

## ENEE 691 OPTICAL COMMUNICATION SYSTEMS

Second Examination, Thursday May 2, 2002, 2:00 - 3:15pm

ANSWER THREE (3) QUESTIONS. IF 4 QUESTIONS ARE ANSWERED, BEST 3 WILL COUNT

(1) Explain the concept of "chirp" in a semiconductor laser, and why it is worse in a directly modulated "ON-OFF" modulation scheme.

The time-dependent frequency change of a particular GaAlAs laser can be written as

$$\Delta\nu(t) = \frac{1}{\pi} \left[ \frac{d}{dt} \ln P(t) + P(t) \right],$$

where  $P$  is the power in mW from the laser. If the output from the laser is a train of almost half sinusoid shaped pulses, where for example one such pulse is

$$P(t) = \sin(\pi t/\tau) + \pi/6 \text{ mW, where } 0 \leq t \leq \tau.$$

Calculate  $\Delta\nu(t)$ .

For a single-mode fiber link with overall dispersion of 10ps/nm/km, estimate the chirp-limited maximum transmission distance if the bit rate  $B = 1/2\tau = 500\text{Mb/s}$ .

(2) Explain in some detail the device physics involved in a double heterostructure semiconductor laser and draw a diagram showing the essential construction details of one such laser of your choice.

What determines the output spectrum of the laser you have described?

(3) Calculate the minimum gain needed for a semiconductor laser to oscillate in which the end facets of the laser act as the mirrors, with  $n=3.5$ . The laser is  $100\mu\text{m}$  long, has distributed loss  $\alpha=10 \text{ m}^{-1}$ . Draw the typical  $P - i$  curve for such a laser.

The output power of a semiconductor laser as a function of current  $i$  is

$$P(i) = ai^2 + bi - c,$$

and the drive current is

$$i(t) = i_0(1 + m \sin \omega_m t).$$

Calculate the threshold current, and the relative second harmonic distortion (ratio of modulated power at frequency  $2\omega_m$  to that at  $\omega_m$ ). If  $a=0.1$ ,  $b=3$ ,  $c=0.2$ , what is the maximum value of  $m$  for less than 1% second harmonic distortion?

(4) Do 2 of the following:

(a) Explain the operation of a digital Mach-Zehnder electrooptic intensity modulator

(b) Calculate the received power in a free space optical link using a transmitter of power 100mW, Gaussian beam spotsize 20mm, beam divergence half angle 3mrad, and radial intensity profile

$$I(r) = I_0 e^{-2r^2/w^2},$$

when the distance to the receiver is 1km, the atmospheric power attenuation is 3dB/km, and the receiver aperture diameter is 100mm.

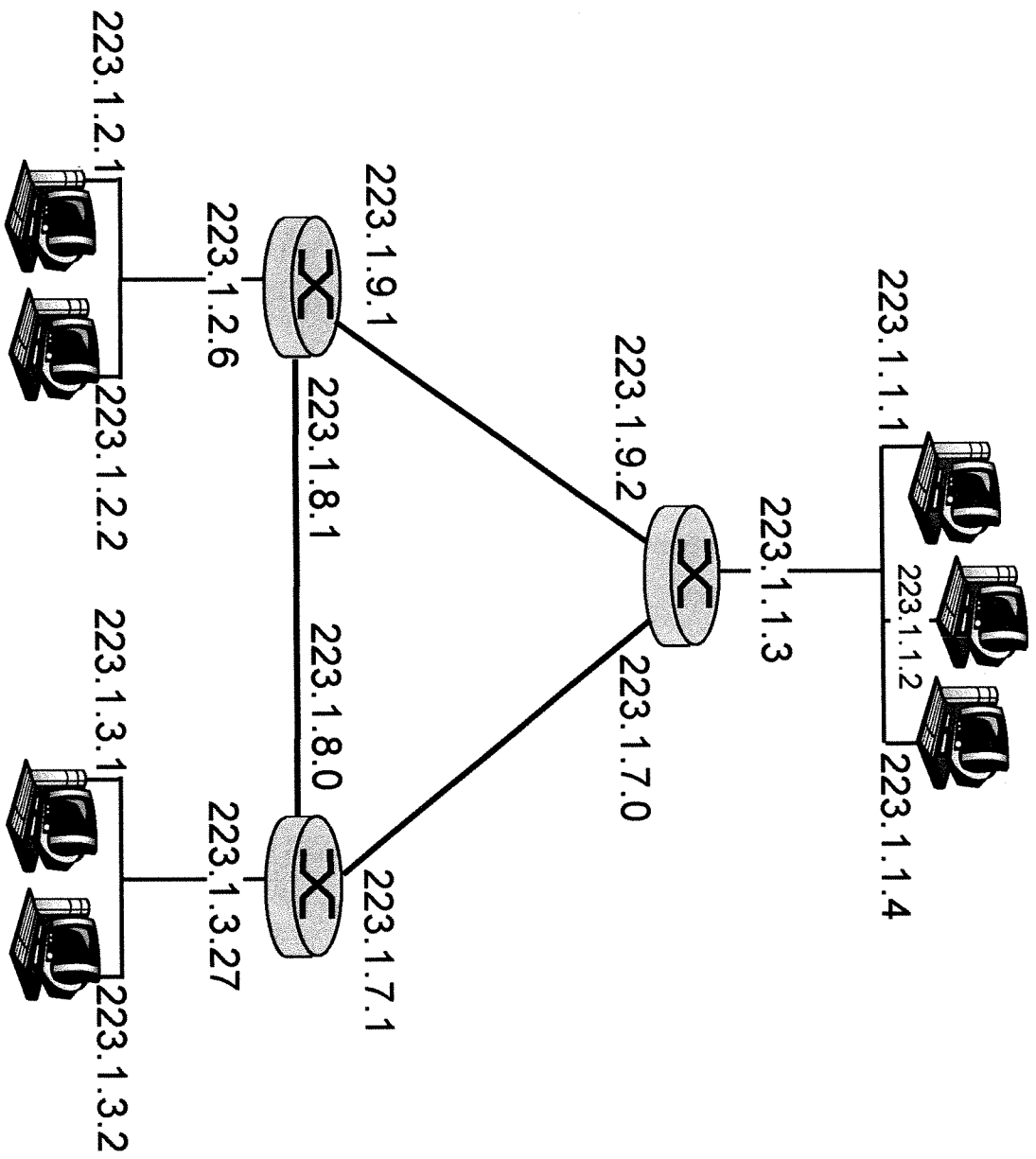
(c) For the network shown in the figure answer the following questions:

(i) How many networks are represented?

(ii) Justify and explain your answer (in terms of the IP addresses and interfaces)

(iii) Describe how a packet moves from host 223.1.2.1 to host 223.1.1.4

(iv) At what level of the Internet protocol stack does this switching take place?



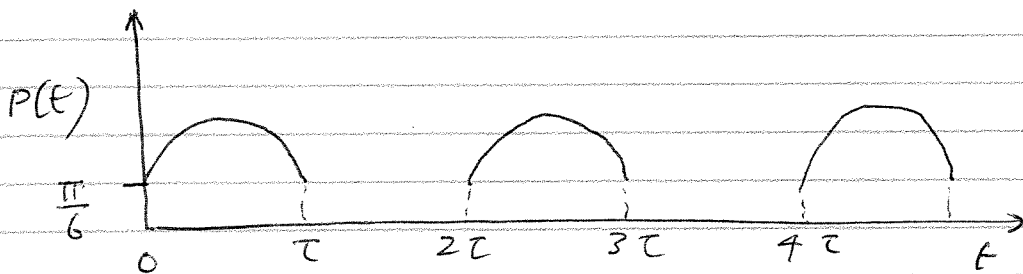
SOLUTIONS

(1) Chirp is  $\Delta \omega(t) = \frac{1}{\pi} \frac{d}{dt} \left[ -\ln P(t) + P(t) \right]$

$$P(t) = \sin\left(\frac{\pi t}{\tau} + \frac{\pi}{6}\right) \quad 0 \leq t \leq \tau$$

The bit rate  $B = \frac{1}{2\tau} = 500 \text{ Mb/s}$ .  $\tau = 1 \text{ ns}$

Clearly a waveform with all "ones" would be



$$\Delta \omega(t) = \frac{1}{\pi} \left[ \frac{\frac{\pi}{\tau} \cos\left(\frac{\pi t}{\tau} + \frac{\pi}{6}\right)}{\sin\left(\frac{\pi t}{\tau} + \frac{\pi}{6}\right)} + \sin\left(\frac{\pi t}{\tau} + \frac{\pi}{6}\right) \right]$$

The largest chirp is clearly at  $t=0$  &  $t=\tau$ , this is where the waveform has the largest derivative

$$\Delta \omega(0) = \frac{1}{\pi} \left[ \frac{\frac{\pi}{\tau} + \frac{\pi}{6}}{\frac{\pi}{6}} \right] = \frac{6}{\pi} \cdot 10^9 \text{ Hz}$$

$$\Delta \omega(5 \times 10^{-10} \text{ s}) = \frac{1}{\pi} + \frac{1}{6} \approx 0$$

$$\Delta \omega(\tau) = \frac{1}{\pi} \left[ \frac{-\frac{\pi}{\tau} + \frac{\pi}{6}}{\frac{\pi}{6}} \right] = -\frac{6}{\pi} \cdot 10^9 \text{ Hz}$$

So take  $|\Delta \omega|_{\max} = \frac{6}{\pi} \times 10^9 \text{ Hz}$

For this type of RZ waveform the effective bandwidth is  $\approx 10^9 \text{ Hz}$

So overall effective BW is  $10^9 \sqrt{\left(\frac{6}{\pi}\right)^2 + 1} = 2.16 \times 10^9 \text{ Hz}$

Use  $\lambda_0 = 810 \text{ nm}$ , this is a GaAlAs laser

$$\lambda = \frac{c}{\nu}, \quad \Delta\lambda = (-) \frac{c}{\nu^2} \Delta\nu = (-) \frac{\lambda^2}{c} \Delta\nu$$

$$\Delta\lambda = (-) \frac{(810 \times 10^{-9})^2}{3 \times 10^8} \cdot 2.16 \times 10^9 = 4.729 \times 10^{-12} \text{ m}$$

The maximum link length will be set by

$$(\Delta\tau)_{\text{dispersion}} \approx \tau$$

$$\text{So } \Delta\tau = 10^{-11} \times 4.729 \times 10^3 \times L = 10^{-9}$$

$$L = 2.12 \times 10^4 \text{ km}$$

$$(3) \quad \gamma_t = \alpha - \frac{1}{e} \ln \sqrt{R_1 R_2} \quad R = \left( \frac{3.5 - 1}{3.5 + 1} \right)^2 = 0.3086$$

$$\gamma_t = 10 - \frac{1}{10^{-4}} \ln(0.3086) \Rightarrow \gamma_t = 1.176 \times 10^4 \text{ m}^{-1}$$

$$\gamma_t = 11.76 \text{ mm}^{-1}$$

$$P(i) = a r_0^2 (1 + m \sin \omega_m t)^2 + b i_0 (1 + m \sin \omega_m t) - c$$

$$= a r_0^2 (1 + m^2 \sin^2 \omega_m t + 2m \sin \omega_m t) + b i_0 (1 + m \sin \omega_m t) - c$$

Remember  $\sin^2 \omega_m t = \frac{1}{2} (1 - \cos 2\omega_m t)$

$$P(i) = a r_0^2 \left[ 1 + \frac{m^2}{2} (1 - \cos 2\omega_m t) + 2m \sin \omega_m t \right] + b i_0 [(1 + m \sin \omega_m t)] - c$$

The required ratio second harmonic is fundamental

$$F = \frac{a r_0^2 \frac{m^2}{2}}{2m a r_0^2 + b i_0} \Rightarrow F = \frac{a m i_0}{4 a i_0 + b i_0}$$

For  $F = 0.01$ ,  $\frac{0.1 \text{ m}}{4 \times 0.1 + 6} = 0.01 \Rightarrow m = 0.69$

(4b) At the receiver  $w = L \theta_{\text{beam}} = 1000 \times 3 \times 10^{-3}$

$$w = 3 \text{ m}$$

The total power is  $P = I_0 \int_0^{\infty} 2\pi r e^{-2r^2/w^2} dr$

gives  $P = \frac{\pi w^2}{2} I_0 \Rightarrow I_0 = \frac{2P}{\pi w^2}$

The received power is  $P_{\text{recd}} = I_0 \int_0^a e^{-2r^2/w^2} 2\pi r dr$

$$P_{\text{recd}} = P \left[ 1 - e^{-2a^2/w^2} \right]$$

$$\frac{a}{w} = \frac{50}{3000} = \frac{1}{60} \quad \text{so} \quad P_{\text{recd}} = P \left( \frac{2a^2}{w^2} \right)$$

$$P_{\text{recd}} = \frac{10^{-1} \times 2 \times 0.5}{3600}$$

3dB/km  $\equiv$  0.5 factor

$$P_{\text{recd}} = 2.78 \times 10^{-5} \text{ W}$$

$$27.8 \text{ } \mu\text{W}$$

For the figure above, answer the following questions:

1. How many networks are represented?

Answer: 6

2. Justify your answer (in terms of the IP address and interface)

Answer: The IP address is associated with an interface for the routers and hosts. The set of nodes (routers and hosts) that have a common interface address (the third octet or position here; e.g., in 223.1.2.6, the "2") comprise a network.

3. Describe how a packet moves from host 223.1.2.1 to host 223.1.1.4

Answer: The packet has a source and destination address. The packet moves from interfaces of the two routers and arrives at the destination. Actual interface numbers should be used in the explanation, and forwarding should be mentioned.

4. At what layer of the Internet protocol stack does this switching take place?

Answer: Layer 3, the Network Layer.

# Getting a datagram from source to dest.

misc fields	223.1.1.1	223.1.2.2	data
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Starting at A, dest. E:

- look up network address of E
- E on *different* network
  - A, E not directly attached
- routing table: next hop router to E is 223.1.1.4
- link layer sends datagram to router 223.1.1.4 inside link-layer frame
- datagram arrives at 223.1.1.4
- continued.....

Dest. Net.	next router	Nhops
223.1.1		1
223.1.2	223.1.1.4	2
223.1.3	223.1.1.4	2

