$

We don't use these lamps for office illumination because it emits quasi-monochromatic light at a wavelength

$$\lambda \approx 580 \text{ nm}$$

Therefore the color rendering index of this lamp  $R_a = 0$ . (0.5)

6. a) photon energy  $E_{\text{phot}} = h \cdot \nu = h \cdot \frac{c}{\lambda}$

$$\Rightarrow E_{\text{phot}} = 1.72 \text{ eV}$$

The band gap of the semiconductor material is  $E_g = E_{\text{phot}} - kT$   
 as  $kT$  is approximately 25 meV the band gap of the semiconductor is approx.

$$E_g \approx 1.7 \text{ eV} \quad (1)$$

6 b) GaAs can be used as substrate material (1)

c) composition:

$$\boxed{\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.4}\text{P}_{0.6}} \quad (1)$$

d)  $m \cdot \frac{\lambda_m}{2} \cdot \frac{1}{n_r} = d$   $m = \text{integer number}$

$$m = \text{Abs} \left( \frac{2d \cdot n_r}{\lambda_m} \right) = 1477 \quad (1)$$

$$\Delta \lambda = \lambda_m - \lambda_{m+1}$$

$$\lambda_m = \frac{2d \cdot n_r}{m}$$

$$\boxed{\Delta \lambda = \frac{2n_r \cdot d}{m} - \frac{2n_r \cdot d}{m+1} = 0.5 \text{ nm}} \quad (1)$$

e)  $2kT \approx 55 \text{ meV}$  ;  $(T = (273 + 45) \text{ K})$  (1)

$$\nu = \frac{c}{\lambda} \quad ; \quad E = h \cdot \nu \quad \Rightarrow \quad E = h \cdot \frac{c}{\lambda}$$

$$\Rightarrow \lambda = \frac{h \cdot c}{E}$$

$$\lambda_1(1.7 \text{ eV}) = 730 \text{ nm}$$

$$\lambda_2(1.755 \text{ eV}) = 707 \text{ nm}$$

number of longitudinal modes

$$\boxed{n_m = \frac{\lambda_1 - \lambda_2}{\Delta \lambda} \approx 46} \quad (1)$$



Examination  
Lasers and Light Sources  
10.02.2012  
11:45 – 12:45

1. Color mixing:
  - a) Which primary colors does an ink jet printer use? 1
  - b) You want to print red color using an ink jet printer on top of a *yellow* sheet of paper. Which primary color(s) do you need? Please explain. 1
  
2. The near point  $a_n$  of a 50 years old person is  $a_n = 0.4$  m.
  - a) Which kind of focusing problem does this person have? 1
  - b) Calculate the far point of this person. 1
  - c) Calculate the refracting power of glasses needed to shift the far point to infinity. 1
  - d) Does the person need reading glasses? If so, calculate the refracting power of the reading glasses. 1
  
3. You mix the light of two monochromatic light sources with wavelengths  $\lambda_1 = 590$  nm,  $\lambda_2 = 490$  nm.
  - a) Calculate the relative intensities  $I_1(590$  nm) and  $I_2(490$  nm) in order to generate light with color chromaticity coordinates that are closest to the white point. Use the attached tabulated color matching functions. 4
  - b) Calculate the combined luminous efficacy of the two light sources with intensities  $I_1$ ,  $I_2$ , if light source 1, and 2 have electrical efficiencies  $\eta_1 = 40\%$  and  $\eta_2 = 60\%$ . 3
  
4. Incandescence lamps:
  - a) Explain why tungsten incandescence lamps with halogen gas filling have higher luminous efficacies and/or longer lifetimes than conventional incandescent lamps. 2
  - b) Which filling gases are used in *conventional* and *halogen* incandescent lamps? Explain the advantages/disadvantages of different filling gases. 2
  
5. A light emitting diode consist of  $\text{Ga}_x\text{Al}_{1-x}\text{As}$  and emits visible radiation with maximum intensity at a wavelength  $\lambda = 620.0$  nm.
  - a) Calculate the corresponding photon energy. 1
  - b) Calculate the band gap of the semiconductor material 1
  - c) How far does the wavelength  $\lambda$  shift, if the temperature  $T$  of the pn-junction increases from  $T = 30^\circ\text{C}$  to  $T = 90^\circ\text{C}$ ? Does it shift to shorter or longer wavelengths? 1
  - d) Which substrate material can be used if the material is grown via epitaxy? 1
  - e) Use the attached figure to estimate its composition (x). 1

**Total 22**

# Sample Solution Examination

1

## Lasers and Light Sources 10.2.1012

1. a) magenta, yellow, cyan (1)

b) yellow paper reflects colors red + green

$\Rightarrow$  green has to be absorbed

magenta absorbs green (1)

cyan absorbs red

$\rightarrow$  magenta on yellow paper generate red color

2. a) near point of normal sighted 50 y.o. person is 50 cm

$\Rightarrow$  person is shortsighted (1)

b)  $A = \frac{1}{a_N} - \frac{1}{a_F}$  ;

$\Rightarrow \frac{1}{a_F} = \frac{1}{a_N} - A$  ;  $A = 2.0 \frac{1}{m}$

$\frac{1}{a_F} = 2.5 \frac{1}{m} - 2.0 \frac{1}{m} = 0.5 \frac{1}{m}$  (1)

$\Rightarrow$  far point is  $a_F = 2m$

c)  $\frac{1}{a_F} + D_{\text{glasses}} = 0$  (1)

$\Rightarrow$  refracting power  $D_{\text{glasses}} = -0.5 \text{ D}$

d) reading distance:  $a_r = 0.3 m$

$\Rightarrow$  reading glasses necessary (1)

$\frac{1}{a_N} + D_{\text{glasses}} = \frac{1}{a_r}$  ;  $D_{\text{glasses}} = \frac{1}{0.3 m} - \frac{1}{0.4 m} = 0.83 \text{ D}$

3a)

Color coordinates:

$$x_1(590\text{nm}) = x_1 = 1.026$$

$$y_1(590\text{nm}) = y_1 = 0.757$$

$$z_1(590\text{nm}) = z_1 = 1.1 \cdot 10^{-3}$$

$$x_2(490\text{nm}) = x_2 = 3.2 \cdot 10^{-2}$$

$$y_2(490\text{nm}) = y_2 = 2.08 \cdot 10^{-1}$$

$$z_2(490\text{nm}) = z_2 = 4.65 \cdot 10^{-1}$$

$$X = \bar{I}_1 \cdot x_1 + \bar{I}_2 \cdot x_2$$

$$Y = \bar{I}_1 \cdot y_1 + \bar{I}_2 \cdot y_2$$

(0.5)

$$Z = \bar{I}_1 \cdot z_1 + \bar{I}_2 \cdot z_2$$

$$x = \frac{\bar{I}_1 \cdot x_1 + \bar{I}_2 \cdot x_2}{\bar{I}_1(x_1 + y_1 + z_1) + \bar{I}_2(x_2 + y_2 + z_2)} = \frac{\bar{I} x_1 + x_2}{\bar{I}(x_1 + y_1 + z_1) + (x_2 + y_2 + z_2)}$$

with  $\bar{I} = \frac{\bar{I}_1}{\bar{I}_2}$

$$y = \frac{\bar{I} y_1 + y_2}{\bar{I}(x_1 + y_1 + z_1) + (x_2 + y_2 + z_2)}$$

(0.5)

white point:  $x_w = y_w = \frac{1}{3}$

distance to white point = min

$$\Rightarrow \left( \frac{\bar{I} x_1 - x_2}{\bar{I}(x_1 + y_1 + z_1) + (x_2 + y_2 + z_2)} - \frac{1}{3} \right)^2 + \left( \frac{\bar{I} y_1 - y_2}{\bar{I}(x_1 + y_1 + z_1) + (x_2 + y_2 + z_2)} - \frac{1}{3} \right)^2 = \min \quad (1)$$

$$\left( \frac{I \cdot A + B}{I \cdot C + D} \right)^2 + \left( \frac{I \cdot A' + B'}{I \cdot C + D} \right)^2 = \min$$

with  $A = \frac{2}{3} x_1 - \frac{1}{3} (y_1 + z_1)$ ;  $A' = \frac{2}{3} y_1 - \frac{1}{3} (x_1 + z_1)$   
 $B = \frac{2}{3} x_2 - \frac{1}{3} (y_2 + z_2)$ ;  $B' = \frac{2}{3} y_2 - \frac{1}{3} (x_2 + z_2)$   
 $C = x_1 + y_1 + z_1$ ;  $D = x_2 + y_2 + z_2$

$$\frac{d}{dI} \left[ \left( \frac{I \cdot A + B}{I \cdot C + D} \right)^2 + \left( \frac{I \cdot A' + B'}{I \cdot C + D} \right)^2 \right] \stackrel{!}{=} 0 \quad (0.5)$$

$$\Rightarrow I = \frac{B(2C - AD) + B'(B'C - A'D)}{A(AD - 2C) + A'(A'D - B'C)} \quad (1)$$

$$\Rightarrow I = \frac{I_1}{I_2} = 0.45 \quad (0.5)$$

3b)  $\eta_1 = 0.4$   $\eta_2 = 0.5$

$$\eta_v = 683 \frac{\text{lm}}{\text{W}} \int_{380}^{780} \eta_e(\lambda) \cdot V(\lambda) d\lambda \quad (0.5)$$

$$\eta_e = \frac{P_{\text{out}}}{P_{\text{in}}} \quad \eta_e(\lambda) = \frac{P_{\text{out},1}}{P_{\text{in},1} + P_{\text{in},2}} \delta(\lambda - \lambda_1)$$

$$+ \frac{P_{\text{out},2}}{P_{\text{in},1} + P_{\text{in},2}} \delta(\lambda - \lambda_2) \quad (0.5)$$

$$\int_{380}^{780} \eta_e(\lambda) \cdot d\lambda = \frac{P_{\text{out},1} + P_{\text{out},2}}{P_{\text{in}}} = \frac{P_{\text{out}}}{P_{\text{in}}} \quad (0.5)$$

$$P_{\text{out},1} = \eta_1 \cdot P_{\text{in},1}$$

$$P_{\text{out},2} = \eta_2 \cdot P_{\text{in},2} \quad (0.5)$$

$$P_{out,1} = I \cdot P_{out,2}$$

(4)

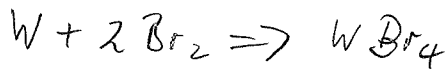
$$\Rightarrow \eta_v = 683 \frac{\text{lm}}{\text{W}} \left( \frac{P_{out,1}}{P_{in,1} + P_{in,2}} \int (R - R_1) + \frac{P_{out,2}}{P_{in,1} + P_{in,2}} \int (R - R_2) \right) V(R) \cdot dR$$

$$\eta_v = 683 \frac{\text{lm}}{\text{W}} \frac{P_{out,1} V(R_1) + P_{out,2} V(R_2)}{P_{in,1} + P_{in,2}} \quad (0.5)$$

$$\Rightarrow \eta_v = 683 \frac{\text{lm}}{\text{W}} \frac{I \cdot V(R_1) + V(R_2)}{\frac{I}{\eta_1} + \frac{I}{\eta_2}} = 119,6 \frac{\text{lm}}{\text{W}} \quad (0.5)$$

4 a)

- Halogen filling avoids blackening of glass bulb



$WBr_4$  does not condense at glass bulb if (0.5)

bulb temperature  $T > 800 K$

because of high vapor pressure

-  $\Rightarrow$  small glass bulbs with thick pressure resistant housing can be used (0.5)

-  $\Rightarrow$  glass bulb can be filled with noble gases of high pressure (up to 6 bars) (0.25)

-  $\Rightarrow$  high gas pressure reduces tungsten evaporation  $\Rightarrow$  higher lifetime (0.25)

-  $\Rightarrow$  higher filament temperature possible (0.25)

-  $\Rightarrow$  higher filament temperature increases luminous efficacy  $\eta_v$  (0.25)

4 b)

conventional incandescent lamp:

(0.25) Nitrogen ( $N_2$ ), krypton ( $Kr$ ), filling pressure: 1 bar (0.25)

halogen incandescent lamp:

Halogen filling: Iodine, Bromine (0.25)

filling pressure: 1-10 mbar (0.25)

noble gas filling: Ar, Kr, Xe

filling pressure  $\approx$  6 bar (0.25)

advantages / disadvantages:

(0.25)  $N_2$  (cheap, low efficacy)  $\Leftrightarrow$   $Kr$  (expensive, high efficacy)

Ar  $\rightarrow$  Kr  $\rightarrow$  Xe

(0.25) efficacy increases, price increases

$$5a) E_{\text{photon}} = h \cdot \nu$$

$$c = \lambda \cdot \nu$$

$$E_{\text{photon}} = h \cdot \frac{c}{\lambda} = 1.24 \text{ eV} \cdot \mu\text{m} \cdot \frac{1}{\lambda} = 2 \text{ eV} \quad (7)$$

$$b) E_g = E_{\text{photon}} - kT \approx 2 \text{ eV} ; kT \approx 26 \text{ meV} \quad (7)$$

at 300K

$$c) E_g = E_{\text{photon}} - kT$$

$$\Delta E_g = \Delta kT = k \cdot \Delta T \quad \Delta T = 60 \text{ K}$$

$$\Rightarrow \Delta E_g = 5.2 \text{ meV}$$

$$\Rightarrow \Delta E_{\text{photon}} = 5.2 \text{ meV}$$

$$E_{\text{photon}} = h \cdot \frac{c}{\lambda}$$

$$\frac{dE_{\text{photon}}}{d\lambda} = -h \cdot \frac{c}{\lambda^2} \Rightarrow \Delta E_{\text{photon}} = -h \cdot \frac{c}{\lambda^2} \cdot \Delta \lambda$$

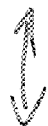
$$\Delta \lambda = -\Delta E_{\text{photon}} \cdot \frac{\lambda^2}{h \cdot c} = -\Delta E_{\text{photon}} \cdot \frac{\lambda}{E_g}$$

$$\Rightarrow \Delta \lambda \approx -1.6 \text{ nm}$$

$\Rightarrow$  wavelength becomes shorter

$$d) \text{GaAs} \quad (7)$$

$$e) \text{Ga}_{0.3}\text{Al}_{0.7}\text{As} \quad (7)$$



$$\text{Ga}_{0.2}\text{Al}_{0.8}\text{As}$$

Examination  
Lasers and Light Sources  
11.02.2011  
14:15 – 15:15

1. Color mixing:
  - a) Which primary colors does an ink jet printer use? 1
  - b) You want to print green color using an ink jet printer on top of a **yellow** sheet of paper. Which primary colors do you need? Please explain. 1
  
2. The far point  $a_f$  of a 20 years old person is  $a_f = 1$  m.
  - a) Which kind of focusing problem does this person have? 1
  - b) Calculate the near point. 1
  - c) Calculate the refracting power of glasses needed to shift the far point to infinity. 1
  
3. You mix the light of three monochromatic light sources with wavelengths  $\lambda_1 = 650$  nm,  $\lambda_2 = 500$  nm and  $\lambda_3 = 450$  nm.
  - a) Calculate the relative intensities  $I_1(650 \text{ nm})$ ,  $I_2(500 \text{ nm})$  and  $I_3(450 \text{ nm})$  in order to get white light. Use the attached tabulated color matching functions. 3
  - b) Calculate the luminous efficacy of all three light sources together with intensities  $I_1$ ,  $I_2$ ,  $I_3$  if light source 1, 2 and 3 have electrical efficiencies  $\eta_1 = \eta_3 = 50\%$  and  $\eta_2 = 100 \%$ . 3
  
4. Incandescence lamps:
 

Explain why tungsten incandescence lamps with gas filling have higher luminous efficacies and longer lifetimes than "vacuum filled" incandescence lamps. 2
  
5. An  $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$  Laser emits radiation with a photon energy  $h\nu = 0.8$  eV.
  - a) Calculate the wavelength of the emitted radiation. 1
  - b) Which substrate material can be used if the material is grown via epitaxy? 1
  - c) Estimate its composition (x, y). 1
  - d) The refraction index  $n_r$  of the laser active material is  $n_r = 3.6$ . The distance between the front and back mirror (deposited via evaporation directly on the cleaved crystal) is  $d = 500 \mu\text{m}$ . Calculate the distance in wavelength units between two neighboring longitudinal laser modes. 2

**Total**

**18**

A1 a) 

|         |
|---------|
| magenta |
| cyan    |
| yellow  |

 ②

b) green: red and blue part of white light must be absorbed  
 yellow paper absorbs blue part  
 cyan absorbs red part  
 magenta absorbs green part  
 $\Rightarrow$  cyan is needed ②

A2 20 year old person:

accommodation width  $|A| = 11.1 \text{ D} \left[ \frac{1}{\text{m}} \right]$

a)  $a_f = 1 \text{ m} \Rightarrow$  person is nearsighted ②

$$\begin{aligned} \text{b) } A &= D_N - D_F = a_n^{-1} - a_f^{-1} \\ \Rightarrow a_n &= (A + a_f^{-1})^{-1} = (11.1 + 1)^{-1} \text{ m} \\ |a_n &= 0.083 \text{ m}| \quad \text{②} \end{aligned}$$

c) refracting power of glasses:  $D_g$

$$a_f' = \infty \Rightarrow D_f' = 0 \text{ D}$$

$$a_f = 1 \text{ m} \Rightarrow D_f = 1 \text{ D}$$

$$D_f' = D_f + D_g$$

$$\Rightarrow \underline{D_g = D_f' - D_f = -1 \text{ D}} \quad \text{②}$$

②

A3 a)

white light:  $X = Y = Z = 1$

$$1 \left\{ \begin{aligned} 1 = X &= I_1 \cdot 2.8 \cdot 10^{-1} + \overbrace{I_2 \cdot 4.9 \cdot 10^{-3} + I_3 \cdot 3.36 \cdot 10^{-2}}^{=0} \\ 1 = Y &= I_1 \cdot 1.07 \cdot 10^{-1} + I_2 \cdot 3.22 \cdot 10^{-1} + I_3 \cdot 3.8 \cdot 10^{-2} \\ 1 = Z &= I_1 \cdot 0 + I_2 \cdot 2.72 \cdot 10^{-1} + I_3 \cdot 1.77 \end{aligned} \right.$$

$$1 = I_1 \cdot X_1 + I_3 \cdot X_3 \quad (1)$$

$$1 = I_1 \cdot Y_1 + I_2 \cdot Y_2 + I_3 \cdot Y_3 \quad (2)$$

$$1 = I_2 \cdot Z_2 + I_3 \cdot Z_3 \quad (3)$$

$$(1) \Rightarrow I_1 \cdot X_1 = 1 - I_3 \cdot X_3 \Rightarrow I_1 = \frac{1 - I_3 \cdot X_3}{X_1} \quad (4)$$

$$(3) \Rightarrow I_2 = \frac{1 - I_3 \cdot Z_3}{Z_2} \quad (5)$$

④, ⑤ in ②

$$1 = \frac{1 - I_3 \cdot X_3}{X_1} \cdot Y_1 + \frac{1 - I_3 \cdot Z_3}{Z_2} \cdot Y_2 + I_3 \cdot Y_3$$

$$1 = \frac{Y_1}{X_1} - \frac{X_3 \cdot Y_1}{X_1} \cdot I_3 + \frac{Y_2}{Z_2} - \frac{Y_2 \cdot Z_3}{Z_2} \cdot I_3 + I_3 \cdot Y_3$$

$$1 - \frac{Y_1}{X_1} - \frac{Y_2}{Z_2} = I_3 \left( Y_3 - \frac{X_3 \cdot Y_1}{X_1} - \frac{Y_2 \cdot Z_3}{Z_2} \right)$$

$$\boxed{I_3 = \frac{1 - \frac{Y_1}{X_1} - \frac{Y_2}{Z_2}}{Y_3 - \frac{X_3 \cdot Y_1}{X_1} - \frac{Y_2 \cdot Z_3}{Z_2}}} = 2.60 \cdot 10^{-1}$$

$$(4) \Rightarrow \boxed{I_1 = \frac{1 - I_3 \cdot X_3}{X_1} = 3.26}$$

$$(5) \Rightarrow \boxed{I_2 = \frac{1 - I_3 \cdot Z_3}{Z_2} = 1.99}$$

exakte Lösung:

$$\begin{array}{l|l} I_1 = 3.227 & \\ I_2 = 1.997 & \\ I_3 = 0.258 & 1 \end{array}$$

oder:

(3)

$$\left[ \frac{I_2}{I_1} = 6.09 \cdot 10^{-7} \quad \frac{I_3}{I_1} = 7.97 \cdot 10^{-2} \right]$$

oder

$$\left[ \frac{I_1}{I_2} = 1.64 \quad \frac{I_3}{I_2} = 1.31 \cdot 10^{-7} \right]$$

oder

1

$$\left[ \frac{I_1}{I_3} = 12.5 \quad \frac{I_2}{I_3} = 7.64 \right]$$

36)  $\eta_1 = \eta_5 = 50\% \quad \eta_2 = 100\%$

electrical input power:

$$\eta_1 P_1 = I_1 \quad ; \quad \eta_2 P_2 = I_2 \quad ; \quad \eta_5 P_3 = I_3$$

$$\Rightarrow \eta_2 P_2 = I_1 \cdot 6.09 \cdot 10^{-7}$$

$$\Rightarrow \eta_5 P_3 = I_1 \cdot 7.97 \cdot 10^{-2}$$

$$\Rightarrow P_1 = \frac{I_1}{\eta_1} \quad ; \quad P_2 = \frac{6.09 \cdot 10^{-7}}{\eta_2} \cdot I_1$$

$$P_3 = \frac{7.97 \cdot 10^{-2}}{\eta_5} \cdot I_1$$

$$P_{in} = P_1 + P_2 + P_3 = 3.77 W \quad \text{[assume } I_1 = 1 W]$$

luminous flux:  $\Phi_v = k_m \int \Phi_{e, \lambda} \cdot V(\lambda) d\lambda$

$$= k_m \cdot (I_1 V(\lambda_1) + I_2 V(\lambda_2) + I_3 V(\lambda_3))$$

$$= 290 \text{ lm} \cdot 1$$

$$\Rightarrow \eta_v = \frac{290}{3.77} \frac{\text{lm}}{W} = 75.7 \frac{\text{lm}}{W}$$

(4)

A4

- gas filling reduces the evaporation rate of tungsten 0.5
- incandescent tungsten filament is surrounded by a highly viscous gas layer 0.25
- diffusion of tungsten atoms through this highly viscous layer is hindered 0.25
- probability that a tungsten atom returns back to filament increases 0.25
- high gas pressure and high atomic mass of gas atoms decrease evaporation rate 0.25
- lower evaporation rate  $\Rightarrow$  longer lifetime
- lower evaporation rate allows higher filament temperature  $\Rightarrow$  higher efficacy 0.25

A5 a)  $E = h \cdot \nu$  ;  $\nu = \frac{c}{\lambda}$

$\Rightarrow E = h \cdot c / \lambda$

or,  $E [\text{eV}] = 1.24 \cdot \frac{1}{\lambda [\mu\text{m}]}$   
 $\boxed{\lambda = \frac{1.24}{0.8} \mu\text{m} = 1.55 \mu\text{m}} \quad \textcircled{1}$

b) substrate : In P  $\textcircled{2}$

c)  $\text{In}_{0.8} \text{Ga}_{0.5} \text{As}_{0.5} \text{P}_{0.1} \quad \textcircled{2}$

d)  $n_r = 3.6$  ;  $d = 50 \mu\text{m}$

$\lambda_{\text{vac}} = 1.55 \mu\text{m}$  ;  $\lambda_{n=3.6} = \frac{1.55 \mu\text{m}}{n_r} = 430 \mu\text{m}$

(5)

number of nodes:

$$N \cdot \frac{R_{n=1.6}}{2} = \underline{500 \mu\text{m}} \quad /$$

$$N = \frac{2.500}{0.430} = 2326$$

$$R_{n=3.6} = \frac{2.500 \mu\text{m}}{N}$$

$$\text{for } N = 2326$$

$$R_{\text{gr}=3.6} = 0.42992 \mu\text{m}$$

$$R_2 = 1.54772 \mu\text{m}$$

$$\text{for } N = 2325$$

$$R_{\text{gr}=3.6} = 0.4301025 \mu\text{m}$$

$$R_2 = 1.548387 \mu\text{m}$$

$$\Rightarrow \underline{\Delta R} = 0.000667 \mu\text{m} = \underline{0.667 \text{ nm}} \quad /$$

Examination  
Lasers and Light Sources  
19.02.2010  
11:45 – 12:45

1. Using an ink jet printer you print the colors blue and yellow on top of each other. What is the resulting color? Please explain. 1
  
2. The near point  $a_n$  of a 20 years old person is  $a_n = 40$  cm.
  - a) Which kind of focusing problem does this person have? 1
  - b) Calculate the refracting power of glasses  $D_g$  needed being able to focus an object at reading distance  $d = 30$  cm. 2
  - c) Calculate the refracting power of glasses needed to shift the far point to infinity. 1
  
3. You mix the light of three monochromatic light sources with wavelengths  $\lambda_1 = 650$  nm,  $\lambda_2 = 520$  nm and  $\lambda_3 = 400$  nm.
  - a) Calculate the relative intensities  $I_1(650 \text{ nm})$ ,  $I_2(520 \text{ nm})$  and  $I_3(400 \text{ nm})$  in order to get white light. Use the attached tabulated color matching functions. 3
  - b) Calculate the luminous efficacy of all three light sources together with intensities  $I_1$ ,  $I_2$ ,  $I_3$  if light source 1, 2 and 3 have electrical efficiencies  $\eta_1 = \eta_2 = \eta_3 = 100 \%$ . 3
  - c) A monochromatic light sources emits radiation at a wavelength  $\lambda = 600$  nm. The radiation is homogeneously emitted into a solid angle  $\Omega = 0.5$  sr. At a distance  $d = 2$  m you measure an illuminance  $E_v = 500$  lx. Calculate the electrical efficiency of the lamp, if the electrical input power is  $P = 10$  W. 2
  
4. Incandescence lamps:
  - a) Explain why tungsten incandescence lamps with halogen filling have higher luminous efficacies and longer lifetimes than conventional incandescence lamps. 2
  
5. A  $\text{Ga}_x\text{Al}_{1-x}\text{As}$  Laser emits radiation at a center-wavelength  $\lambda \approx 750$  nm.
  - a) Calculate the band gap of the semiconductor material. 1
  - b) Which substrate material can be used if the material is grown via epitaxy? 1
  - c) Estimate its composition (x, y). 1
  - d) The refraction index  $n_r$  of the laser active material is  $n_r = 3.4$ . The distance between the front and back mirror (deposited via evaporation directly on the cleaved crystal) is  $d = 200 \mu\text{m}$ . Calculate the distance in wavelength units between two neighboring longitudinal laser modes. 1
  
6. Laser doping:
  - a) Why is the laser doping process so much faster than conventional furnace diffusion? 1
  - b) What is the reason for the observed threshold energy? 1
  
- Total** **20**

19.02.2010

A1: Blue color absorbs red and green part of white light.  
 yellow absorbs blue color of white light.  
 $\Rightarrow$  Blue + yellow absorbs all colors  
 $\Rightarrow$  resulting color is black ①

A2: a) Table 1.1:  $\Rightarrow$  at Age 20, near point for normal sighted person should be  $a_N = 9 \text{ cm}$   
 $\Rightarrow$  person is ~~short~~ sighted. ①

b) Table 1.1 ~~in  $\text{mm}$   $1.1$~~   
 $\Rightarrow |A| = 11.1 \quad 1$   
 $40 \text{ cm} \Rightarrow D_N = 2.5 \text{ D}$   
 $30 \text{ cm} \Rightarrow D'_N = 3.3 \text{ D}$   


---

 $\Delta D_N = 0.8 \text{ D}$

refracting power of glasses  
 is  $D_g = 0.8 \text{ D}$  ②

c)  $A = D_F - D_N \Rightarrow D_F = A + D_N$

$$D_F = -11.1 \text{ D} + 2.5 \text{ D} = -8.6 \text{ D}$$

$$D_F + D_g = \frac{1}{\infty} \quad ; \Rightarrow \underline{D_g = +8.6 \text{ D}} \quad ①$$

A3: a) white light:

$\Rightarrow$  color coordinates  $X = Y = Z$

$$X = Z \cdot L_2 \cdot \bar{X} \quad ; \quad Y = Z \cdot L_2 \cdot \bar{Y} \quad ; \quad Z = Z \cdot L_2 \cdot \bar{Z}$$

$\Rightarrow$

$$X = I_1 \bar{X}(650\text{nm}) + I_2 \bar{X}(520\text{nm}) + I_3 \bar{X}(400\text{nm})$$

$$Y = I_1 \bar{Y}_{650} + I_2 \bar{Y}_{520} + I_3 \bar{Y}_{400}$$

$$Z = I_1 \bar{Z}_{650} + I_2 \bar{Z}_{520} + I_3 \bar{Z}_{400}$$

Assume :  $X = Y = Z$

③

|   | $I_1$                | $I_2$                | <del><math>I_3</math></del> | $I_3$                |
|---|----------------------|----------------------|-----------------------------|----------------------|
| 1 | $2,83 \cdot 10^{-1}$ | $6,33 \cdot 10^{-2}$ |                             | $1,43 \cdot 10^{-2}$ |
| 1 | $1,07 \cdot 10^{-1}$ | $7,1 \cdot 10^{-1}$  |                             | $3,96 \cdot 10^{-4}$ |
| 1 | 0                    | $7,8 \cdot 10^{-2}$  |                             | $6,78 \cdot 10^{-2}$ |

$$z) \quad \underline{I_1 = 2.62} \quad ; \quad \underline{I_2 = 1.005} \quad ; \quad \underline{I_3 = 16.75}$$

$$\text{or: } \frac{I_1}{I_2} = 2.60 \quad ; \quad \frac{I_1}{I_3} = 0.156 \quad ; \quad \frac{I_2}{I_3} = 0.0600$$

$$\frac{I_2}{I_1} = 0.384 \quad ; \quad \frac{I_3}{I_1} = 6.39 \quad ; \quad \frac{I_3}{I_2} = 16.66$$

$$b) \eta_V = k_m \int_{380 \text{ nm}}^{780 \text{ nm}} \eta_{e\lambda} \cdot V(\lambda) \cdot d\lambda \quad 0.5$$

$$\eta_{e\lambda} = \frac{P_{\text{out}, R_1} \cdot \delta(\lambda - R_1) + P_{\text{out}, R_2} \cdot \delta(\lambda - R_2) + P_{\text{out}, R_3} \cdot \delta(\lambda - R_3)}{P_{\text{in}, R_1} + P_{\text{in}, R_2} + P_{\text{in}, R_3}} \quad 0.5$$

$$P_{\text{in}, R_n} = \frac{P_{\text{out}, R_n}}{\eta_{R_n}} \quad 0.5$$

$$\Rightarrow \eta_{e\lambda} = \frac{P_{\text{out}, R_1} \cdot \delta(\lambda - R_1) + P_{\text{out}, R_2} \cdot \delta(\lambda - R_2) + P_{\text{out}, R_3} \cdot \delta(\lambda - R_3)}{\frac{P_{\text{out}, R_1}}{\eta_{R_1}} + \frac{P_{\text{out}, R_2}}{\eta_{R_2}} + \frac{P_{\text{out}, R_3}}{\eta_{R_3}}}$$

(3)

$$P_{\text{out}, R_1} = \text{const} \cdot \bar{I}_1 ; P_{\text{out}, R_2} = \text{const} \cdot \bar{I}_2 ; P_{\text{out}, R_3} = \text{const} \cdot \bar{I}_3$$

$$\Rightarrow \eta_{e\lambda} = \frac{\bar{I}_1 \cdot \delta(\lambda - R_1) + \bar{I}_2 \cdot \delta(\lambda - R_2) + \bar{I}_3 \cdot \delta(\lambda - R_3)}{\frac{\bar{I}_1}{\eta_1} + \frac{\bar{I}_2}{\eta_2} + \frac{\bar{I}_3}{\eta_3}}$$

$$\Rightarrow \eta_V = k_m \left[ \frac{\bar{I}_1 \cdot V(R_1) + \bar{I}_2 \cdot V(R_2) + \bar{I}_3 \cdot V(R_3)}{\frac{\bar{I}_1}{\eta_1} + \frac{\bar{I}_2}{\eta_2} + \frac{\bar{I}_3}{\eta_3}} \right] \quad 0.5$$

$$\eta_1 = \eta_2 = \eta_3 = 1 ; V(R_1) = 1.07 \cdot 10^{-1}$$

$$V(R_2) = 7.1 \cdot 10^{-1}$$

$$V(R_3) = 3.96 \cdot 10^{-4}$$

$$\Rightarrow \eta_V = 683 \frac{\text{lm}}{\text{W}} \left[ \frac{2.62 \cdot 1.07 \cdot 10^{-1} + 1.005 \cdot 7.1 \cdot 10^{-1} + 16.75 \cdot 3.96 \cdot 10^{-4}}{2.62 + 1.005 + 16.75} \right]$$

$$\underline{\eta = 33.5 \frac{\text{lm}}{\text{W}}}$$

$$6) E_v = \frac{\Phi_v}{A} \quad 0.5$$

$$\Omega = \frac{A}{d^2} \Rightarrow A = \Omega \cdot d^2 \quad 0.5$$

$$② E_v = \frac{\Phi_v}{\Omega \cdot d^2} \Rightarrow \Phi_v = E_v \cdot \Omega \cdot d^2$$

$$\Phi_v = 500 \frac{\text{lm}}{\text{m}^2} \cdot 0.5 \text{ sr} \cdot 4 \text{ m}^2 = 1000 \text{ lm}$$

$$\Phi_v = k_m \cdot \int_{380 \text{ nm}}^{780 \text{ nm}} \Phi_{e,\lambda} \cdot V(\lambda) \cdot d\lambda$$

$$\Phi_{e,\lambda} = \Phi_e \cdot f(\lambda - 600 \text{ nm}) \quad 0.5$$

$$\Rightarrow \Phi_v = k_m \cdot \Phi_e \cdot V(600 \text{ nm}) ; V(600 \text{ nm}) = 6,37 \cdot 10^{-1}$$

$$\Rightarrow \Phi_e = \frac{\Phi_v}{k_m \cdot V(600 \text{ nm})} = \frac{1000 \text{ lm}}{683 \frac{\text{lm}}{\text{W}} \cdot 6,37 \cdot 10^{-1}} = 2.32 \text{ W}$$

$$P_{\text{out}} = \Phi_e$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{2.32 \text{ W}}{10 \text{ W}} = \underline{23.2 \%} \quad 0.5$$

A4:

Halogen Filling avoids slackening of glass bulb.

=> small glass bulbs with <sup>0.25</sup> low volume and <sup>0.5</sup> thick glass walls can be used

(2) => thick glass walls enables high pressure gas filling <sup>0.25</sup>

=> low volume allows use of expensive noble gas filling: Kr or even Xe <sup>0.25</sup>

=> high gas pressure and high atomic mass of filling gas atoms reduces tungsten atom evaporation at filament surface. <sup>0.25</sup>

=> lower evaporation allows for higher operation temperature of tungsten filament <sup>0.25</sup>

=> efficacy  $\eta_v$  increases due to higher T. <sup>0.25</sup>

=> live time increases due to lower <sup>0.25</sup> evaporation.

AS:

a)  $E = h \cdot \nu$  ;  $\nu = \frac{c}{\lambda}$

$\Rightarrow E = \frac{h \cdot c}{\lambda}$

①  $E = \frac{1.24}{\lambda}$  ;  $\lambda$  in  $\mu\text{m}$  ;  $E$  in eV

$750 \text{ nm} \Rightarrow \underline{E = 1.65 \text{ eV}}$

b) epitaxy requires substrate with same

① lattice constant

$\Rightarrow$  GaAs can be used

c) Fig. 5.6

$\Rightarrow$  estimated composition at  $E_g = 1.65 \text{ eV}$ :

$\frac{\text{Ga}}{\text{Al}} \approx \frac{7}{3}$  (  $\frac{8}{2}$  ;  $\frac{6}{4}$  also possible )

①  $\Rightarrow \underline{\text{Ga}_{0.7} \text{Al}_{0.3} \text{As}}$

d) 2nd lasing condition:  $m \cdot \frac{\lambda_m n_r}{2} = d$

$\lambda_m = \frac{2d}{m \cdot n_r}$  ;  $\frac{d\lambda_m}{dm} = - \frac{2d}{m^2 \cdot n_r} = - \frac{\lambda_m}{m}$

$\Rightarrow d\lambda_m = - \frac{\lambda_m}{m} \cdot dm$  ;  $dm = 1$

$\Rightarrow \Delta\lambda_m = - \frac{\lambda_m}{m} \cdot 1$  ;  $m = \frac{2d}{\lambda_m n_r}$

$\Rightarrow \Delta\lambda_m = - \frac{\lambda_m^2 \cdot n_r}{2d} \Rightarrow |\Delta\lambda_m| = \frac{0.75^2 \mu\text{m}^2 \cdot 3.4}{400 \mu\text{m}}$

$$① |\Delta R_m| = 4.78 \text{ nm}$$

A6:

- a) furnace diffusion: Silicon is solid  
laser doping: Silicon is liquid

① diffusion constant in liquid  
silicon is 6-7 orders of magnitude  
larger than in solid silicon.

- b) threshold energy is energy required  
to heat the silicon up to melting  
temperature.

②

Examination  
Lasers and Light Sources  
27.03.2009  
9:00 – 10:30

1. Using an ink jet printer you print the colors red and blue on top of each other. What is the resulting color? Please explain. 1
  
2. The near point  $d_n$  of a 20 years old person is  $d_n = 50$  cm.
  - a) Estimate his/her width of accommodation. Which kind of focusing problem does this person have? 1
  - b) Does he/she need glasses while reading/driving a car? If so, what is the corresponding refracting power of the glasses?  
Can he/she use the reading glasses also for driving?  
Use a ray tracing figure for explanation. 2
  
3. You mix the light of three monochromatic light sources with wavelengths  $\lambda_1 = 600$  nm,  $\lambda_2 = 500$  nm and  $\lambda_3 = 400$  nm.
  - a) Calculate the relative intensities  $I(600 \text{ nm})$ ,  $I(500 \text{ nm})$  and  $I(400 \text{ nm})$  in order to get white light. Use the attached tabulated color matching functions. 3
  - b) Calculate the luminous efficacy of all three light sources together, if light source 1, 2 and 3 have electrical efficiencies  $\eta_1 = 15 \%$ ,  $\eta_2 = 10 \%$ ,  $\eta_3 = 20 \%$ . 3
  
4. You compare two halogen incandescence lamps. Both lamps have a rated input-power  $P_{in} = 100$  W and the same rated life time and gas filling. The only difference is the rated input-voltage  $V_{in}$ ;  $V_{in}$  (lamp 1) = 12 V;  $V_{in}$  (lamp 2) = 230 V.
  - a) Which lamp has the higher luminous efficacy? Please explain. 1
  - b) Estimate the luminous efficacy of lamp 2 if its filament temperature amounts to 3000 K. 2
  - c) Calculate the luminous flux  $\Phi_V$  of the lamp and the luminous intensity  $I_V$ , if 90 % of the emitted light is directed into a solid angle  $\Omega_s = 0.2$  sr. 1
  - d) Calculate the assembling distance to a painting if you want to illuminate the painting with an illuminance  $E_V = 300$  lx. 1
  - e) Explain and discuss 3 possibilities how to increase the luminous efficacy of incandescence lamps. 2
  
5. An LED emits radiation at a wavelength  $\lambda = 870$  nm.
  - a) Calculate the band gap of the semiconducting material. 1
  - b) Calculate the width  $\Delta\lambda$  of the emitted spectrum in wavelength units, if the temperature of the pn-junction is  $T = 330$  K. 2
  
6.
  - a) What is the difference between longitudinal and transversal laser modes? Please explain. 2
  - b) Why is it more difficult to realize an ultraviolet laser than an infrared laser? Please explain. 1

**Total 23**

# Examination

## Lasers and Light Sources

27.03.2003

- 1.) red extracts blue and green part, 0.25  
 blue extracts red and green part <sup>0.25</sup> of white  
 light.

$\Rightarrow$  red, green and blue parts are extracted  
 $\Rightarrow$  the resulting color is black. 0.5

- 2.) a) according to table 1.1 the accommodation  
 width is  $A = 11.1$  <sup>0.5</sup> D  $\Rightarrow$  Person is farsighted.  
 $\Rightarrow a_N = 0.09 \text{ m}$

- b) near point:  $a_N = 0.5 \text{ m}$

for reading the near point must be

$$a'_N = 0.3 \text{ m or less} \quad 0.25$$

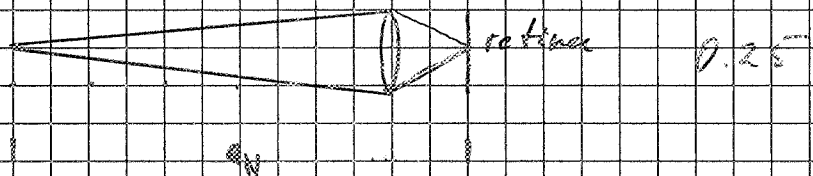
$$\Rightarrow 0.3 \text{ m} > a'_N > 0.09 \text{ m}$$

$\Rightarrow$  person needs reading glasses 0.25

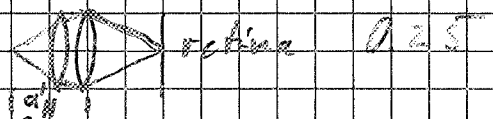
$$\text{refracting power of glasses } D_g = \frac{1}{a'_N} - \frac{1}{0.5} \text{ D}$$

$$\Rightarrow +9 \text{ D} > D_g > +1.33 \text{ D} \quad 0.5$$

(2)



unaccommodated eye without glasses



accommodated eye with glasses

For  $D_g = +9 \text{ D}$  the far point is exactly  $a_F = \infty$ .

$\Rightarrow$  The person can also use the reading glasses  
 for driving 0.5

3.) a)

|        | $\bar{x}$           | $\bar{y}$            | $\bar{z}$         |
|--------|---------------------|----------------------|-------------------|
| 600 nm | 1.0622              | 0.637                | $8 \cdot 10^{-4}$ |
| 500 nm | $4.9 \cdot 10^{-3}$ | 0.323                | 0.272             |
| 400 nm | 0.01437             | $3.96 \cdot 10^{-4}$ | 0.06785           |

$$X = 1.0622 \cdot I_1 + 4.9 \cdot 10^{-3} I_2 + 0.01437 \cdot I_3$$

$$Y = 0.637 I_1 + 0.323 \cdot I_2 + 3.96 \cdot 10^{-4} \cdot I_3$$

$$Z = 8 \cdot 10^{-4} I_1 + 0.272 \cdot I_2 + 0.06785 \cdot I_3$$

white light:  $X = Y = Z$

assume:  $X = 1$ ,  $Y = 1$ ,  $Z = 1$

solve equation system:

$$I_1 = \frac{\begin{vmatrix} 1 & 4.9 \cdot 10^{-3} & 0.01437 \\ 1 & 0.323 & 3.96 \cdot 10^{-4} \\ 1 & 0.272 & 0.06785 \end{vmatrix}}{\text{Det}_{\text{hom}}} \cdot 0.5 = 0.8167$$

$$I_3 = \frac{\begin{vmatrix} 1.0622 & 4.9 \cdot 10^{-3} & 1 \\ 0.637 & 0.323 & 1 \\ 8 \cdot 10^{-4} & 0.272 & 1 \end{vmatrix}}{\text{Det}_{\text{hom}}} \cdot 0.5 = 8.757$$

$$I_2 = \frac{\begin{vmatrix} 1.0622 & 1 & 0.01437 \\ 0.637 & 1 & 3.96 \cdot 10^{-4} \\ 8 \cdot 10^{-4} & 1 & 0.06785 \end{vmatrix}}{\text{Det}_{\text{hom}}} \cdot 0.5 = 1.4897$$

with  $\text{Det}_{\text{hom}} = \begin{vmatrix} 1.0622 & 4.9 \cdot 10^{-3} & 0.01437 \\ 0.637 & 0.323 & 3.96 \cdot 10^{-4} \\ 8 \cdot 10^{-4} & 0.272 & 0.06785 \end{vmatrix} \cdot 0.5$

relative intensities:

$$\frac{I_1}{I_2} = 0.548 \quad ; \quad \frac{I_1}{I_3} = 0.0932$$

or:

$$\frac{I_2}{I_1} = 1.824 \quad ; \quad \frac{I_3}{I_1} = 0.170$$

or:

$$\frac{I_3}{I_2} = 10.72 \quad ; \quad \frac{I_3}{I_1} = 5.878$$

$$b) \quad \eta_v = K_m \int_{380 \text{ nm}}^{780 \text{ nm}} \eta_{e\lambda} \cdot V(\lambda) \cdot d\lambda$$

assume:  $P_{in} = 1 \text{ W}$  (input power)

$$\textcircled{3} \quad P_{in} = P_1 + P_2 + P_3$$

$$P_1 = \frac{I_1}{\eta_1} \quad ; \quad P_2 = \frac{I_2}{\eta_2} \quad ; \quad P_3 = \frac{I_3}{\eta_3} \quad 0.5$$

$$I_2 = \frac{I_1}{0.548} \quad ; \quad I_3 = \frac{I_1}{0.0932}$$

$$\Rightarrow P_{in} = \frac{I_1}{\eta_1} + \frac{I_1}{0.548 \cdot \eta_2} + \frac{I_1}{0.0932 \cdot \eta_3} = I_1 \cdot 78.51$$

$$\Rightarrow I_1 = \frac{1 \text{ W}}{78.51} \quad ; \quad I_2 = \frac{1 \text{ W}}{78.51 \cdot 0.548} \quad ; \quad I_3 = \frac{1 \text{ W}}{78.51 \cdot 0.0932} \quad 0.5$$

$$\eta_{e1} = \frac{\delta(R - R_1)}{78.51} \quad \eta_{e2} = \frac{\delta(R - R_2)}{78.51 \cdot 0.548} \quad ; \quad \eta_{e3} = \frac{\delta(R - R_3)}{78.51 \cdot 0.0932} \quad 0.5$$

(3)

0.5

$$q_v = k_m \cdot \int \left( \frac{\delta(2-600\text{mm})}{78.57} + \frac{\delta(2-500\text{mm})}{78.57 \cdot 0.549} + \frac{\delta(2-400\text{mm})}{78.57 \cdot 0.0932} \right) \cdot \frac{1}{(2)} \delta 2$$

780mm  
380mm

$$q = 13.5 \text{ km/W} \quad 1$$

# Examination

## Lasers and Light Sources

27.03.2009

4.) a) lamp 1 uses higher current and lower voltage compared to lamp 2.

As a consequence the diameter of the incandescent filament is larger. Thicker filaments have

① longer lifetimes at the same temperature or can be operated at higher temperatures at the same lifetime.

Higher temperatures result in higher luminous efficiencies.

⇒ lamp 1 has higher luminous efficacy compared to lamp 2

② b)  $T = 3000\text{K}$ ; from fig 4.14 ⇒  $\eta_v = 22 \pm 2 \frac{\text{lm}}{\text{W}}$

c)  $\Phi_v = 100\text{W} \cdot 22 \frac{\text{lm}}{\text{W}} = 2200 \text{ lm}$  0.5

①  $I_v = 0.9 \cdot \Phi_v / \Omega_s = 9900 \frac{\text{lm}}{\text{sr}}$  0.5

d)  $E_v = 300\text{lx} = 300 \frac{\text{lm}}{\text{m}^2}$

illuminated area:  $A = d^2 \cdot \Omega_s$ ;  $d$  = assembling distance

①  $E_v = \frac{0.9 \cdot \Phi_v}{A} \Rightarrow d = \sqrt{\frac{0.9 \cdot \Phi_v}{E_v \cdot \Omega_s}} = 5.74 \text{ m}$

e) - inert gas filling with high atomic mass:  
↳ high viscosity of gas reduces evaporation of tungsten

② - halogen gas filling.

↳ allows to reduce the diameter of the glass bulb.

⇒ higher pressure of gas filling possible

⇒ low volume allows to use expensive Xe-gas filling.

$\frac{2}{5}$

- coiled tungsten wire:

increases the "effective" wire diameter

$\Rightarrow$  reduced evaporation, when lamp filled with inert gas

# Examination

## Lasers and Light Sources

27.03.2009

5) a)  $\lambda = 870 \text{ nm}$

$$E_g \approx h \cdot \nu \quad ; \quad \nu = \frac{c}{\lambda}$$

①  $E_g(\text{eV}) = \frac{1.24}{\lambda[\mu\text{m}]}$

$$\Rightarrow E_g \approx 1.42 \text{ eV}$$

b)  $T = 330 \text{ K}$

$$kT = 26 \text{ meV} \cdot \frac{330}{300} \Rightarrow kT \approx 29 \text{ meV}$$

②  $|\Delta R| = \frac{2kT}{h \cdot c} \cdot \lambda^2 = \frac{52 \text{ meV}}{1.24 \text{ eV} \cdot \mu\text{m}} \cdot (870 \text{ nm})^2$

$$= 0.035 \mu\text{m}$$

$$\Rightarrow \Delta R \approx 35 \text{ nm}$$

- 6.) a) Longitudinal laser modes determine the wavelength of the emitted laser radiation. They depend on the length of the optical resonator  $d$  according to:

$$m \cdot \frac{\lambda_m}{2} = d$$

with  $\lambda_m$  = wavelength in active medium,  
 $m$  = integer number

②

transversal laser modes determine the intensity distribution of the laser radiation in directions perpendicular to the emitted laser radiation:

Transversal Electromagnetic Modes TEM<sub>mn</sub>

$m, n$  = integer numbers

fundamental (Gaussian) Mode is

TEM<sub>00</sub>

- b) The relation between the Einstein coefficients for spontaneous emission  $A$  and stimulated emission  $B$  is given by:

$$\frac{A}{B} = \frac{8\pi h}{c^3} \cdot \nu^3$$

④

with  $h$  = Planck's constant,  $c$  = speed of light in vacuum

and  $\nu$  = frequency of the radiation.

Spontaneous emission is the competing process to the stimulated emission.