King's College London

UNIVERSITY OF LONDON

M.Sci. EXAMINATION

CP/4750 Image Capture and Sensor Technology

Summer 2005

Time allowed: THREE Hours

Candidates must answer THREE questions.
No credit will be given for answering further questions.

The approximate mark for each part of a question is indicated in square brackets.

You must not use your own calculator for this paper.
Where necessary, a College calculator will have been supplied.

TURN OVER WHEN INSTRUCTED

Physical Constants

Permittivity of free space	ϵ_0	$= 8.854 \times 10^{-12}$	$\mathrm{F\,m^{-1}}$
Permeability of free space	μ_0	$= 4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$
Speed of light in free space	c	$= 2.998 \times 10^{8}$	$\mathrm{m\,s^{-1}}$
Gravitational constant	G	$= 6.673 \times 10^{-11}$	$\mathrm{N\,m^{2}\,kg^{-2}}$
Elementary charge	e	$= 1.602 \times 10^{-19}$	C
Electron rest mass	m_{e}	$= 9.109 \times 10^{-31}$	kg
Unified atomic mass unit	m_{u}	$= 1.661 \times 10^{-27}$	kg
Proton rest mass	m_{p}	$= 1.673 \times 10^{-27}$	kg
Neutron rest mass	m_{n}	$= 1.675 \times 10^{-27}$	kg
Planck constant	h	$= 6.626 \times 10^{-34}$	$\mathrm{J\,s}$
Boltzmann constant	k_{B}	$= 1.381 \times 10^{-23}$	$\mathrm{J\,K^{-1}}$
Stefan-Boltzmann constant	σ	$= 5.670 \times 10^{-8}$	$\mathrm{W\,m^{-2}\,K^{-4}}$
Gas constant	R	$= 8.314$	$\mathrm{J\,mol^{-1}\,K^{-1}}$
Avogadro constant	N_{A}	$= 6.022 \times 10^{23}$	$\mathrm{mol^{-1}}$
Molar volume of ideal gas at STP		$= 2.241 \times 10^{-2}$	$\mathrm{m^{3}}$
One standard atmosphere	P_0	$= 1.013 \times 10^{5}$	$\mathrm{N\,m^{-2}}$

Answer THREE questions

1)

a) State Stefan's Law and Wien's Displacement Law for black body radiation.

[3 marks]

b) The energy spectrum radiated by a black body is given by:

$$dU_\nu = \frac{8\pi h}{c^3} \frac{\nu^3}{\exp\left(\frac{h\nu}{kT}\right) - 1} d\nu.$$

Explain the meanings of the symbols in this expression, and sketch the variation of $dU_\nu/d\nu$ with ν for two different temperatures.

[5 marks]

c) An infrared sensor has a collecting aperture diameter of 10 cm and has a detector that is sensitive to wavelengths around 10 μm. The detector has a bandpass filter that can transmit radiation in a 3 % bandwidth, centred on 10 μm. The system is used to observe a distant object through an atmosphere that is 90 % transmitting in the 10 μm spectral region and is at a background temperature of 300 K. The object subtends a solid angle of 2×10^{-13} steradians at the sensor, and it is at a black-body temperature of 900 K.

i) Find the signal power that is incident on the detector.

[4 marks]

ii) Find the background power striking the detector, if the detector has a field of view of 8×10^{-7} steradians.

[4 marks]

iii) What is the maximum post-detector bandwidth which may be used to achieve a signal-to-noise ratio of 10 dB?

[4 marks]

2)

a) Briefly explain each of the following terms

i) an ideal photon detector,

[2 marks]

ii) specific detectivity,

[2 marks]

iii) the Weiner-Khintchine relationship.

[2 marks]

b) The probability $p(n,k)$ of detecting n photons in a unit time interval, when the average photon arrival rate is k, is governed by the Poisson probability distribution

$$p(n,k) = \frac{k^n}{n!} \exp(-k) .$$

Show that the variance $\overline{n^2}$ and the mean number, $\overline{n}$, are related by

$$\overline{n^2} - \overline{n}^2 = \overline{n}.$$

(Hint: $x^2 = x(x-1) + x$.)

[5 marks]

c) Calculate the minimum number of photons, received in unit time, required to form a digital signal with a bit error rate of less than 10^{-8}.

[4 marks]

d) A minimum tolerable signal to noise ratio for a telephone system is 10 dB for a bandwidth of 4 kHz. Estimate the minimum optical signal power required to achieve this in an analogue optical transmission system if the only source of sound is shot noise, the wavelength used is $\lambda = 1.5$ μm and the detector has unit efficiency.

[5 marks]

3) Write an essay on *two* of the following topics:

a) The structure and operation of an electron-multiplying charge-coupled device (EMCCD), including an explanation of how it differs from a conventional charge-coupled device (CCD) detector, and a comparison of their characteristics.

[10 marks]

b) The design considerations for a thermal imager, working at wavelengths in the region of 10 μm. Concentrating on one application for a thermal imager, include in your answer discussions of any desirable properties of the optical components, and of the image surveying and capture methods.

[10 marks]

c) The physical principles of operation of three types of thermal radiation detectors. Comment on the suitability of each type of detector for particular applications in thermal imaging and metrology.

[10 marks]

4)

a) Explain what is meant by the terms:

i) intrinsic photoexcitation, and

ii) extrinsic photoexcitation.

[4 marks]

b) Describe the photoconductive effect and the photovoltaic effect. Explain how devices based on each effect can be used to detect photons, and comment on their merits.

[6 marks]

c) A photodiode contains a p-n junction. The density of the acceptors is N_A, and the density of the donors is N_D, with $N_A >> N_D$. A reverse bias of $-V_A$ is applied. Show that the width w of the depletion layer is

$$w = \sqrt{\frac{2\epsilon\left(\phi - V_A\right)}{eN_D\left(1 + \frac{N_D}{N_A}\right)}}$$

where $\epsilon = \epsilon_r \epsilon_0$ is the permittivity of the junction region and ϕ is the height of the potential barrier across the junction.

[6 marks]

d) A p-n junction photodiode with an active area of 1 mm^2 has $N_A = 5\times10^{14}$ cm^{-3}, $N_D = 10^{17}$ cm^{-3}, $\phi = 0.15$ V, and $\epsilon_r = 15$. Estimate the upper limit for the frequency response when the photodiode is operated at a reverse bias of 1.5 V, with a load resistance of 1.5 MΩ.

[4 marks]

5)

a) Explain briefly each of the following terms:

i) quantum efficiency,

[2 marks]

ii) signal to noise ratio,

[2 marks]

iii) noise equivalent power,

[2 marks]

iv) background-limited detection,

[2 marks]

v) avalanche breakdown.

[2 marks]

b) A laser is used to transmit a signal from a satellite that is orbiting the Earth at a height of 4.5×10^7 m to a ground station that is equipped with a receiving dish of diameter 2 m. The laser beam has a wavelength of 540 nm and radiates into a solid angle of 10^{-6} steradian. A data rate of 1 Mbit/s is required at a signal-to-noise ratio of 15 dB. What is the minimum laser power required, assuming that the receiver has an ideal detector and there is no atmospheric absorption or distortion?

[10 marks]