OPTICAL COMMUNICATION SOLUTIONS 2003

(1) a) Need $V < 2.405$ CE

$$V = r_0 k_0 \sqrt{n_c^2 - n_{cl}^2} \cong \frac{r_0 2\pi}{\lambda_0} \sqrt{2n\,\Delta n}$$

$$2.405 = \left(3\mu m\,(2\pi)/1.502\mu m\right)\sqrt{2\times 3 \times \Delta n}$$

gives $\Delta n \cong 0.013$

b) Since the V number is proportional to $\sqrt{n_1^2 - n_2^2}$, raising the Δn will increase the number of supported modes BW

c) 1600 - 2000 nm is at the long wavelength side of the attenuation minimum, in this region interatomic vibrations dominate the loss, esp Si-O stretching vibration BW

d) For an LED we estimate ΔE to be $\sim 2kT$. At room temp this is $\sim 50\,meV$. The minimum energy will be $E_g \cong 1.24\,eV\cdot\mu m / 1.31\mu m = 0.947 eV$ CE

Then $\lambda_{min} \cong 1.24\,eV\cdot\mu m / (0.947 + .05) = 1.244\,\mu m$

$\Delta\lambda \cong 1310 - 1244 = \underline{66\ nm}$

e) Long haul systems work at ~ 1310 or 1550 nm wavelength. Si, with a bandgap of 1.1 eV, is transparent at those wavelengths BW

CE = computed example
BW = bookwork
NT = new theory
TA = theor. application

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f) 40 Gbit/s (purely memory this one!) BW
Limited by electronics & dispersion.

g) DFB lasers use gratings as the reflective elements to form the resonant cavity, which are λ selective, and so can have a much narrower spectrum than F-P lasers. BW

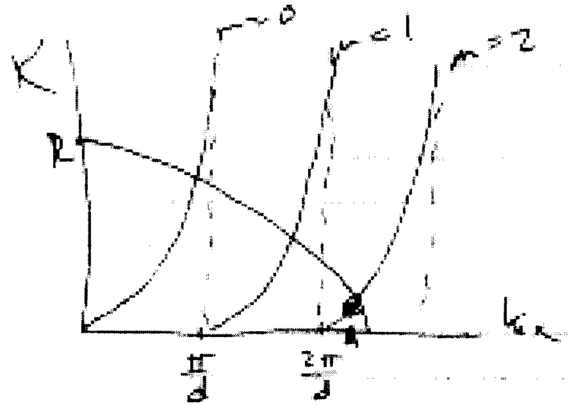
h) The maximum slope efficiency ($\eta = 1$) for a laser is $\frac{hc}{e\lambda}$. In this case CE

$$S_{max} = \frac{6.63\times10^{-34} \times 3.\times10^{8}}{1.6\times10^{-19} \times 0.78\times10^{-6}} = 1.59 \text{ W/A}$$

i) The pump laser λ must be $< \lambda_{signal}$, must correspond to a strong absorption band for Er that results in an efficient transition to the metastable state, and must be manufacturable as a high power laser diode. BW

j) Conservation of power applies. Input -10 dBm $= 0.1$ mW. First output port, -20 dBm $= 0.01$ mW, leaving 0.09 mW on the other output, $= -10.46$ dBm. CE

② a)



TA

$\frac{\pi}{d} = 0.5236 \times 10^6\ m^{-1}$

$k_{1x} = 1.19 \times 10^6\ m^{-1}$ is slightly $> 2\pi/d$

$\therefore\ m = 2$

$\frac{k_{1x} d}{2} = 3.57 \quad K = k_{1x} \tan\frac{k_{1x} d}{2} = 0.542 \times 10^6\ m^{-1}$

$\sqrt{k_{1x}^2 + K^2} = 1.308 \times 10^6 = R < 3\pi/d$

Therefore $m = 2$ is the highest mode

There are 3 modes, $m = 0, 1, 2$.

b) $n' = \frac{c}{v_p} = \frac{3}{2.027} = 1.480$

TA

$k_{1x}^2 + \beta^2 = n_c^2 k_0^2$

$(k_{1x}/k_0)^2 + n'^2 = n_c^2$

$n_c = \sqrt{1.480^2 + \left(\frac{1.19 \times 10^6}{2\pi}\right)^2} = 1.507$

c) $\frac{k_{1x} d}{2} = X \quad \frac{Kd}{2} = Y$

TA

$X^2 + Y^2 = (Rd/2)^2$

$Y^2 = X^2 \tan^2 X$

$X^2(1 + \tan^2 X) = \frac{X^2}{\cos^2 X} = (Rd/2)^2$

$X = \frac{Rd}{2} \cos X = \left(\frac{1.308 \times 6}{2}\right) \cos X = 3.924 \cos X$

From diagram we estimate that the $m=0$ solution has $\frac{k_{1x} d}{2} \cong \frac{\pi}{2}$. With this starting point,

trial and error gives $X = 1.247$

$k_{1x} = 2X/d = 0.4156 \times 10^6\ m^{-1}$

$n' = \sqrt{n_1^2 - \left(\frac{k_{1x}}{k_0}\right)^2} = 1.504$

(3)

a) $\tau_g = \frac{L}{c}\left(n - \lambda\, dn/d\lambda\right)$ NT

We can estimate $\Delta\tau_g$ in this case using 2 terms of the series expansion:

$$\Delta\tau_g \doteq \frac{d\tau_g}{d\lambda}\Delta\lambda + \frac{d^2\tau_g}{d\lambda^2}\frac{\Delta\lambda^2}{2}$$

$$\frac{d\tau_g}{d\lambda} = \frac{L}{c}\left(\frac{dn}{d\lambda} - \frac{dn}{d\lambda} - \lambda\frac{d^2n}{d\lambda^2}\right) = -\frac{L}{c}\left(\lambda\frac{d^2n}{d\lambda^2}\right)$$

$$\frac{d^2\tau_g}{d\lambda^2} = \frac{-L}{c}\left(\frac{d^2n}{d\lambda^2} + \lambda\frac{d^3n}{d\lambda^3}\right)$$

Taking $d^2n/d\lambda^2 = 0$:

$$|\Delta\tau_g| = (L/c)(\lambda\, d^3n/d\lambda^3)\,\Delta\lambda^2/2$$

b) $\sigma_R^2 = \sigma_o^2 + \sigma_D^2$, $\sigma_D = DL\cdot\sigma_\lambda$ TA

here $\sigma_\lambda \doteq \sigma_{\lambda s}$

$$\sigma_R^2 = \sigma_o^2 + (DL\sigma_{\lambda s})^2$$

$$(\sigma_R/\sigma_o)^2 = 1 + \left(\frac{DL\sigma_{\lambda s}}{\sigma_o}\right)^2 = 1.25^2 = 1.56$$

$(DL\sigma_{\lambda s}/\sigma_o) = 0.75$, need $\sigma_o > 1.33\, D\cdot L\cdot\sigma_{\lambda s}$

c) For transform limited pulses $\sigma_\omega\sigma_o = \frac{1}{2}$ NT

But $\sigma_\lambda/\lambda \doteq \sigma_\omega/\omega$, $\sigma_\lambda \doteq \frac{\lambda^2}{2\pi c}\sigma_\omega$

This gives $\sigma_\lambda = \frac{1}{2\sigma_o}\left(\frac{\lambda^2}{2\pi c}\right)$.

$\sigma_R^2 = \sigma_o^2 + A^2/\sigma_o^2$ where $A = DL\lambda^2/4\pi c$

$$\frac{\partial\sigma_R^2}{\partial\sigma_o} = 2\sigma_o - \frac{2A^2}{\sigma_o^3} = 0 \text{ for } \sigma_o = \sqrt{A}$$

So $\sigma_o = \sqrt{\frac{DL\lambda^2}{4\pi c}}$, giving $\frac{\sigma_R}{\sigma_o} = \sqrt{2}$.

4 a) $\eta = \frac{1}{1+\tau_{rr}/\tau_{nr}} = \frac{1}{1+1/5} = 0.833$ CE

b) The 4 mechanisms & solutions are: BW

i) light goes downward

– add a mirror at base, but need either a heterostructure or very short path length

ii) absorption before leaving semiconductor

– heterostructure used so bandgap is greater outside active region

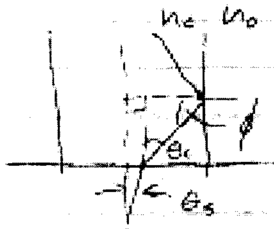
iii) surface (Fresnel) reflection

– antireflection coating, $\lambda/4$ thick, $n = \sqrt{n_1 n_2}$

iv) Total internal reflection

– add a dome of glass/plastic, or shape semiconductor surface to reduce angle.

c)



need $\sin\phi > n_o/n_c$

$\therefore \cos\phi < \sqrt{1-(n_o/n_c)^2}$

$\cos\phi = \sin\theta_c$ TA

$\sin\theta_c < \sqrt{n_c^2 - n_o^2}/n_c$

$n_s \sin\theta_s = n_c \sin\theta_c$

$\sin\theta_s < \sqrt{n_c^2 - n_o^2}/n_s$

Need $\theta_s < \sin^{-1}(NA/n_s)$ where $NA = \sqrt{n_c^2 - n_o^2} = 0.1$, $n_s \approx 3.5$, $\theta_{max} \approx 1.64°$

$f = \int_0^{\theta_{max}} 2\pi \sin\theta \, d\theta \Big/ \int_0^{\pi} 2\pi \sin\theta \, d\theta$

$= [\cos\theta]_0^{\theta_{max}} \big/ [\cos\theta]_0^{\pi} = (1-\cos\theta)/2 \approx \theta^2/4$

$f \approx \sin^2\theta/4 = \frac{NA^2}{4 n_s^2} = \frac{.1^2}{4(3.5)^2} = .00020$

d) $\tau = L/v_g$ $\Delta\tau_g \approx \Delta n L/c$ TA

$= n' L/c$ Need $\Delta\tau_g < \left(\frac{1}{4}\right)\frac{1}{B}$

gives $B < c/4L\Delta n$

5

a) Shot noise is given in terms of equivalent photocurrent per $\sqrt{\Delta f}$ as

$I_s^* = \sqrt{2eI_{ph}}$ TA

We need to convert this to be expressed w.r.t. received optical power Φ_R. Assuming $\eta = 1$, $I_{ph} = e\Phi_R/h\nu = e\lambda\Phi_R/hc$

then $\Phi_s^* = \frac{hc}{e\lambda}\sqrt{2e^2\lambda\Phi_R/hc} = \sqrt{2hc\Phi_R/\lambda}$

$\Phi_s^* = 5\,pW/\sqrt{Hz}$ for

$$(5\times10^{-12})^2 = \frac{2(1.6\times10^{-19})^2\, 1.5\times10^{-6}\,\Phi_R}{6.65\times10^{-34}\times3\times10^{8}}$$

$\Phi_R = 94\,\mu W$

b) $SNR = \dfrac{\Phi_R}{[NEP + \Phi_s^*](\Delta f)^{1/2}}$ TA

$SNR = 10\,dB = 10$, $\Phi_s^* = \sqrt{\dfrac{2e^2\lambda\Phi_R}{hc}}$

$\Delta f = B/2$

Where receiver noise dominates:

$10 \simeq \dfrac{\Phi_T e^{-\alpha L}}{NEP\sqrt{B/2}}$, $\dfrac{10^2 B}{2} = \left(\dfrac{10^{-2} e^{-\alpha L}}{5\times10^{-12}}\right)^2$

$B = 8\times10^{16} e^{-2\alpha L}$

$\alpha = \dfrac{dB/km}{4.3} = 0.1\,km^{-1}$

$\log B = 16.9 - 0.2L\log e = 16.9 - .087L$

Where shot noise dominates:

$SNR \simeq \dfrac{\Phi_R}{\sqrt{\dfrac{2hc\Phi_R}{\lambda}}\sqrt{\Delta f}}$ $10\sqrt{\dfrac{B}{2}} = \sqrt{\dfrac{\lambda\Phi_R}{2hc}}$

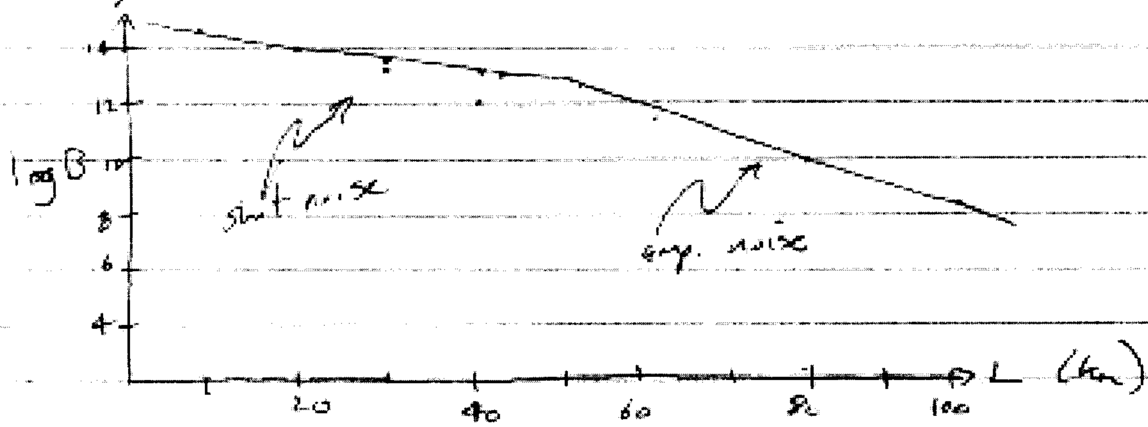
$B = \dfrac{\lambda\Phi_T e^{-\alpha L}}{100hc}$ $\log B = \log\left(\dfrac{1.5\times10^{-6}\times10^{-2}}{100\times6.6\times10^{-34}\times3\times10^{8}}\right)$

$- 0.1L\log e$

(5) b) (continued)

For shot noise case

$$\log B = 14.9 - .043L$$



c) With the amplifier, Φ_R increases by 20dB, NEP is unaffected where NEP dominates: 7A

$$\frac{10^2 B}{2} = \left(\frac{e^{-\alpha L}}{5\times10^{-12}}\right)^2 \qquad B = e^{-.2L}\times 8\times10^{20}$$

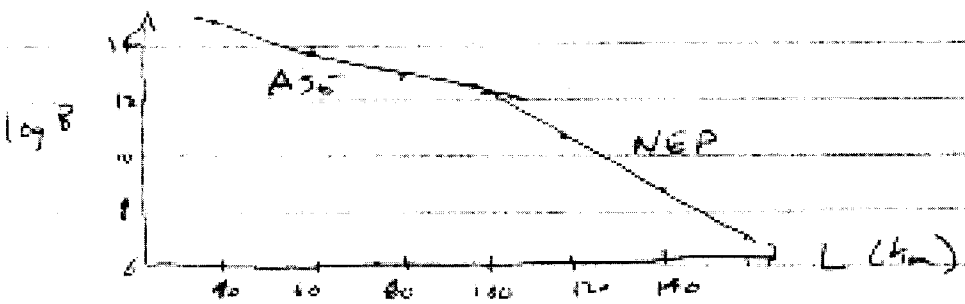
$$\log B = 21 - 0.087L$$

For the shot/ASE case:

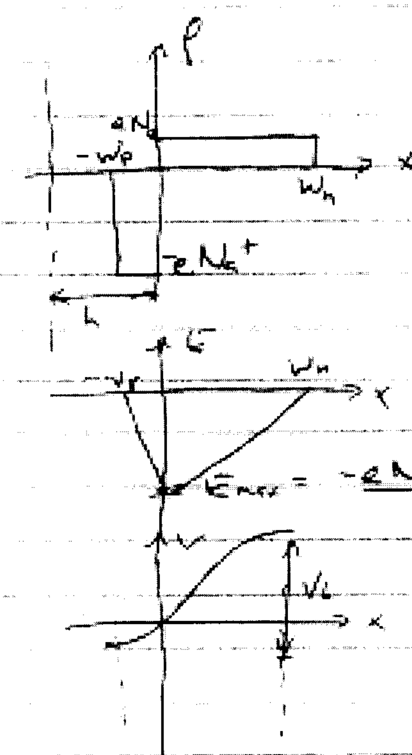
4 dB is a ratio of 2.5 in electrical SNR, 1.58 in optical SNR.

$$\frac{10^2 B}{2} = \frac{1}{2.5}\left(\frac{1.5\times10^{-6}\, e^{-\alpha L}}{2\times 6.6\times10^{-34}\times 3\times10^{8}}\right)$$

$$B = 3\times10^{16} e^{-.1L} \qquad \log B = 16.5 - .043L$$



6 a) 7A



$\mathcal{E}_{max} = \frac{-eN_A^+ w_p}{\varepsilon} = \frac{-eN_D w_n}{\varepsilon}$

$V_b = |\mathcal{E}_{max}|(w_n + w_p)/2$

$w_n = \frac{N_A^+}{N_D} w_p \qquad V_b = \left(\frac{eN_A^+ w_p}{\varepsilon}\right)\left(\frac{N_A^+}{N_D} + 1\right) w_p / 2$

$V_b = \frac{eN_A^+}{2\varepsilon}\left(\frac{N_A^+}{N_D} + 1\right) w_p^2 = \frac{1.6\times10^{-19}\times10^{20}}{2\times17\times8.85\times10^{-12}}(6)\, w_p^2$

$w_p = 1.49\sqrt{V_b}$ (in μm)

$w_p = 10$ μm for $V_b = 45.2$ V

$W = (5+1)w_p = 8.9\sqrt{V_b} = 10$ μm for $V = 1.25$ V

b) 7A

$\eta = e^{-\alpha x_1} - e^{-\alpha x_2}$

$x_1 = h - w_p \qquad x_2 = h + w_n$

$\eta = e^{-\alpha(h - w_p)} - e^{-\alpha(h + 5w_p)}$

$= e^{-\alpha h}\left(e^{\alpha w_p} - e^{-\alpha 5 w_p}\right) \qquad \alpha h = 10^5\times10^{-5} = 1$

$\eta = e^{-1}\left(e^{1.49\times10^5\sqrt{V_b}} - e^{-7.45\times10^5\sqrt{V_b}}\right)$

To get $\eta = 0.9$: $0.9e = e^{\alpha w_p} - e^{-5(\alpha w_p)} = 2.446$

gives $\alpha w_p = 0.9$ $w_p = 0.9\times10^{-5}$ m $= 9$ μm $= 1.49\sqrt{V_b}$

$V_b = 36.5$ V

(b)

c) If $R \propto (\text{residual } p \text{ thickness})^{-1}$ then NT

$$R = \frac{A}{h - w_p}$$

and we know $C \propto \frac{1}{w_n + w_p}$ ie. $C = \frac{B}{w_n + w_p}$

But $w_n + w_p = 6 w_p$

$$RC = \frac{AB/6}{(h - w_p) w_p}$$

$\frac{\partial RC}{\partial w_p} = 0$ at $\frac{\partial \left(\frac{1}{RC}\right)}{\partial w_p} = 0 = \frac{6}{AB}(h - 2w_p)$

$w_p = \frac{h}{2} = 5 \mu m$