AUDITORNE

(9.) Promatramo prijamnike sa dominirajućim toplinskim šumom, dom. kvantnim šumom i s opt. pretpojačalom. Odredit osjetljivost prijamnika u sva 3 slučaja ako promatramo mjesečnost signala brzinom 10 Gb/s uz BER $= 10^{-9}$ i na valnoj duljini 1.55 μm. Kvantna dpl. $\eta = 80\%$ Faktor dodatnog šuma $F_A = 3$. $n_{sp} = 1.5$ kod opt. pojačala, a kod PIN diode jednak broj fotona je 10x veći nego kod dom. kvantnog šuma.

$BER = 10^{-9} \Leftrightarrow Q = 6$

$$\overline{P_{pr}} = \frac{1}{2}\bar{n} h\nu \cdot \frac{1}{T} = \frac{1}{2}\frac{\bar{m} \cdot c}{\eta \cdot \lambda} h \cdot B_o$$

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

a) APD - kvantni šum

$$\begin{cases} \frac{S}{N} = \frac{I^2}{\sigma_K^2 + \sigma_T} = \frac{I^2}{\sigma_K^2} \\ Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0} \cong \frac{I_1}{\sigma_K} \end{cases}$$

→ zanemarujemo signal u nuli

$\sigma_K + \sigma_T \quad \sigma_1$

$$\Rightarrow \boxed{\frac{S}{N} = Q^2}$$

$$\frac{S}{N} = \frac{\bar{m}}{F_A} \Rightarrow \bar{m} = \left(\frac{S}{N}\right) \cdot F_A = Q^2 F_A$$

$$\overline{P_{pr}} = \frac{1}{2}\frac{ch}{\eta\lambda} \cdot Q^2 \cdot F_A \cdot B_o = 86.57 \text{ nW}$$

$$= -40.6 \text{ dBm}$$

$(-46.8??)$

b) PIN – termički šum

$$\frac{S}{N} = \frac{I^2}{\sigma_k^2 + \sigma_T^2} = \frac{I^2}{\sigma_T^2}$$

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} = \frac{I_1}{2\sigma_T}$$

$\sigma_k + \sigma_T$; σ_T

$$\frac{S}{N} = 4Q^2$$

$$\left(\frac{S}{N}\right)_{KVANTNI} = Q^2 = \overline{m}_{KVANTNO}$$

$$\overline{m}_{PIN} = 10 \cdot \overline{m}_{KVANTNI} = 10 \cdot Q^2 = 10 \cdot 6^2 = 360$$

$$\overline{P_{pr}} = \frac{1}{2} \frac{\overline{m}}{\eta} \frac{c}{\lambda} h \cdot B_0 = 289\,mW = +35.4\,dBm$$

APD je optimalniji, treba manja snaga da radimo s istim BER-om nego kod PIN

c) PIN dioda + pretpojačalo

– dominantan kvantni šum

$$\frac{S}{N} = Q^2$$

$$\frac{S}{N} = \frac{G \cdot P_{ul}}{4 \cdot S_{sp} \Delta f} \cdot \eta$$

$$S_{sp} = (G-1) n_{sp} h\nu$$

↳ spektralna gustoća

$$\frac{S}{N} = \frac{G P_{ul}}{4(G-1) n_{sp} h\nu \Delta f} \cdot \eta = \frac{P_{ul}}{4 n_{sp} \cdot h\nu \Delta f} \eta = \quad (P_{ul} = 2 \cdot \overline{P_{pr}})$$

$$\left[\frac{G}{G-1} \approx 1 \quad \text{(veliko pojačanje)}\right]$$

$$= \frac{2 \overline{P_{pr}} \eta}{4 n_{sp} h\nu \Delta f} \quad (\Delta f = \frac{B_0}{2}) = \frac{S}{N} = Q^2$$

$$\overline{P_{pr}} = \frac{1}{\eta} Q^2 n_{sp} h\nu B_0 = -40.63\,dBm$$

se sastoji od opt. predpoj. i PIN diode.
... prijenosa R 2.5 Gb/s $\lambda = 1.55\,\mu m$, $n_{sp} = 2$
... opt. pojačala a kvantna djel. PIN diode je 85%
Ako je BER 10^{-12} odredi osjetljivost prijamnika.
Ako je srednja snaga odašiljača 1 mW odredi min. i maks. duljinu trase, s tim da su gušenja $\alpha = 0.2\,dB/km$
ako je opterećenje prijamnika na 0.1 mW

$$\left(\frac{S}{N}\right) = Q^2$$

$$\left(\frac{S}{N}\right) = \frac{G P_{ul}}{4 S_{sp} \Delta f} \eta = \frac{G P_{ul} \eta}{4(G-1) n_{sp} h \nu \Delta f} = \dots \Rightarrow$$

(idealni prijemnik)

$$\overline{P_{pl}} = -44.32\,dBm$$

$$P_{pr\,max} = 0.1\,mW = -10\,dBm$$

$$\overline{P_{odaš}} = 1\,mW = 0\,dBm$$

[odašiljač] —— ? —— [dioda]

0 dBm

−10 dBm

−44.32 dBm

$$L_{min} = \frac{(\overline{P_{od}} - \overline{P_{pr\,max}})}{\alpha} = \frac{0 - (-10)}{0.2} = 50\,km$$

$$L_{max} = \frac{(\overline{P_{od}} - P_{pr\,min})}{\alpha} = \frac{0 - (-44.32)}{0.2} = 221.6\,km$$

ZADAC 1

$$\frac{\Delta T}{L} = \frac{n_1}{n_2}\frac{\Delta n}{c} \Rightarrow \frac{\Delta T}{L} = \frac{\Delta n}{c} \Rightarrow \Delta n = \frac{c\Delta T}{L}$$

$n_1 \approx n_2$

(11.) $\frac{\Delta T}{L} = 10\ ns/km$

$n_1 = 1.46$

$L = 10\ km$

$$\Delta n = 3\cdot 10^8 \frac{m}{s} \cdot 10 \frac{10^{-9}}{10^3} = 3\cdot 10^{-3}$$

$$NA = \sqrt{2n\Delta n} = 0.0936$$

$$B_0 L \leq \frac{1}{2}\frac{n_2}{n_1}\frac{c}{\Delta n} \approx \frac{1}{2}\frac{c}{\Delta n} = 5\cdot 10^{10}\ m/s$$

$$B_0 \leq \frac{5\cdot 10^{10}}{10^4} = 5\ Mb/s$$

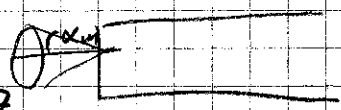
(12.)

$\Delta n = n_1 - n_2$

$\alpha_m > 7°$

$B_0 L \geq 20 \frac{Mb}{s} km$

$n_1 = 1.46$



$NA \overset{del}{=} \sin\alpha_m = 0.12187$

$NA = \sqrt{2n\Delta n} > 0.12187$

$$\Rightarrow \Delta n > \frac{\sin^2\alpha_m}{2n_1} = 0.005086$$

$$B_0 L = \frac{c}{2\Delta n} > 20\ Mb/s\ km$$

$$\Delta n < \frac{c}{2B_0 L} = 0.0075$$

$\Delta n \in \langle 0.0051, 0.0075 \rangle$

$\alpha_m \in \langle 7°, 8.51° \rangle$

$B_0 L_{MAKS} \in \langle 20 \frac{Mb}{s} km, 29.5 \frac{Mb}{s} km \rangle$

(13) $2a = 50\ \mu m$

$\Delta = \frac{\Delta n}{n} = 0{,}01$

$n_1 = 1{,}46$

$\lambda_0 = 1{,}3\ \mu m$

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} a \sqrt{\underbrace{(n_1 - n_2)}_{\Delta n}(n_1 + n_2)} \overset{\approx 2n_1}{} = 24.95$$

$\Delta n = 0.01\, n$

$$M = \frac{\alpha}{\alpha + 2} \cdot \frac{V^2}{2} = (\alpha \approx \infty) \approx \frac{V^2}{2}$$

$$M \approx \frac{V^2}{2} = 311 \text{ modova}$$

$V < 2.405$

$$\frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} < 2.405$$

(14) $n_1 = 3.6$

$n_2 = 3.55$

$\lambda = 1.3\ \mu m$

$\Theta = 85°$

$$\operatorname{tg}\left(\frac{\pi n_1 d \cos\Theta}{\lambda} - \frac{m\pi}{2} \right) = \frac{\sqrt{n_1^2 \sin^2\Theta - n_2^2}}{n_1 \cos\Theta}$$

($m = 0$ (osnovni, dominantni mod))

$$M = 1 + \operatorname{int}\left\{ 2\frac{d}{\lambda} \sqrt{n_1^2 - n_2^2} \right\}$$

$$\frac{d}{\lambda} = \frac{1}{\pi n_1 \cos\Theta} \operatorname{arctg}\left(\frac{\sqrt{n_1^2 \sin^2\Theta - n_2^2}}{n_1 \cos\Theta} \right) =$$

$$= \frac{1}{\pi \cdot 3.6 \cos 85°} \underbrace{\operatorname{arctg}\left(\frac{\sqrt{3.6^2 \sin^2 85° - 3.55^2}}{3.6 \cos 85°} \right)}_{\text{u radijanima}}$$

$$\frac{d}{\lambda} = 1.033$$

$M = 1 + \operatorname{int}\{1.235\} = 2 \rightarrow$ šire se 2 moda

имеет одномодовый:

$$2\frac{d}{\lambda}\sqrt{n_1^2-n_2^2} < 1 \Rightarrow d < 1.087\,\mu m$$

(15.) $n_1 = 3.6$
$n_2 = 3.57$
$\lambda = 1.55\,\mu m \Rightarrow TE_0$ (1 мода)
$\lambda = 1.3\,\mu m \Rightarrow TE_0, TE_1$ (2 моды)

a) $\lambda_1 = 1.55\,\mu m$

$$2\frac{d}{\lambda_1}\sqrt{n_1^2-n_2^2} < 1 \Rightarrow d < 1.296\,\mu m$$

b) $\lambda_2 = 1.3\,\mu m$

$$1 < 2\frac{d}{\lambda_2}\sqrt{n_1^2-n_2^2} < 2 \Rightarrow 1.087\,\mu m < d < 2.174\,\mu m$$

$\Rightarrow 1.087\,\mu m > d > 1.296\,\mu m$

(16.) $n_1 = 1.48$
$n_2 = 1.46$
$\lambda = 1.55\,\mu m$
$M = 4$ (TE) моды

$\theta_3 \simeq \theta_c$

$$\theta_c = \arcsin\frac{n_1}{n_2} = 80.57^\circ$$

$$\operatorname{tg}\left(\frac{\pi n_1 d\cos\theta_c}{\lambda} - \frac{m''_{II}}{2}\right) = \frac{\sqrt{n_1^2\sin^2\theta_c - n_2^2}}{n_1\cos\theta_c}$$

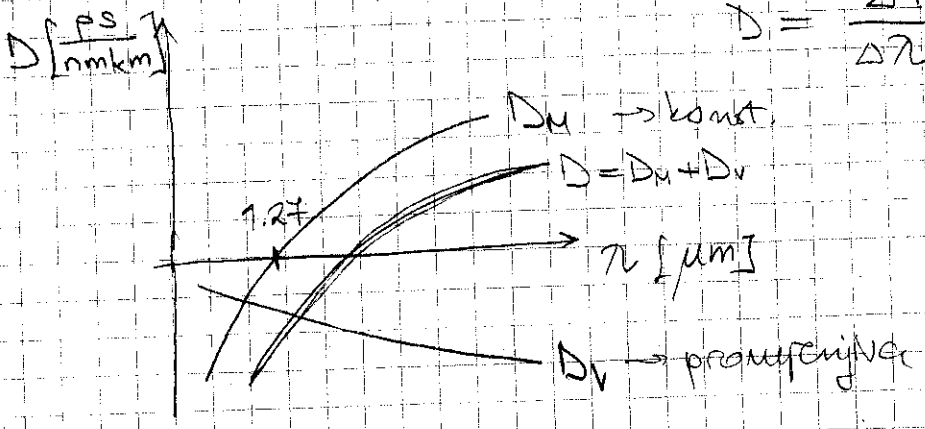
$$\Rightarrow d = \left\{\operatorname{arctg}\left[\underbrace{\frac{\sqrt{n_1^2\sin^2\theta_c - n_2^2}}{n_1\cos\theta_c}}_{=0 \text{ при } \sin\theta_c = \frac{n_2}{n_1}}\right] + \frac{3\pi}{2}\right\} \cdot \frac{\lambda}{\pi n_1\cos\theta_c}$$

$$d = \frac{3\pi}{2}\cdot\frac{\lambda}{\pi n_1\cos\theta_c} = 9.59\,\mu m$$

17.

$D = D_M + D_V$ → valovodna
↳ materijalna

$$D = \frac{\Delta T}{\Delta\lambda L} \left[\frac{ps}{nm\,km}\right]$$



$$D_M \cong 122\left(1 - \frac{\lambda_{ND}}{\lambda}\right)$$

$$D_V = -\frac{\Delta n}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

D_V (iz grafa na služb. šal.)

$V = 2 \Rightarrow$

$$\Rightarrow V\frac{d^2(Vb)}{dV^2} = 0.5$$

$V = 1.5 \rightarrow$

$$\Rightarrow V\frac{d^2(Vb)}{dV^2} = 1.1$$

nulta disperzija

$$D_M = 122\left(1 - \frac{\lambda_{ND}}{\lambda}\right) = 122\left(1 - \frac{1.27}{1.55}\right) = 22\ \frac{ps}{nm\cdot km}$$

$V = 1.5 \Rightarrow D = 0 \Rightarrow D_V = -22\ \frac{ps}{nm\cdot km}$

$2a = ?$

$$D_V = -\frac{\Delta n}{c\lambda}\left(V\frac{d^2(Vb)}{dV^2}\right)_{=1.1} \Rightarrow \Delta n = -D_V\frac{c\lambda}{V\frac{d^2(Vb)}{dV^2}} = 0.0093$$

$$V = \frac{2\pi}{\lambda} a\sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} a\sqrt{(n_1 - n_2)(n_1 + n_2)} \Rightarrow$$

$$V \cong \frac{2\pi}{\lambda} a\sqrt{\Delta n \cdot 2n_1}$$

$$2a = \frac{V\lambda}{\pi\sqrt{\Delta n \cdot 2n_1}} = 4.5\ \mu m$$

$2a = 9\,\mu m$

$n_1 = 1.46$

$n_2 = 1.458$

$\lambda_{ND} = 1.27\,\mu m$

$L = 50\,km$

$\Delta\lambda = 5\,nm$

$\lambda = 1.55\,\mu m$

$D = \frac{\Delta T}{\Delta\lambda \cdot L} \Rightarrow \Delta T = |D|\,\Delta\lambda \cdot L = |D_M + D_V| \cdot \Delta\lambda \cdot L$

$D_M = 122\left(1 - \frac{\lambda_{ND}}{\lambda}\right) = 122\left(1 - \frac{1.27}{1.55}\right) = 22.04\ ps/nm\,km$

$D_V = -\frac{\Delta n}{c\lambda} V \frac{d^2(Vb)}{dV^2}$

$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{9\pi}{1.55}\sqrt{1.46^2 - 1.458^2} = 2.03$

$\Rightarrow V\frac{d^2(Vb)}{dV^2} = 0.5$ (očitamo iz grafa)

$D_V = -\frac{0.002}{3\cdot 10^8 \cdot 1.55\cdot 10^{-6}} \cdot 0.5 = -2.15\cdot 10^{-6} = -2.15\ \frac{ps}{nm\cdot km}$

$$\frac{ps}{nm\cdot km} = \frac{10^{-12}\,s}{10^{-9}\,m \cdot 10^{3}\,m} = 10^{-6}\ \frac{s}{m^2}$$

$D = D_M + D_V = 22.04 - 2.15 = 19.89\ ps/nm\cdot km$

$\Delta T = |D| \cdot \Delta\lambda \cdot L = 19.89\left[\frac{ps}{nm\cdot km}\right] \cdot 5\,[nm] \cdot 50\,[km] =$

$= 4972.5\,ps = 4.97\,ns$

$B_0 \le \frac{1}{2\Delta T} = \frac{1}{2|D| \cdot L \cdot \Delta\lambda} = \frac{1}{2\cdot 4.97\cdot 10^{-9}} \cong 100\ Mbit/s$

→ zbog $\Delta\lambda$ je maks. brzina tako mala

(19.) DCF svetlovod

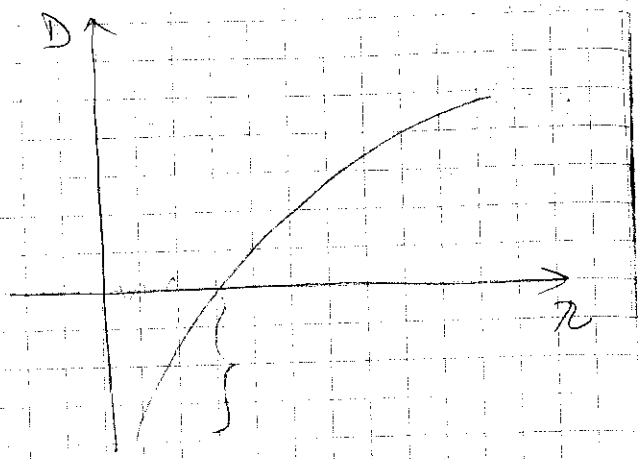
$L = 80\ km$

$D = 18\ ps/nm.km$

$\alpha = 0.2\ dB/km$

$D_{DCF} = -104\ ps/nm.km$

$\alpha_{DCF} = 0.5\ dB/km$



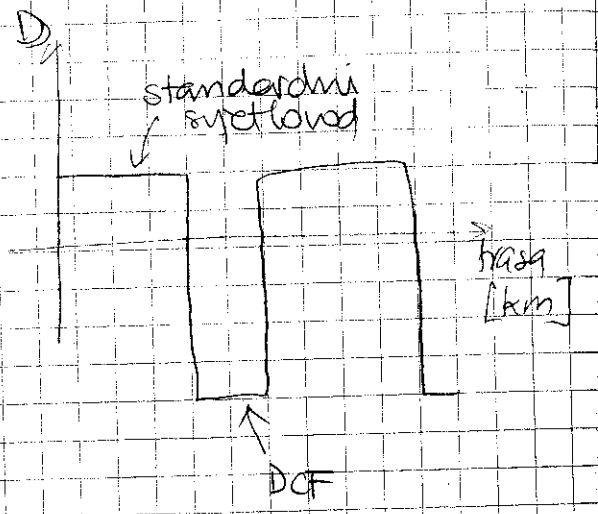
$\Delta T = \Delta\lambda \cdot |D| \cdot L$

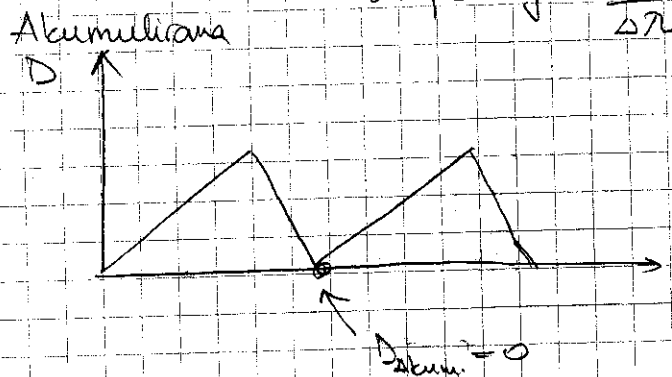
$DCF \approx -100\ ps/nm.km$

Ako D varira duž trase:

$$\Delta T = \Delta\lambda \int_{trasa} D(z)\,dz$$

akumulirana disperzija $\frac{\Delta T}{\Delta\lambda}$





$$D_{Akum} = \int D(z)dz = \int_0^L D\,dz + \int_L^{L+L_{DCF}} D_{DCF}\,dz = \boxed{D \cdot L + D_{DCF} \cdot L_{DCF} = 0}$$

$$L_{DCF} = -\frac{D \cdot L}{D_{DCF}} = -\frac{18 \cdot 80}{-104} = 13.85\ km$$

Gušenje prije DCF-a:

$$g = \alpha \cdot L = 0.2 \cdot 80 = 16\ dB$$

Gušenje poslije DCF-a:

$$g = \alpha_{DCF} \cdot L_{DCF} + \alpha \cdot L = 0.5 \cdot 13.85 + 0.2 \cdot 80 =$$

$$= 22.9\ dB$$

$\lambda = 1.55\,\mu m$

$L = 100\,km$

$D = 17\,ps/nm\cdot km$

$\alpha = 0.2\,dB/km$

$\frac{\partial D}{\partial \lambda} = 0.056\,ps/nm^2 km$

$D_{DCF} = -104\,ps/nm\,km$

$\alpha_{DCF} = 0.5\,dB/km$

$\frac{\partial D_{DCF}}{\partial \lambda} = -0.35\,ps/nm^2 km$

$\lambda_1 = 1.5\,\mu m,\ \lambda_2 = 1.6\,\mu m$

$$D(\lambda) = D(\lambda_0) + \frac{\partial D}{\partial \lambda}\Big|_{\lambda=1.55} \cdot (\lambda - \lambda_0)$$

($\lambda_0 \uparrow 1.55$)

1. korak:

$$L_{DCF} = -\frac{D\cdot L}{D_{DCF}} = -\frac{17\cdot 100}{-104} = 16.346\,km$$

2. korak:

a) $D_{Akum}|_{\lambda_0 = 1.5\mu m} = D(\lambda)\cdot L + D_{DCF}(\lambda) L_{DCF} =$

$$= \left(D(\lambda_0) + \frac{\partial D}{\partial \lambda}\Big|_{\lambda_0}\right) L\cdot\Delta\lambda + \left(D_{DCF}(\lambda_0) + \frac{\partial D_{DCF}}{\partial \lambda}\Big|_{\lambda_0}\right) L_{DCF}\Delta\lambda$$

$\left(D(\lambda_0) + D_{DCF}(\lambda_0)\right) = 0$

$$D_{Akum}|_{\lambda_0} = \frac{\partial D}{\partial \lambda}\Big|_{\lambda_0} L\Delta\lambda + \frac{\partial D_{DCF}}{\partial \lambda}\Big|_{\lambda_0} L_{DCF}\Delta\lambda$$

$$= 0.056\cdot(1500-1550)\cdot 100 - 0.35\cdot(1500-1550)\cdot 16.346$$

$$= -280 + 286 = 6\,\frac{ps}{nm}$$

$D_{Akum}(\lambda = 1.5\mu m) = 6\,\frac{ps}{nm}$ //

b) $\lambda_0 = 1.6\,\mu m$

$$D_{Akum}|_{\lambda_0} = \frac{\partial D}{\partial \lambda}\Big|_{\lambda_0} L\cdot\Delta\lambda + \frac{\partial D_{DCF}}{\partial \lambda}\Big|_{\lambda_0} L_{DCF}\cdot\Delta\lambda = -6\,\frac{ps}{nm}$$

Ukupno gušenje:

$$\alpha\cdot L + \alpha_{DCF}\cdot L_{DCF} = 20 + 8.173 = 28.173\,dB$$