BIOPHOTONICS ENGINEERING

FINAL EXAM

INSTRUCTIONS: Answer questions ONE and any other THREE. All questions carry equal marks. Make sure you carried a calculator. A range of formulae likely to be of benefit in the solution of these questions are provided at the end of the paper.

Planck's Constant (h) = 6.626×10^{-34} J.s

Speed of light in a vacuum (c_0) = 3×10^{8} $m.s^{-1}$

1eV = 1.602×10^{-19} J

Charge of an electron = 1.602×10^{-19} C

Mass of an electron = 9.109×10^{-31} kg

1. Answer all parts

Selective photothermolysis plays an important role in many medical and cosmetic treatments.

a) Explain what is meant by this term. [2 marks]

b) For each of the following applications, identify the target chromophore and explain briefly their underlying mechanisms.

i. Correcting vascular malformations [3 marks]

ii. Removing tattoos [3 marks]

iii. Removing body hair [3 marks]

A Q-Switched laser has a peak pulse power of 100MW at 532nm wavelength. It is used for removing tattoos.

c) What pulse width is required in order to deliver 400mJ of energy per pulse? [1 mark]

d) If the pulse energy is spread over a circular spot with a 4mm radius, what is its irradiance? [1 mark]

e) What is the photon energy (in electron volts) at this wavelength? [2 mark]

f) As a simplified model, the skin has an absorption coefficient of 20/cm and a scatter coefficient of 10/cm. Assuming the skin has a reflectance of 8%, what is the irradiance 3mm below the surface of the skin? [3 marks]

g) How many optical penetration depths does 3mm represent? [2 marks]

2. Answer all parts

A long-distance biosensor application requires light pulses to be sent down a fibre optic cable.

a) Define what is meant by *dispersion* in the fibre optic cable and state why it is undesirable? [2 marks]

b) Describe briefly the underlying mechanisms behind the following three causes of dispersion

i. Modal [3 marks]

ii. Material [3 marks]

iii. Waveguide [3 marks]

A multimode step-index fibre has a length (L) 5km. Its core (n_1) and cladding (n_2) refractive indices are 1.48 and 1.47 respectively.

c) Show that the time delay (Δt) between the arrival of the fastest and slowest modes in the fibre optic cable is given by: [5 marks]

$$\Delta t = \frac{Ln_1}{c_0}\left(\frac{n_1 - n_2}{n_2}\right)$$

d) Calculate the absorption loss in the cable (in dB) if its attenuation coefficient is $70 \times 10^{-6}/m$ [1 mark]

e) A biorecognition element is directly immobilized on to the end face of the fibre optic cable, and has a refractive index of 2.1. If the light in the fibre can be considered to be normal to the end face, calculate the reflectance at the end face. [3 marks]

3. Answer all parts

a) Define the terms below and give their units of measurement:

i. Radiant flux [2 marks]

ii. Luminous flux [2 marks]

iii. Luminous efficacy [2 marks]

iv. Luminous intensity [2 marks]

v. Illuminance [2 marks]

An array of LEDs has a luminous intensity of 60 (standard units). It is placed 3m from a screen. A bulb placed 2.3m from the screen has the same illuminance on the screen. You can treat the LED array and the bulb as point sources.

b) Calculate the luminous intensity of the bulb. [4 marks]

c) Calculate the luminous flux of the bulb. [2 marks]

d) If the bulb draws 417mA at 240V, calculate luminous efficacy of the bulb. [2 marks]

e) Three LEDs of colours red, green and blue are placed side by side and produce the same radiant flux. To the human eye, which one will appear the brightest and why? [2 marks]

4. Answer all parts

a) Briefly explain the reasons why photosensitiser drugs used in Photodynamic Therapy (PDT) tend to accumulate in cancerous regions. [5 marks]

b) Identify five highly desirable properties of an ideal photosensitiser drug. [5 marks]

An LED array is used to apply PDT to a skin cancer. The radiant flux of a single LED is measured using a thermal power meter. The detector has a response time of 2s.

c) How long will it take the detector to reach 5% of its 'true' temperature value? [4 marks]

d) The specific heat capacity of the sensor is 200 J/kg.K and has a mass of 3g. Calculate the thermal conductance of the insulating support between the sensor and the heat sink. [1 mark]

e) What is the sensor's maximum temperature rise if the radiant flux from the LED falling on the sensor is 100mW? [1 mark]

f) If the response time is halved by increasing the thermal conductance, what is its new maximum temperature rise? [2 marks]

g) What is a more suitable way of improving the maximum temperature rise without sacrificing response time, and vice versa? [2 marks]

5. Answer all parts

a) Describe the following bioimaging techniques.

i. Optical Coherence Tomography [5 marks]

ii. Fluorescence Resonance Energy Transfer (FRET) [5 marks]

Phosphor-covered white light LEDs are used as a light source.

b) What is the radiant flux the PN junction can produce if the internal quantum efficiency is 70% and is driven with a current of 30mA. The photons emitted at the junction have energy 2.697eV (blue). [2 marks]

The phosphor coating on the PN semiconductor chip absorbs some of the emitted photons and fluoresces at 560nm (yellow). Assume there are no reflections at the semiconductor to phosphor coating interface.

c) Calculate the energy lost as heat by a single photon in completing this process. [3 marks]

Only half the PN junction emitted photons are absorbed by the phosphor layer causing fluorescence; the remainder pass straight through the phosphor layer without any losses.

d) Calculate the radiant flux emanating from the phosphor coating [3 marks]

Due to the relatively high blue light intensity, and the lack of green and red light in the LED output, the light appears slightly blue rather than pure white.

e) Suggest a simple way this could be remedied inside the LED with the phosphor coating. [2 marks]

BIOPHOTONICS ENGINEERING - EQUATION SHEET

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

For TM waves

$$\frac{E_r}{E_i} = \frac{n_1 cos\theta_2 - n_2 cos\theta_1}{n_1 cos\theta_2 + n_2 cos\theta_1}$$

$$\frac{E_t}{E_i} = \frac{2n_1 cos\theta_1}{n_1 cos\theta_2 + n_2 cos\theta_1}$$

For TE waves

$$\frac{E_r}{E_i} = \frac{n_1 cos\theta_1 - n_2 cos\theta_2}{n_1 cos\theta_1 + n_2 cos\theta_2}$$

$$\frac{E_t}{E_i} = \frac{2n_1 cos\theta_1}{n_1 cos\theta_1 + n_2 cos\theta_2}$$

$$d \times sin\theta = m\lambda \text{ (constructive interference)}$$

$$Intensity\ I = 4I_0 cos^2 \frac{\pi L}{\lambda}$$

$$v_g = \frac{c_0}{n - \lambda_0 \frac{dn}{d\lambda_0}} \text{ and } v_p = \frac{c_0}{n}$$

$$\sigma_\tau = |D_\lambda| \sigma_\lambda L \text{ where } D_\lambda = -\frac{\lambda_0}{c_0} \frac{d^2 n}{d\lambda_0^2}$$

$$P_{out} = P_{in} e^{-\alpha L}$$

$$R_c \approx a \frac{n_2}{n_1 - n_2}$$

$$B_{if} = 4\pi^2 \frac{|\mu_{if}|^2}{6\varepsilon_0 h^2}$$

$$A_{if} = \left(\frac{8\pi h}{\lambda^3}\right) B_{if}$$

$$\Delta\lambda_0 = \frac{2kT}{hc} \lambda_0^2$$

$$\phi(t) = \phi_{max} \left(1 - e^{-t/\tau}\right)$$

$$Responsivity = \frac{e\eta}{hf}$$

$$For\ minima, a \times sin\theta = m\lambda$$

$$sin\theta_m = m\frac{\lambda}{2d}$$

$$mode\ velocity\ (v_m) = c \times cos\theta_m$$

$$\max number\ of\ TE\ modes \doteq \frac{sin\bar{\theta}_c}{\lambda/_{2d}}$$

$$sin\alpha_{max} = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}$$

$$V_p = \pi m_{max}$$

$$m_{max} \approx \frac{4}{\pi^2}V^2$$

$$\lambda_c = \frac{2\pi a}{2.405}NA$$

$$\sigma_\tau \approx \frac{L\Delta}{2c_1}\ where\ \Delta \approx \frac{n_1 - n_2}{n_1}\ and\ c_1 = \frac{c_0}{n_1}$$

$$t = \frac{L}{c_0}\left(n - \lambda_0\frac{dn}{d\lambda_0}\right)$$

$$I(x) = I_0e^{-\alpha x}$$

$$\eta_{abs} = \frac{P_{abs}}{P_{in}} = (1 - R)(1 - e^{-\alpha d})$$

$$\lambda = \frac{h}{mv}$$

$$E_n = \frac{n^2h^2}{8ma^2}$$

$$\Psi_n(x) = \sqrt{\frac{2}{a}}\sin\left(\frac{n\pi}{a}x\right)$$