National Exams – December 2017

98-Phys-B2, Electro-Optical Engineering

3 hours duration

NOTES:

1. If doubt exists as to the proper interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement about any assumptions made.
2. Candidates may use one of two calculators, the Casio or Sharp approved models.
3. This is a **"Closed-Book"** examination. The candidate may have a single 8.5 inch by 11 inch sheet (both sides) of hand-written notes as an aid for the examination.
4. Any **five** questions constitute a complete paper. Only the first five questions as they appear in your answer book will be marked.
5. All questions are of equal value. Marking scheme is on page 5.
6. This examination paper has 5 pages.

Values of common constants:

$\varepsilon_o = 8.854 \times 10^{-12}$ F/m

$\mu_o = 4\pi \times 10^{-7}$ H/m

$c = 2.998 \times 10^{8}$ m/s

$q = 1.602 \times 10^{-19}$ C

$h = 6.626 \times 10^{-34}$ J·s

$K = 1.381 \times 10^{-23}$ J/°K

0°K = -273°C

1 Å = 1.0×10^{-10} m

Si	$\varepsilon_r = 11.8$
Si	$n = 3.42$
Si	$E_g = 1.11$ eV
Ge	$\varepsilon_r = 16.0$
Ge	$n = 4.01$
Ge	$E_g = 0.67$ eV
GaAs	$\varepsilon_r = 13.2$
GaAs	$n = 3.63$
GaAs	$E_g = 1.41$ eV
InGaAsP	$n = 3.4$
$LiNbO_3$	$\varepsilon_r = 32$
$LiNbO_3$	$r = 30$ pm/V
$LiNbO_3$	$n_o = 2.30$

Useful formulas:

$$\int \frac{dx}{a^2 + x^2} = \frac{1}{a}\arctan\left(\frac{x}{a}\right)$$

$$P(n) = \frac{N^n \exp(-N)}{n!}$$

$$Al_xGa_{1-x}As \quad E_g(eV) = 1.424 + 1.266x + 0.266x^2$$

$$I_s = R_o\sqrt{P_o P_1}\cos\theta$$

$$n(E) = n_0 - \frac{1}{2} r n_0^{\,3} E$$

$$x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Question 1

A silica step-index fiber that is used for optical communication at a wavelength of 850 nm has a numerical aperture 0.2, a core refractive index 1.500 and a core diameter of 100 μm.

a) Calculate the maximum angle of acceptance in air for this fiber.
b) Calculate the maximum angle of acceptance if the fiber is immersed in water (water has refractive index 1.33).
c) What is the refractive index of the cladding layer?
d) How many modes does the fiber support?
e) Calculate the intermodal dispersion in the fiber (in units of [ns/km]).
f) What would the diameter of the fiber need to be to make it single mode?

Question 2

(a) Sketch the longitudinal cross-section of a PIN photodiode, clearly showing the different doped semiconductor regions and the metal electrodes defining the active region. For an applied reverse voltage, plot the charge distribution and electric field distribution in the device as a function of distance through the device. Clearly label important features of your plots. Explain operation of the device when light is incident upon the surface.

(b) If the PIN photodetector diode is reverse biased and has a load resistance R_L, write the equation governing the photocurrent when the diode is under illumination at a detectable wavelength. What is this mode of operation called? Sketch the IV curve.

(c) Sketch a typical responsivity curve for a Silicon photodetector vs. wavelength of incident light. Briefly explain the shape of the curve. Determine the band edge wavelength.

(d) A PIN photodetector has a response time τ given by

$$\tau^2 = \tau_{RC}^2 + \tau_{drift}^2$$

Explain each term on the right hand side of this equation. Why is there an optimum width for the intrinsic region of the device to minimize τ?

Question 3

A InGaAsP laser has a cavity length of 500 μm and a cavity width of 1.5μm. The depth of the lasing region is 35nm. The laser emits light at a wavelength of 1.55 μm and has a threshold current of 37.5 mA. The threshold electron concentration is 2.6×10^{18} cm^{-3}.
The material loss is 15 cm^{-1}.

a) What is the photon lifetime in the cavity?
b) What is the spontaneous carrier lifetime?
c) What is the mode spacing? If the optical gain bandwidth is 2 nm, how many modes exist?
d) If the laser is operated at three times the threshold current, what is the optical power output?

Question 4

A digital fiber optic system must transmit over a distance of 40km with a maximum bit-error rate (BER) of 10^{-12}. The baseband analog signal bandwidth is 100kHz. This signal is sampled at the Nyquist rate and converted into a 9 bit NRZ digital light pulse for transmission.

The following components are available:

Laser: InGaAs Fabry-Perot laser with an output power of 10 mW at $\lambda = 900$ nm.
Fiber: Multi mode step-index fiber with a diameter of 100 μm, core index 1.500, cladding index 1.495, and an attenuation of 3.5 dB/km at 900 nm.
Detector: Silicon avalanche diode, bandwidth = 1 GHz.

Coupling loss:
3 dB between the laser and the fiber, and
2 dB between the fiber and the detector.

The maximum permitted pulse broadening is half a bit period. The detector needs an average of minimum 400 photons/bit to achieve a BER value of 10^{-12} . The system security margin should be 5 dB.

a) What is the maximum distance between repeaters if the fiber system is dispersion limited?
b) What is the maximum distance between repeaters if the fiber system is attenuation limited?
c) How many repeaters are needed in the fiber system and how long is each link in the system? (Assume each repeater has the same available components as listed).
d) How many modes are present in the fiber?

Question 5

A longitudinal electro-optic Pockel cell modulator of $LiNbO_3$ is designed for digital amplitude pulse modulation of the red laser line (624 nm) from a HeNe laser. The crystal has cylindrical geometry with a diameter of 20mm and a length of 30 mm. The RC limited bandwidth of the modulator is 1.0 MHz, where R is the load resistance and C is the (parallel plate) capacitance of the crystal.

a) Make a sketch of the Pockel-cell modulator together with the necessary external components that are needed and explain its general operation.
b) Calculate the minimum "half-wavelength" voltage needed for the modulator.
c) What are the values for R and C?
d) What electrical power is needed to operate the modulator if a sinusoidal voltage supply is used?

Question 6 rework this one.

A *pin* diode operating at wavelength 0.83 μm has an external quantum efficiency of 50% and a dark current of 0.5nA at temperature 295K. The diode is loaded by a transimpedance amplifier having feedback resistor 50 kΩ and open loop gain 32. The diode has resistance 1MΩ and capacitance 1pF. The amplifier has input capacitance 6pF and input resistance 10MΩ. The desired post-detection bandwidth is 10 MHz.

(a) What is the diode's responsivity at wavelength 0.83 μm?

(b) What is the bandwidth of the diode-transimpedance amplifier combination? Is equalization necessary?

(c) If the required SNR is 55 dB, what incident optical power is required expressed in dBm?

Question 7

Consider an optimal graded index fiber with a core diameter of 30 μm and a refractive index of 1.474 at the center of the core and a cladding refractive index of 1.453. Suppose that the fiber is coupled to a laser diode operating at 1300 nm with a spectral linewidth (FWHM) of 3nm . The fiber has material dispersion coefficient -5ps km^{-1} nm^{-1} at this wavelength.

(a) Calculate the total dispersion

(b) Estimate the BL product for this fiber.

(c) Estimate the BL product for a multimode stepped index fiber having the same core radius, core/cladding indices, and material dispersion coefficient.

(d) Compare your answers for the two different fibers and explain the difference using sketches.

Question 1
Marking: 20 marks distributed as
(a) 3 marks
(b) 2 marks
(c) 3 marks
(d) 4 marks
(e) 4 marks
(f) 4 marks

Question2
Marking: 20 marks distributed as
(a) 6 marks
(b) 5 marks
(c) 4 marks
(d) 5 marks

Question 3
Marking: 20 marks distributed as
(a) 5 marks
(b) 5 marks
(c) 4 marks
(d) 6 marks

Question 4
Marking: 20 marks distributed as
(a) 5 marks
(b) 6 marks
(c) 5 marks
(d) 4 marks

Question 5
Marking: 20 marks distributed as
(a) 5 marks
(b) 5 marks
(c) 5 marks
(d) 1 marks
(e) 4 marks

Question 6
Marking: 20 marks distributed as
(a) 6 marks
(b) 7 marks
(c) 7 marks

Question 7
Marking: 20 marks distributed as
(a) 5 marks
(b) 4 marks
(c) 4 marks
(d) 4 marks
(e) 3 marks