THE UNIVERSITY OF ADELAIDE
AUSTRALIA

**EXAMINATION FOR THE DEGREE OF B.E. and Eng. Masters**

**Semester 2 2004**

**4041 OPTICAL COMMUNICATION ENGINEERING**
**7045 PHOTONICS FOR COMMUNICATION**

Official Reading Time: 10 mins
Writing Time: 120 mins
Total Duration: 130 mins

**Instructions:**

- This is a closed book examination.
- Attempt **ALL** FOUR questions.
- All questions carry equal marks; part marks are given in brackets where appropriate.
- Begin each answer on a new page.
- Examination materials must not be removed from the examination room.
- **ANSWERS TO QUESTIONS SHOULD BE EXPRESSED CLEARLY AND WRITTEN LEGIBLY. THESE ASPECTS OF PRESENTATION WILL BE TAKEN INTO ACCOUNT IN ASSESSMENT.**

**Materials:**

- One Pink Book
- The use of calculators is permitted, this equipment to be supplied by the candidate. No pre-recorded material nor calculator instruction book is permitted, and calculators with remote communication links will be barred from the examination room.
- Formulae sheets (3 pages) are attached at the end of the paper.

**DO NOT COMMENCE WRITING UNTIL INSTRUCTED TO DO SO.**

Question 1 begins on page 2

1. Consider a heterodyne receiver for a digital optical fibre communications system.

   (a) Briefly explain how a heterodyne receiver detects phase, given that photodetectors can only detect amplitude or optical power.
   (2 marks)

   (b) What type of modulation scheme can a heterodyne system permit that is not otherwise achievable with direct detection using a standard receiver?
   (1 mark)

   (c) State the key advantage of phase detection over amplitude detection.
   (1 mark)

   (d) Heterodyne receivers offer increased sensitivity. Briefly state why.
   (1 mark)

   (e) Using a heterodyne receiver, compute the local-oscillator (LO) power required to make the SNR 1 dB *less* that the quantum limit. You may assume the IF bandwidth is 500 MHz and the received optic power is constant at 5 nW when a binary "1" is received. The dark current of the photodetector is $I_D$ = 2 nA, and its responsivity is $\rho$ = 0.5 A/W. Assume the temperature is 27ºC and a load resistance of 100 Ω.
   (11 marks)

   (f) If this were *not* a heterodyne system, then the receiver's bandwidth could be as small as 250 MHz. For this case determine the signal power required to achieve a SNR equal to that in part (e). (4 marks)

**You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.**

2. (a) A compact disc (CD) has several levels of error detection and correction. Provide a very brief description of the following, and explain their purpose:

   (i) Eight to Fourteen Modulation (EFM)
   (2 marks)

   (ii) Reed-Solomon Code
   (2 marks)

   (iii) Interleaving
   (2 marks)

(b) A DVD is a storage technology which provides sufficient data capacity and data rate to store high quality standard-definition video. Given that a conventional audio compact disc (CD) can store up to 73 minutes of audio, derive the approximate number of hours of standard definition TV (SDTV) video that a DVD can store using all its available layers.
(5 marks)

(c) Assume that one day we will have 10 billion homes on planet earth, each home having one phone on average. If these phones were to transmit simultaneously over one 4 MHz line, using frequency division multiplexing (FDM), what is the bandwidth required? Could a single optical beam, with a spectral wavelength $\lambda$ = 1 μm, carry this multiplexed signal? (3 marks)

(d) Still using the same case of 10 billion phones and same spectral frequency, now assume digital modulation, with time division multiplexing (TDM) and a data rate of 64 kbps for each voice message. Demonstrate whether the single optical beam can carry this frequency or not.
(2 marks)

(e) A fibre telephone cable contains 144 fibres, at the T3 standard, implying each fibre is capable of carrying 672 voice messages. A conducting telephone cable contains 900 copper twisted pairs, and each pair can carry 24 messages. Compare the capacities of the fibre and conducting cables. How many of the conducting cables are required to equal the capacity of the fibre cable? Repeat the calculation if each fibre operates at the DS-4 standard (Note: DS-4 allows upto 4032 voice messages per fibre).
(4 marks)

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3. (a) Prove Johnson's thermal noise formula $\langle e_n^2 \rangle = 4kTR\Delta f$, where the symbols have all their usual meanings, by taking the following steps:

(i) Consider a resistor in parallel with a capacitor. Draw the equivalent circuit assuming the noisy resistor can be modelled by a single source in series with a lumped ideal resistor. Label the source $\langle e_n^2 \rangle$. Label the mean square noise across the capacitor Label the source $\langle v_n^2 \rangle$. Label the mean square noise current through the loop $\langle i_n^2 \rangle$. The angle brackets represent temporal averages.

(1 mark)

(ii) Apply Kirchhoff's voltage law (KVL) around the loop, and write down the equation in terms of time limited variables $e_n(t,\tau)$, $v_n(t,\tau)$ and $i_n(t,\tau)$, assuming that we sample these random signals for a finite time window of duration $\tau$. Here we assume the window is sufficiently long and that stationarity holds. Briefly explain what stationarity means.

(2 marks)

(iii) Assuming this equation is free of delta functions, now write down the same equation in terms of window-limited Fourier transformed variables, $V_n(\omega,\tau)$ and $I_n(\omega,\tau)$.

(1 mark)

(iv) By substituting in the relation $I_n(\omega,\tau) = j\omega C V_n(\omega,\tau)$ and then applying Plancherel's theorem (i.e. the energy theorem), prove that,

$$\langle e_n^2 \rangle = \lim_{\tau\to\infty} \frac{1}{2\pi} \int_0^{+\infty} 2\frac{|E_n(\omega,\tau)|^2}{\tau} d\omega .$$

(6 marks)

(v) Explain why we cannot take the limit inside the integral without first taking ensemble averages. Now, by assuming the system is ergodic, i.e. $\lim_{\tau\to\infty} \langle e_n^2 \rangle_\tau = \overline{e_n^2}$, where the overbar indicates ensemble averaging, show that,

$$\langle e_n^2 \rangle = \frac{1}{2\pi} \int_0^{+\infty} S(\omega) d\omega$$

where $S(\omega)$ is the one-sided power spectral density (PSD).

(3 marks)

(vi) Explain why for thermal noise, we can simply rewrite this expression as $\langle e_n^2 \rangle = \frac{1}{2\pi} S_0 \Delta\omega$, where $S_0$ is a constant PSD.

(1 mark)

(vii) By identical arguments to part (v), we can write down a similar expression for the mean square noise voltage across the capacitor as

$$\left\langle v_n^2 \right\rangle = \frac{1}{2\pi} \int_0^{+\infty} \lim_{\tau\to\infty} \frac{2\overline{V_n^2}}{\tau}\, d\omega .$$

Now, substitute this into $\left|V_n\right|^2 = \dfrac{\left|E_n\right|^2}{1+(\omega RC)^2}$, and then show that

$$\left\langle v_n^2 \right\rangle = \frac{1}{2\pi} S_0 \frac{\pi}{2RC} .$$

(2 marks)

(viii) From the equipartition theorem you may assume that $\frac{1}{2} C \left\langle v_n^2 \right\rangle = \frac{1}{2} kT$. Use this relation to now finally arrive at the thermal noise formula.

(2 marks)

(b) A laser diode has a RIN of -135 dB/Hz. A receiver bandwidth of 1 GHz and a received average power of 20 μW.

(i) Compute the laser noise power at the receiver.

(1 mark)

(ii) Compute the average laser noise current if the detector has a responsivity of 0.3 A/W.

(1 mark)

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4. Consider a single mode fibre operating at 1550 nm. The specification is to transmit 400 Mbps NRZ data over the 100 km fibre link with a bit error rate (BER) of $10^{-9}$ or better.

(a) Given that $\tau = 1/R_{NRZ}$ and allowing for the system rise time to be 70% of $\tau$, compute the system rise time $t_S$.

(1 mark)

(b) Given a material dispersion of $M$ = -20 ps/nm/km and a waveguide dispersion of $M_g$ = 4.5 ps/nm/km, compute the fibre rise time, $t_F$. The spectral linewidth is given as 0.15 nm.

(1 mark)

(c) If the rise time of the light source is $t_{LS} = 1$ ns, find an upper limit on the photodetector rise time $t_{PD}$.

(4 marks)

(d) Assume a basic BJT amplifier circuit at the receiver. If the photodetector has a transit time limited rise time of $t_{TR} = 0.5$ ns and a junction capacitance of $C_d = 1$ ,
calculate an upper limit on the load resistor. (2 marks)

(e) Given that the fibre loss is 0.25 dB/km, the coupling efficiency to the fibre is 3 dB, there are two connectors with 1 dB loss each, there are 50 splices with 0.1 dB loss each and that the source power is 5 dBm, find the power at the receiver.

(2 marks)

(f) Calculate the optical power needed to achieve the specified BER assuming a quantum limited system. Comment on the result. You may assume dark current is negligible and therefore the expression for probability of an error $P_e = e^{-n_s}$ holds. The quantum efficiency of the detector is $\eta$ = 0.7. (4 marks)

(g) Now calculate the optical power needed to achieve the specified BER assuming a thermal limited system. Comment on the result. You may assume a detector responsivity of $\rho$ = 1 A/W and a noise figure of $F$ = 2. Room temperature conditions hold, thus let $T$ = 300 K.

(6 marks)

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