King's College London

UNIVERSITY OF LONDON

M.Sci. EXAMINATION

CP/4755 Optical Information Processing

Summer 2002

Time allowed: 3 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

Answer THREE questions

1a) The diagram shows an electro-optic linear amplitude modulator utilising the material lithium niobate, $LiNbO_3$. Explain the purpose of each of the components and suggest a preferred value for the angle β.

[3 marks]

b) When an electric field E_y is applied to $LiNbO_3$, the optical indicatrix, described in terms of the principal axes (x, y and z), the attendant electro-optic coefficients $r_{i,j}$ and the ordinary and extraordinary refractive indices (n_o and n_e) are given by:

$$\left(\frac{1}{n_o^2} - r_{22}E_y\right)x^2 + \left(\frac{1}{n_o^2} + r_{22}E_y\right)y^2 + \frac{z^2}{n_e^2} + 2r_{51}E_y yz = 1.$$

Show that a new set of principal axes may be defined:

$$x = x'$$

$$y = y'\cos\theta - z'\sin\theta$$

$$z = z'\cos\theta + y'\sin\theta$$

when

$$\theta = \frac{-r_{51}E_y}{(1/n_e^2 - 1/n_o^2 - r_{22}E_y)}.$$

You may assume that θ is small.

[3 marks]

c) If $r_{51} = 28.0 \times 10^{-12}$ m V^{-1}, $r_{22} = 3.40 \times 10^{-12}$ m V^{-1}, $n_e = 2.21$, $n_o = 2.30$ and there is an applied voltage of 1 kV across a 1 mm thick crystal, calculate the value for θ. Comment on your answer.

[3 marks]

d) Write down the form of the optical indicatrix in this new coordinate system.

[3 marks]

Continued next page

e) In the limit of small θ, show that the perturbed refractive indices for waves travelling in the x', y' and z' directions become:

$$n_{x'} = n_o\left(1 + \frac{1}{2}n_o^2 r_{22} E_y\right)$$

$$n_{y'} = n_o\left(1 - \frac{1}{2}n_o^2 r_{22} E_y\right)$$

$$n_{z'} = n_e$$

[3 marks]

f) Explain what is meant by the term *half-wave voltage*. Calculate a value for this quantity for the modulator of part (c), if the crystal is 10 mm long and the wavelength of light used is 532 nm.

[3 marks]

g) Explain in which way the expression for half-wave voltage would differ if the electro-optic modulator utilised an applied field in the z direction.

[2 marks]

2a) Draw a diagram to illustrate the principle of light modulation using an acousto-optic modulator.

[3 marks]

b) Describe the nature of the principal diffracted orders from the modulator when the diffraction process is considered to be in (i) the *thin* regime and (ii) the *thick* regime.

[4 marks]

c) An acousto-optic modulator of sound column thickness L, containing a medium of refractive index n with acoustic velocity v, is to be used to modulate light of wavelength λ. Using the Uncertainty Principle, or otherwise, obtain an expression for the lower frequency limit at which the modulator can be used in the thick grating regime. Obtain a value for this lower limit if $n = 1.60$, $L = 1$ cm, $\lambda = 532$ nm and $v = 2000$ m s^{-1}.

[4 marks]

d) The acousto-optic modulator of part (c) has an aperture size D and is to be used as a radio-frequency channelised receiver utilising light of wavelength λ. Draw a diagram to illustrate how such a system could be implemented.

[3 marks]

e) Obtain expressions for the angle of diffraction and the spatial channel resolution of your system.

[3 marks]

f) Obtain an expression for the maximum number of separable channels which could be resolved with your channel analyser and comment on the physical significance of this result.

[3 marks]

3) A computer-generated on-axis Fourier hologram is fabricated as a binary level surface relief structure consisting of a rectangular array of $N \times N$ pixels in a cell that is replicated $M \times M$ times.

Draw an optical scheme showing how the reconstruction of the hologram function could be achieved.

[4 marks]

Describe the main features of the reconstruction taking account of the following:

a) the encoded function in the Fourier hologram,

[1 mark]

b) the focal length of the reconstruction lens,

[1 mark]

c) the pixellation of the hologram,

[1 mark]

d) binarisation,

[1 mark]

e) the pixel shape,

[1 mark]

f) the replication of the basic cell,

[1 mark]

g) the finite extent of the overall hologram structure.

[1 mark]

Calculate a maximum value for the diffraction efficiency of the reconstruction from the hologram.

Note:

$$\int_0^1 \left(\frac{\sin(\pi.x)}{\pi.x} \right)^2 dx \approx 0.45$$

[4 marks]

How could such a hologram be used in an optoelectronic implementation of a Hopfield model of a neural network?

[5 marks]

4) Explain the basic physical principles which can give rise to superior performances from all-optical or optoelectronic information processing architectures, over their purely electronic counterparts.

[4 marks]

Show that in an optical pattern recognition system, in the presence of random additive noise, the maximum signal-to-noise ratio at the output is achieved when a matched filter is used with:

$$H(u,v) = S^*(u,v)$$

where $S(u,v)$ represents the spectrum of the pattern to be recognised and $H(u,v)$ is the filter function. You may assume the Schwarz inequality applies, where the symbols have their usual meanings:

$$|\int\int U(x,y)V^*(x,y)dxdy|^2 \leq \int\int |U(x,y)|^2 dxdy \cdot \int\int |V(x,y)|^2 dxdy$$

[7 marks]

Draw a labelled diagram to explain the optical implementation of a vector-matrix multiplication operation. Give an example of a modern information processing architecture which could exploit an optical vector-matrix multiplier.

[3 marks]

Briefly describe the operation of the optical system illustrated in the figure.

[4 marks]

Compare the operation of the illustrated system to that of a vector-matrix multiplier. Give an example of an application which could exploit the properties of the system shown in the figure.

[2 marks]

5) Describe, with the aid of a suitably labelled diagram, the operation of a coherent optical data processor which could be used for performing spatial filtering operations. Explain the role of each of the constituent elements of the processor.

[6 marks]

It is proposed to use a coherent optical processor to sharpen the image of a scene which has been blurred by linear motion. By considering the blurring of a point object, linearly smeared by an amount $2\Delta x$, show that a 1D deblurring filter is given by

$$H(u) = \frac{u\Delta x}{\sin(u\Delta x)}$$

and sketch this function.

[6 marks]

Explain how this filter function could be realised by the combination of an amplitude transparency function, $A(u)$, and a binary level phase filter, $\phi(u)$. Give reasons why perfect image restoration would not be achieved in practice.

[4 marks]

A computer generated holographic element is designed to implement the deblurring filter function by having a transmittance

$$A(u) \cdot T(u) = \frac{1}{2} A(u) \cdot [1 + \cos(\phi(u) + \beta u)] .$$

Outline the criteria used in choosing a suitable value for β. Describe the light distribution at the output plane of the coherent processor when the hologram is inserted into the spatial frequency domain.

[4 marks]