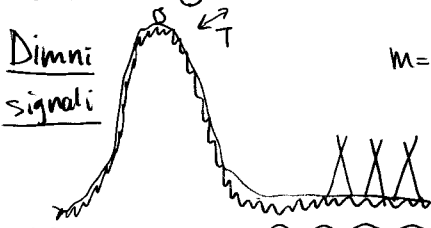


Optične komunikacije #1

20/2/2014

ŠUM
Dimni signali



$$I = \frac{1}{2} \log_m \left(1 + \frac{W_s}{W_n} \right)$$

$m = \text{nabor znakov}$

$$I = \frac{1}{2} \log_2 \left(1 + \frac{W_s}{W_n} \right) [\text{bit}]$$

Zmogljivost: $C = \frac{dI}{dt} = \frac{1}{2T} \log_2 \left(1 + \frac{W_s}{W_n} \right)$

$$B = \frac{1}{2T} \quad C = B \log_2 \left(1 + \frac{P_s}{P_n} \right)$$

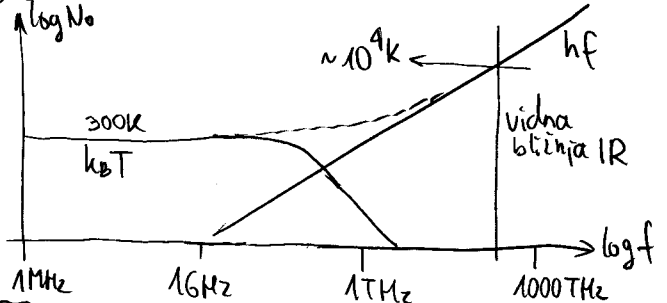
Moč šuma: toplotni šumi:

$$P_N = B N_0$$

Zrnatni šumi:

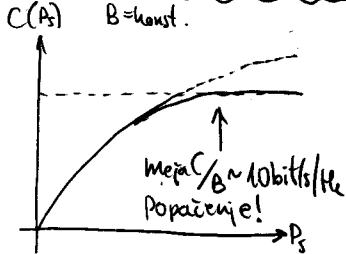
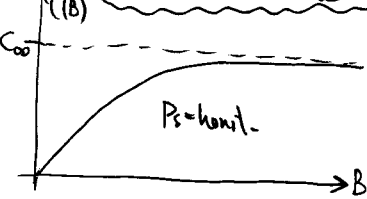
$$N_0 = k_B T \quad k_B = 1.38 \cdot 10^{-23} \text{ J/K}$$

$$N_0 = hf \quad h = 6.626 \cdot 10^{-34} \text{ Js}$$



$$C = B \log_2 \left(1 + \frac{P_s}{N_0 B} \right)$$

$$C_{\infty} = \lim_{B \rightarrow \infty} C = \frac{P_s}{N_0 \ln 2}$$

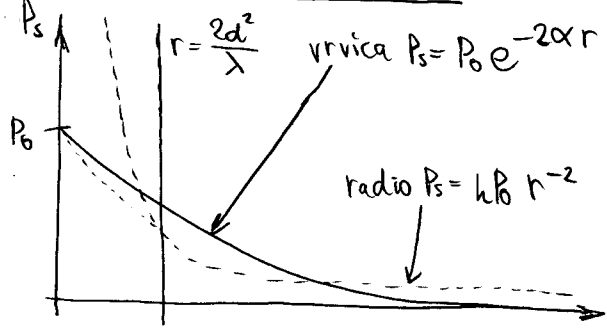


Dvovod:

$$Z_u = \sqrt{\frac{L/e}{C/e}}$$

$$\alpha = \frac{R/e}{2Z_u}$$

Vrvična / brezvrvična zveza:



Domest telefona:

prenosna parica $Z_u = 100 \Omega$
 $r = 25 \text{ km}$

zračni dvovod $Z_u = 600 \Omega$
 $r = 150 \text{ km}$

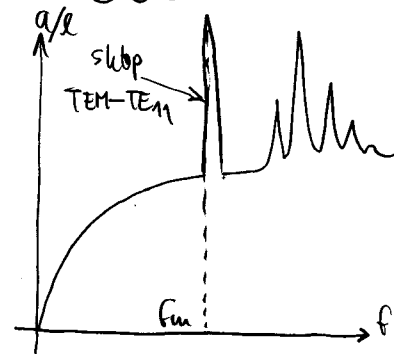
Pupinove tuljave $Z_u \uparrow$

Koaksialni kabl:

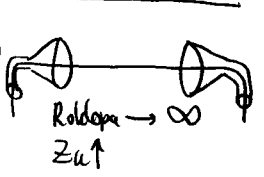
$B \sim 100 \text{ MHz}$
 $a/e \sim 20 \text{ dB/km}$

Višji rodovi:

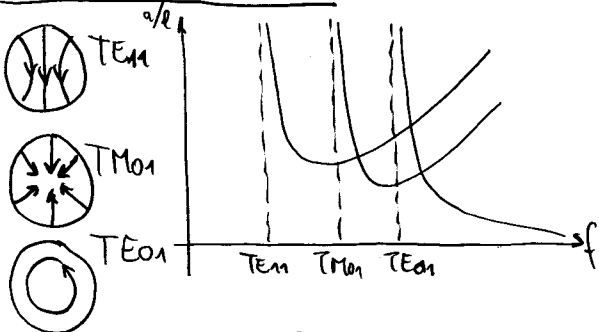
$$f_{\text{m}} = \frac{c_0 / T E_r}{\pi (R_{\text{zile}} + R_{\text{oklopa}})}$$



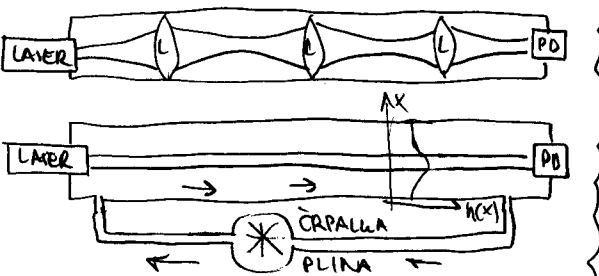
Goubaujev vod:



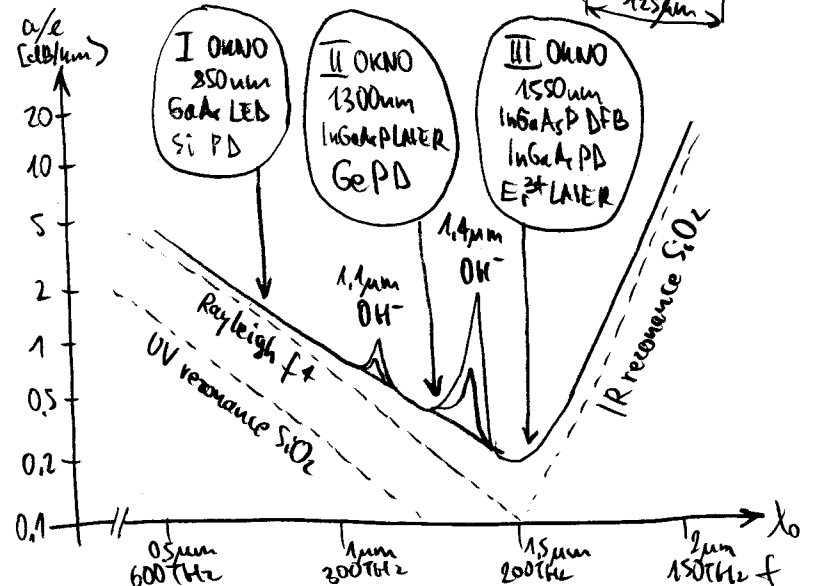
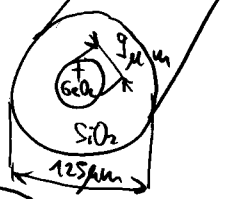
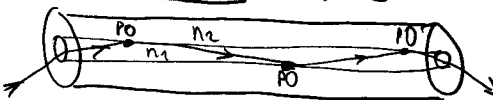
Okrugli kovinski valovod:



Laserske zveze:



Svetlobno vlakno: $n_1 > n_2$



Ponovitev elektrodinamike:

1. ME: $\text{rot } \vec{H} = \vec{j} + j\omega \epsilon \vec{E}$
2. ME: $\text{rot } \vec{E} = -j\omega \mu \vec{H}$
3. ME: $\text{div } \epsilon \vec{E} = \rho$

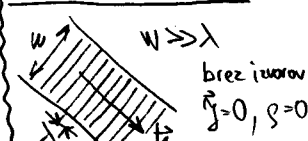
$$(x, y, z) \rightarrow \vec{\nabla} = \vec{i}_x \frac{\partial}{\partial x} + \vec{i}_y \frac{\partial}{\partial y} + \vec{i}_z \frac{\partial}{\partial z}$$

$$\text{rot } \vec{H} = \vec{\nabla} \times \vec{H} = \begin{vmatrix} \vec{i}_x & \vec{i}_y & \vec{i}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix}$$

$$\vec{D} = \epsilon \vec{E}$$

$$\text{div } \vec{D} = \vec{\nabla} \cdot \vec{D} = \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z}$$

Žarček = ravninski val



Ugibanje resitev:

$$\vec{E} = \vec{E}_0 e^{-j\vec{k} \cdot \vec{r}} (e^{j\omega t})$$

Poenostavitve: $\vec{\nabla} = -j\vec{k}$

$$3. ME: 0 = \rho = \text{div } \epsilon \vec{E} = -j\epsilon \vec{k} \cdot \vec{E}$$

Zahteva $\vec{k} \perp \vec{E}$

$$1. ME: -j\vec{k} \times \vec{H} = +j\omega \epsilon \vec{E}$$

$$2. ME: -j\vec{k} \times \vec{E} = -j\omega \mu \vec{H}$$

$$\vec{H} = \frac{1}{\omega \mu} \vec{k} \times \vec{E}$$

$$-\vec{k} \times (\vec{k} \times \vec{E}) = \omega^2 \mu \epsilon \vec{E}$$

$$\vec{k} \times (\vec{k} \times \vec{E}) = \vec{k} (\vec{k} \cdot \vec{E}) - \vec{E} (\vec{k} \cdot \vec{k})$$

$$\vec{k} \cdot \vec{E} = 0 \rightarrow -\vec{E} k^2 = \omega^2 \mu \epsilon \vec{E}$$

$$k^2 = \omega^2 \mu \epsilon \rightarrow k = \omega \sqrt{\mu \epsilon}$$

$$\text{Hitrost: } \omega t - \vec{k} \cdot \vec{r} = \text{konst} \rightarrow v = \frac{\omega}{k} = \frac{1}{\sqrt{\mu \epsilon}}$$

$$\text{Valovna dolžina: } k\lambda = 2\pi \rightarrow \lambda = \frac{2\pi}{k}, k = \frac{2\pi}{\lambda}$$

$\vec{k} \equiv$ valovni vektor $[rd/m]$

$k \equiv$ valovno število $[rd/m]$

$$k = |\vec{k}| = \omega \sqrt{\mu \epsilon}$$

$$\vec{H} \perp \vec{E}, \vec{H} \perp \vec{k}, \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu}{\epsilon}} = Z$$

$$\text{Pojavitev: } \vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^* = \vec{i}_k \frac{|\vec{E}|^2}{2Z} \hat{S} \parallel \vec{k}$$

$$\text{Hitrost: } \omega t - \vec{k} \cdot \vec{r} = \text{konst} \rightarrow v = \frac{\omega}{k} = \frac{1}{\sqrt{\mu \epsilon}}$$

$$\text{Valovna dolžina: } k\lambda = 2\pi \rightarrow \lambda = \frac{2\pi}{k}, k = \frac{2\pi}{\lambda}$$

Prazen prostor: ϵ_0, μ_0

$$c_0 = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 2.9979 \dots \cdot 10^8 \text{ m/s} \approx 3 \cdot 10^8 \text{ m/s}$$

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \equiv \text{DEFINICIJA AMPERA}$$

$$\epsilon_0 = \frac{1}{\mu_0 c_0^2} \approx \frac{1}{4\pi \cdot 9 \cdot 10^9} \frac{\text{As}}{\text{Vm}}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 120\pi \Omega = 377 \Omega$$

Snov: $\epsilon = \epsilon_0 \epsilon_r, \mu = \mu_0 \mu_r$

$$\epsilon_r \geq 1, \mu_r \geq 1 \quad \text{BREZ 12608 } \delta = 0$$

$$n = \frac{c_0}{v} = \frac{c_0}{\frac{1}{\sqrt{\mu_r \epsilon_r}}} = \frac{c_0}{1} \sqrt{\mu_r \epsilon_r}$$

$$n = \sqrt{\mu_r \epsilon_r} \equiv \text{lomni količnik}$$

$$k = nk_0, \lambda = \frac{\lambda_0}{n}, Z = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}}$$

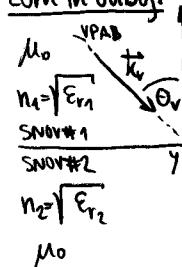
Dielektrik = neferomagnetik

$$\mu_r = 1, \mu = \mu_0, \epsilon_r \geq 1$$

$$n = \sqrt{\epsilon_r}, n = \frac{c_0}{v} = \frac{c_0}{\frac{1}{\sqrt{\epsilon_r}}} = \frac{c_0}{1} \sqrt{\epsilon_r}$$

$$Z = \frac{Z_0}{\sqrt{\epsilon_r}} = \frac{Z_0}{n}, k = nk_0 = k_0 \sqrt{\epsilon_r}$$

Lom in odboj:



$$\vec{k}_r = \vec{i}_x k_{rx} + \vec{i}_z k_{rz}$$

$$\vec{k}_t = \vec{i}_x k_{tx} + \vec{i}_z k_{tz}$$

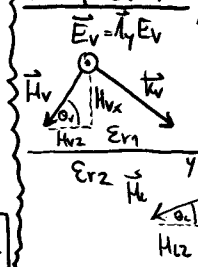
$$|\vec{k}_r| = |\vec{k}_i| = k_1, \sin \theta_r = \frac{k_{rx}}{k_1}$$

$$\sin \theta_t = \frac{k_{tx}}{k_2}, \frac{\sin \theta_r}{\sin \theta_t} = \frac{n_2}{n_1}$$

$$\vec{k}_t = \vec{i}_x k_{tx} + \vec{i}_z k_{tz}$$

$$\vec{k}_t = \vec{i}_x k_{tx} + \vec{i}_z k_{tz}$$

Odbojnost TE:



Prestopni pogoji: $\vec{D}_n = \vec{D}_t, \vec{B}_t = \vec{B}_t$

$$1. E_v + E_o = E_L$$

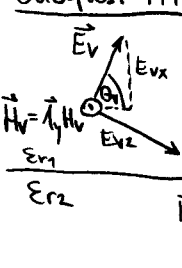
$$2. H_{vx} + H_{ox} = H_{Lx} \quad (\text{linearno odvisna})$$

$$3. H_{vz} + H_{oz} = H_{Lz}$$

$$-E_v \cos \theta_i + \frac{E_o}{Z_1} \cos \theta_o = -\frac{E_L}{Z_2} \cos \theta_L$$

$$(E_v - E_o) n_1 \cos \theta = (E_v + E_o) n_2 \cos \theta_L$$

Odbojnost TM:



Prestopni p: 1. $H_v + H_o = H_L$

$$2. (E_v + E_o) \epsilon_r = E_L \epsilon_r$$

$$3. E_{vz} + E_{oz} = E_{Lz}$$

$$E_v \cos \theta_i - E_o \cos \theta_o = (E_v + E_o) \frac{Z_2}{Z_1} \cos \theta_L$$

$$(E_v - E_o) n_2 \cos \theta = (E_v + E_o) n_1 \cos \theta_L$$

$$\Gamma_{TM} = \frac{E_o}{E_v} = \frac{n_2 \cos \theta - n_1 \cos \theta_L}{n_2 \cos \theta + n_1 \cos \theta_L} \cdot \frac{n_2 \epsilon_r}{n_1 \epsilon_r}$$

$$\Gamma_{TE} = \frac{E_o}{E_v} = \frac{n_1 \cos \theta - n_2 \cos \theta_L}{n_1 \cos \theta + n_2 \cos \theta_L}$$

$$\cos \theta_L = \sqrt{1 - \sin^2 \theta} = \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2 \theta}$$

$$\Gamma_{TE} = \frac{\cos \theta - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}{\cos \theta + \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}$$

$$\Gamma_{TM} = \frac{\left(\frac{n_2}{n_1}\right)^2 \cos \theta - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}{\left(\frac{n_2}{n_1}\right)^2 \cos \theta + \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}$$

$$\Gamma_{TM} = \frac{\left(\frac{n_2}{n_1}\right)^2 \cos \theta - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}{\left(\frac{n_2}{n_1}\right)^2 \cos \theta + \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}$$

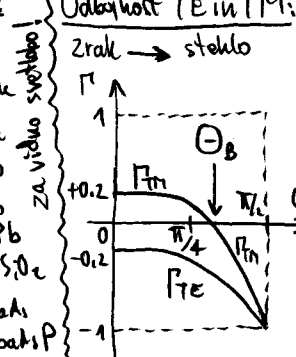
$$\Gamma_{TM} = \frac{\left(\frac{n_2}{n_1}\right)^2 \cos \theta - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}{\left(\frac{n_2}{n_1}\right)^2 \cos \theta + \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta}}$$

Fresnel-ove odbojnosti

Lomni količnik:

- $n=1 \rightarrow$ vakuum
- $n=1.00045 \rightarrow$ zrak
- $n=1.33 \rightarrow$ voda
- $n \sim 1.5 \rightarrow$ steklo
- $n \sim 1.8 \rightarrow$ kristalno steklo Pb
- $n=1.46 \rightarrow$ steklo SiO2
- $n=3.5-4$ Si, GaAs
- polprevodniki InGaAs, P

Odbojnost TE in TM:



Brewsteri $\theta_B (\Gamma_{TM}=0)$

$$\left(\frac{n_2}{n_1}\right)^2 \cos^2 \theta_B - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta_B} = 0$$

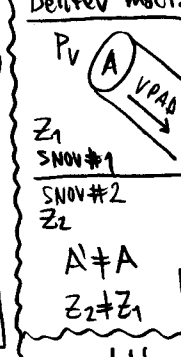
$$\left(\frac{n_2}{n_1}\right)^4 \cos^2 \theta_B = \left(\frac{n_2}{n_1}\right)^2 - \sin^2 \theta_B$$

$$\left(\frac{n_2}{n_1}\right)^2 = \alpha \rightarrow (\alpha^2 - 1) \cos^2 \theta_B = \alpha - 1$$

$$\cos^2 \theta_B = \frac{1}{\alpha + 1}, \sin^2 \theta_B = \frac{\alpha}{\alpha + 1}$$

$$\tan^2 \theta_B = \alpha \rightarrow \theta_B = \arctan \frac{n_2}{n_1}$$

Delitev moči:



$$P = AS = A \frac{|\vec{E}|^2}{2Z}$$

$$P_o = P_v |\Gamma|^2$$

$$P_L = P_v - P_o$$

$$P_L = P_v (1 - |\Gamma|^2)$$

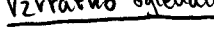
Zaladi: pravokotni vpadi na steklo

$$zrak \rightarrow \text{steklo } |\Gamma| = 0.2$$

$$P_v \rightarrow P_L = P_v (1 - |\Gamma|^2) = 0.96 P_v$$

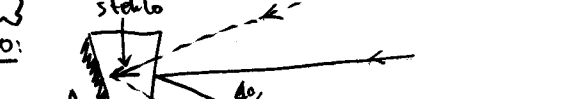
$$P_o = P_v |\Gamma|^2 = 0.04 P_v (-14 \text{ dB})$$

Vzratno ogledalo:



$$P_v \rightarrow P_L = P_v (1 - |\Gamma|^2) = 0.96 P_v$$

$$P_o = P_v |\Gamma|^2 = 0.04 P_v (-14 \text{ dB})$$



$$P_v \rightarrow P_L = P_v (1 - |\Gamma|^2) = 0.96 P_v$$

$$P_o = P_v |\Gamma|^2 = 0.04 P_v (-14 \text{ dB})$$

Optične komunikacije # 3

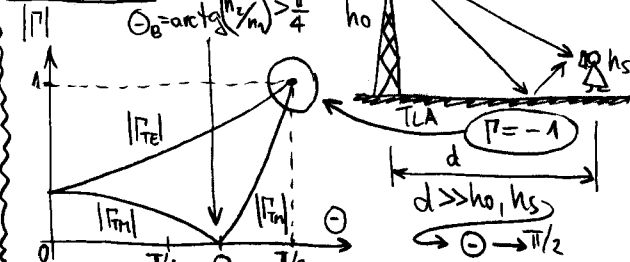
6/3/2014

Ponovitev: Fresnel-ovi odbijnosti

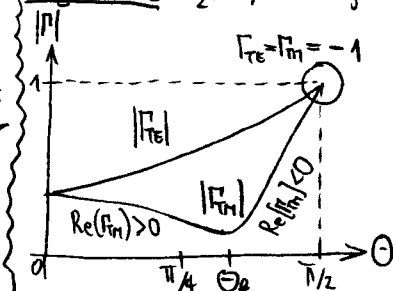
$$r_{TE} = \frac{\cos\theta - \sqrt{(n_2/n_1)^2 - \sin^2\theta}}{\cos\theta + \sqrt{(n_2/n_1)^2 - \sin^2\theta}}$$

$$r_{TM} = \frac{(n_2/n_1)^2 \cos\theta - \sqrt{(n_2/n_1)^2 - \sin^2\theta}}{(n_2/n_1)^2 \cos\theta + \sqrt{(n_2/n_1)^2 - \sin^2\theta}}$$

Zgled $n_2 > n_1$:

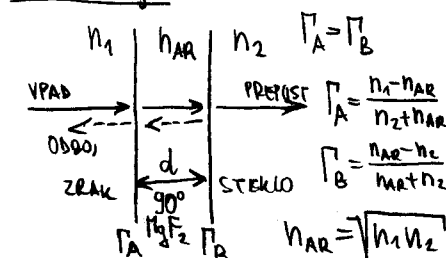


Izgubni n_2 : $\epsilon_2 \neq 0$, $n_2 = n_2' + jn_2''$

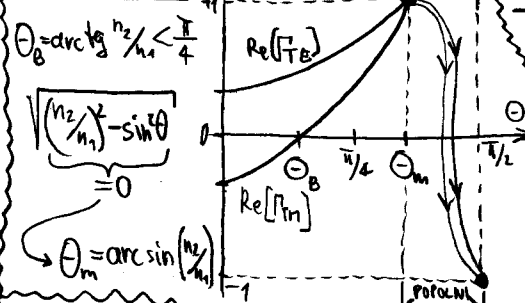


AR sloj:

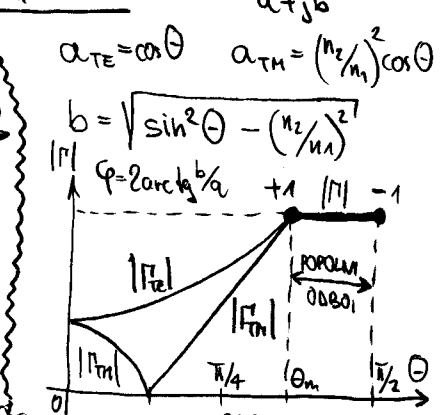
$$d = \lambda_{AR}/4$$



Zgled $n_2 < n_1$:

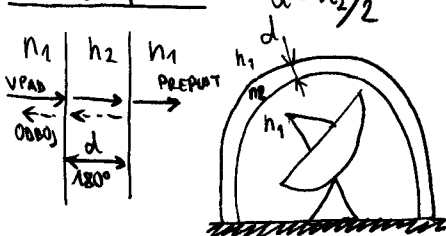


$$\theta_m < \theta < \frac{\pi}{2} \rightarrow r = \frac{a-jb}{a+jb}$$

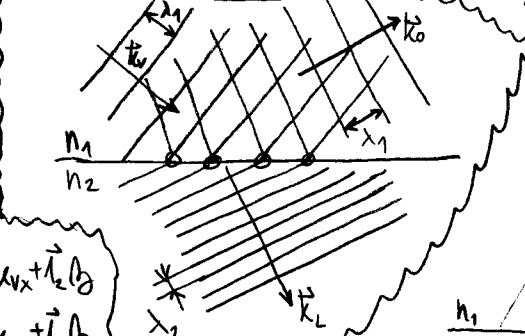


Prozoren pokrov:

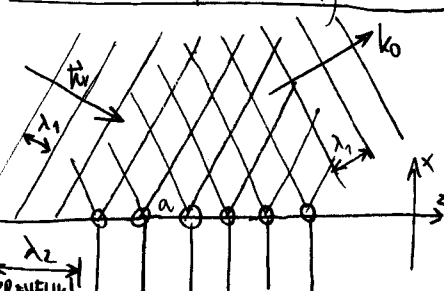
$$d = \lambda_2/2$$



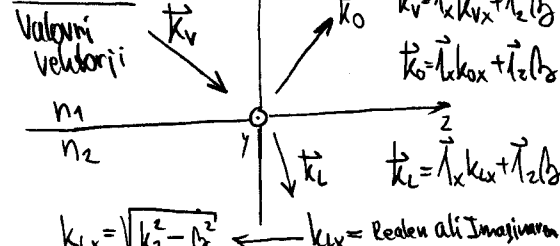
Lom + odbij $n_2 > n_1$:



Popolni odbij $n_2 < n_1$; $\theta > \theta_m$:



Ponovitev:



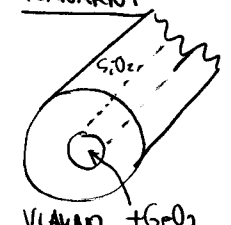
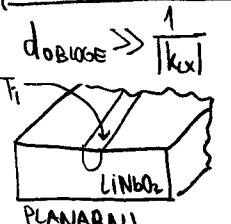
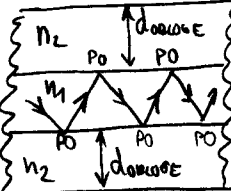
$$\alpha = \frac{\lambda_1}{\sin\theta_v} = \frac{\lambda_2}{\sin\theta_L}$$

$$\sin\theta_L = \frac{\lambda_2}{\alpha} > 1 \rightarrow \theta_L = ?; k_{Lx} = \text{img!}$$

$$E_L = E_0 e^{i(k_{Lx}x - \beta z)}$$

Dielektrični valovod:

$$n_1 > n_2$$

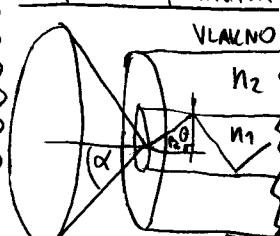


Relativna razlika n:

$$\Delta = \frac{n_1 - n_2}{n_1}$$

$$\Delta \ll 1 \rightarrow \text{šibkolomno vlakno}$$

Numerična apertura NA:



$$NA = \sin\alpha_m = n_1 \sqrt{1 - (n_2/n_1)^2}$$

$$NA = \sqrt{n_1^2 - n_2^2}$$

Sklopni izkoristek vira:

$$\eta = \frac{P_{\text{izhodno}}}{P_{\text{vstopna}}} = \frac{\Omega}{4\pi}$$

$$\Omega = \frac{A}{r^2} = \frac{2\pi r h}{r^2} = 2\pi(1 - \cos\alpha)$$

$$\eta = \frac{1}{2}(1 - \sqrt{1 - NA^2}) \approx \frac{NA^2}{4}$$

$$\eta \approx 1.5$$

$$\text{Zgled: } NA = 0.2 \rightarrow \eta = 0.01 = 1\%$$

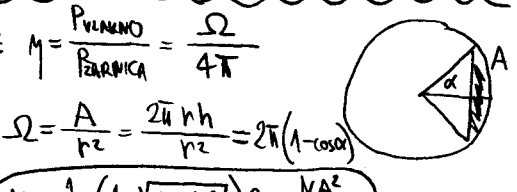
$$\text{Šibkolomno: } NA \approx n_1 \sqrt{2\Delta} \rightarrow \Delta = \frac{1}{2} \left(\frac{NA}{n_1} \right)^2 = 0.009$$

$$\text{Razširitev impulza: } \ell = 10 \text{ km}$$

$$\text{Ravni žarek: } t_1 = \frac{n_1 \ell}{c_0} \quad n_1 \approx 1.5 \quad \Delta \approx 0.009$$

$$\text{Cikcakajoci: } t_2 = \frac{n_2 \ell}{c_0 \sin\theta} = \frac{n_2^2 \ell}{n_1^2 c_0}$$

$$\Delta t = t_2 - t_1 = \frac{n_2 \ell}{c_0} \left(\frac{n_1}{n_2} - 1 \right)$$



$$\Delta t \approx \frac{n_2 \ell}{c_0} \Delta = \frac{1.5 \cdot 10^4 \text{ m} \cdot 0.009}{3 \cdot 10^8 \text{ m/s}} = 0.45 \mu\text{s}$$

$$\text{Zmogljivost: } C = \frac{1}{T}; T > 3\Delta t$$

$$C = \frac{1}{3\Delta t} = 740 \text{ kbit/s}$$

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$$C = \frac{1}{3\Delta t} = 740 \text{ kbit/s}$$

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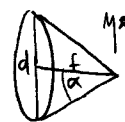
$$C = \frac{1}{3\Delta t} = 740 \text{ kbit/s}$$

Ponovitev:

$$\Delta = \frac{n_1 - n_2}{n_1} \ll 1$$

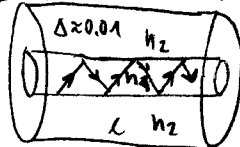
$$NA = \sqrt{n_1^2 - n_2^2}$$

$$NA \approx n_1 \sqrt{2\Delta}$$



$$NA = \sin \alpha \approx \frac{1}{2f/d}$$

Ponovitev: $l = 10 \text{ km}$



$$\Delta t \approx \frac{ln_1}{c_0} \Delta \sim 0,5 \mu s$$

GI vlakno

50/125 G.651 (ITU)

62.5/125 H (rač.)

$\Delta \sim 0,01$, $NA \sim 0,2$

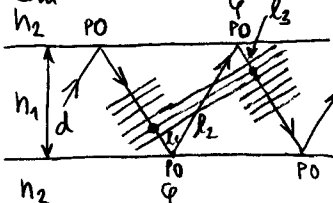


$$\Delta t \approx \frac{ln_1}{c_0} \Delta^2$$

$$l = 10 \text{ km} \rightarrow \Delta t \sim 5 \text{ ns}$$

Prečna fazna rezonanca:

$$\Theta_m < \Theta < \frac{\pi}{2}$$



$$\Gamma = \frac{a-jb}{a+jb} \rightarrow \varphi = 2 \arctan \frac{b}{a}$$

$$\alpha_{TE} = \cos \Theta \quad \alpha_{TM} = \left(\frac{n_2}{n_1} \right)^2 \cos \Theta$$

$$b = \sqrt{\left(\frac{n_2}{n_1} \right)^2 - \sin^2 \Theta}$$

$$\cos \Theta = \sqrt{1 - \sin^2 \Theta}$$

$$\cos \Theta_m = \sqrt{1 - \left(\frac{n_2}{n_1} \right)^2}$$

Normirana frekvenca!

$$k_0 n_1 d \cos \Theta_m = k_0 d NA = V$$

$$l_2 = \frac{d}{\cos \Theta}$$

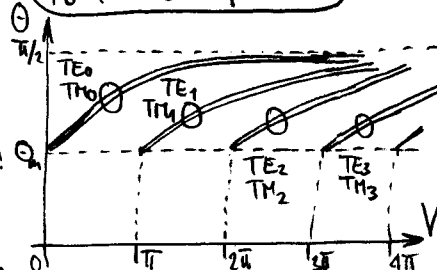
$$l_1 + l_3 = l_2 \cos 2\Theta$$

$$l_1 + l_2 + l_3 = \frac{d}{\cos \Theta} (1 + \cos 2\Theta)$$

$$l_1 + l_2 + l_3 = 2d \cos \Theta$$

$$k_1(l_1 + l_2 + l_3) - 2\varphi = m \cdot 2\pi$$

$$k_0 n_1 d \cos \Theta - \varphi = m\pi$$



Zgled: $d = 1 \mu m$, $\lambda = 633 \text{ nm}$

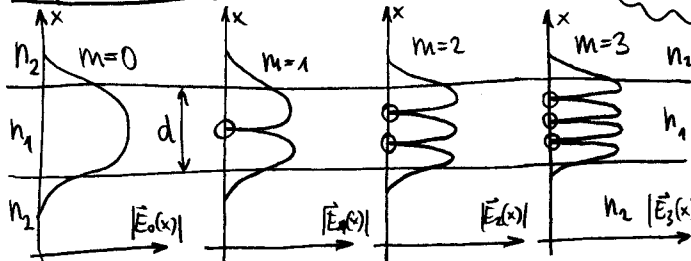
$n_1 = 1,5 \approx \text{steklo}$

$n_2 = 1 \approx \text{zrak}$

$$m < \frac{V}{\pi} = 3533 \text{ rodov TE+TM!}$$

$$V = \frac{2\pi}{\lambda_0} d NA = \frac{2\pi}{633 \cdot 10^{-9} \text{ m}} \cdot 1 \cdot 10^{-6} \cdot 0,2 \approx 1000$$

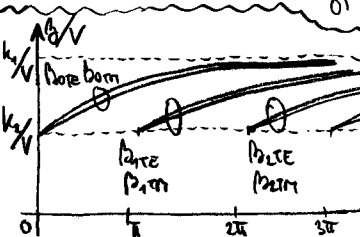
Polje rodov (m):



$$k_x = k_1 \cos \Theta$$

$$k_y = k_1 \sin \Theta$$

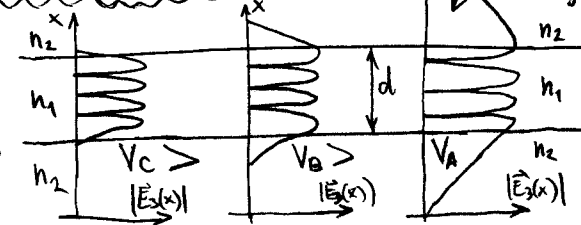
Fazna konstanta:



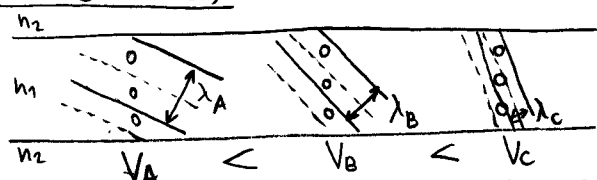
Zgled

$m=3$

Polje (V):

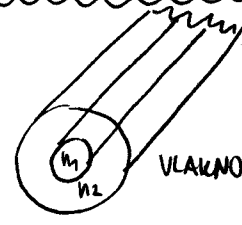
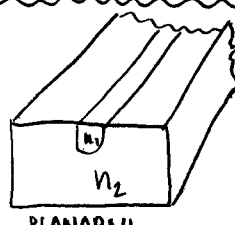


Valovne fronte (V):

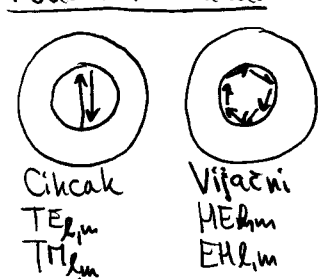


2D valovodi

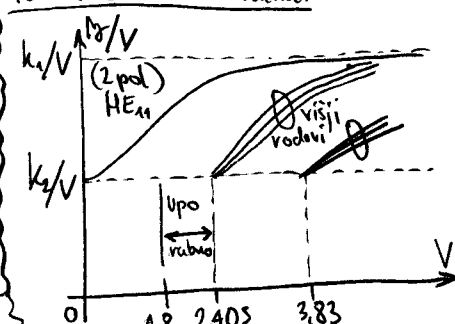
2 indeksa n_1, n_2 rodov



Rodovi v vlaknu:



Fazna konstanta v vlaknu:



Definicija $V = k_0 a NA$ a = polmer jedra!

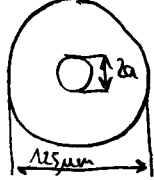
Vlakno G.652 $2a = 9 \mu m - 10 \mu m$

9/125 ali 10/125

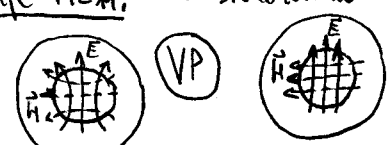
$NA \sim 0,1$

$$\lambda_0 = \frac{2\pi a NA}{2,405}$$

$$\lambda_0 \sim 1,25 \mu m$$

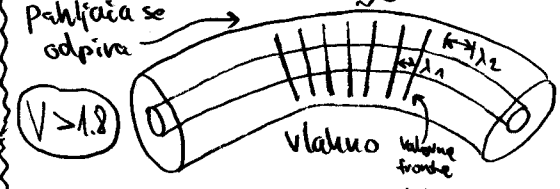


Polje HE_{11} : \rightarrow šiblo lomno $HE_{11} = LP_{01}$



Tuneliranje na krivinski

pahljača se odpira



Uporabni pas $HE_{11} \rightarrow 1,8 < V < 2,405$

$$G.652 \rightarrow 1,67 \mu m > \lambda_0 > 1,25 \mu m$$

EM rešitev: $\Delta E_z + k^2 E_z = 0$

$$\Delta H_z + k^2 H_z = 0$$

jedro:

$$E_z, H_z = C_1 J_m(k_0 a) \begin{cases} \sin m\varphi \\ \cos m\varphi \end{cases} e^{-j\beta z}$$

obloga:

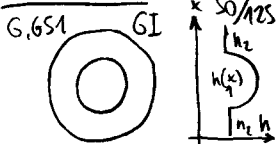
$$E_z, H_z = C_2 K_m(k_0 b) \begin{cases} \sin m\varphi \\ \cos m\varphi \end{cases} e^{-j\beta z}$$

$$E_z, H_z \rightarrow E_\varphi, H_\varphi, E_\rho, H_\rho$$

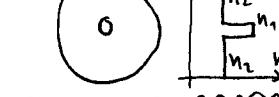
+ prestopni pogoji

Optične komunikacije #5 20/3/2014

Ponovitev:



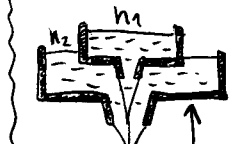
G.652 SI



G.653 DSF



Talilni posodi:



večenje vlakna

toplota

$\alpha \sim 1000 \text{ dB/km}$

(umazanija posod)

izdelava plastičnih vlaken

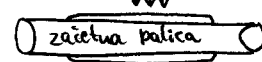
Čiste surovine:

SiCl_4 = tekočina
 GeCl_4 = tekočina
 O_2 = plin
 F_2 = plin
 POCl_3 = tekočina

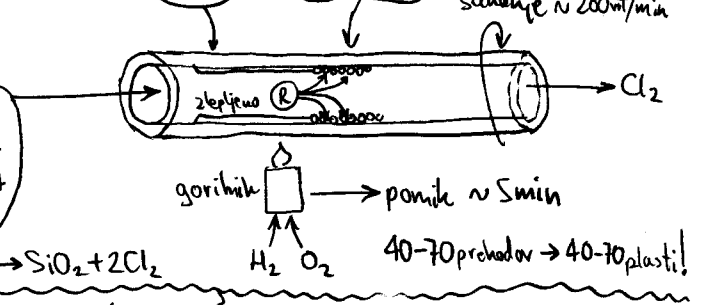
nosilni plin
 hlapi SiCl_4
 hlapi GeCl_4
 O_2, F_2

$\text{SiCl}_4 + \text{O}_2 + \text{toplota} \rightarrow \text{SiO}_2 + 2\text{Cl}_2$

OCVD:



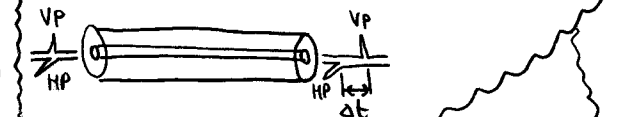
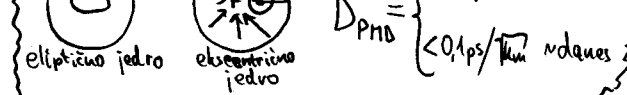
MCVD:



Kolaps: cev \rightarrow preform

PMD: $b_{VP} \neq b_{HP}$ $\langle \Delta t \rangle = D_{PMD} \sqrt{L}$ ($L > 300 \text{ m}$)

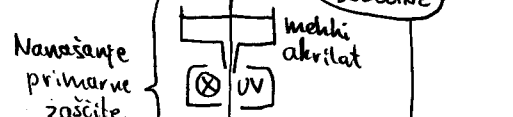
$D_{PMD} = \begin{cases} 10 \text{ ps}/\sqrt{\text{km}} \sim 1980 \\ < 0,1 \text{ ps}/\sqrt{\text{km}} \text{ ndques} \end{cases}$



Vlečenje vlakna:

ponik

Sušenje proti PMD $\sim 20 \text{ cm vlakna/obrat}$



Nanašanje primarne zaštite

mekhi akrilat

trši akrilat

Hitrost vlečenja $2 \text{ m/s} - 10 \text{ m/s}$

vlakno + PZ $250 \mu\text{m} \phi$ cena $\sim 8 \text{ \$/km}$

PANDA vlakno:

B_2O_3

SiO_2

jedro GeO_2

Možno dvostrano ohranjanje polarizacije

visoka cena $\sim 30 \text{ \$/m}$

Brusenje ferule:

Ravno (MMF): umazanija?

FC SC

sklepljenje odboja - 11 dB

Kriviško (SMF):

\rightarrow sklepljenje 0,2 dB

FC-PC SC-PC

odboj - 40 dB

Kotno - kriviško (analogni prenos):

odboj \rightarrow sklepljenje $\sim 0,5 \text{ dB}$

FC-APC SC-APC

odboj - 70 dB

ZELEN

Tesna zaštita:

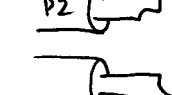
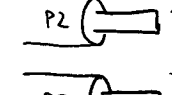
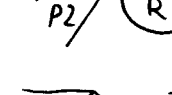
(TIGHT)



0,9 mm

Mikrokrivine! (slabljenje)

Rezanje SiO_2 vlaken:



Ohlapna zaštita: (LOOSE)

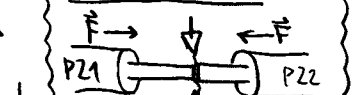
čev $\phi 3 \text{ mm}$

čelatina

vlakno

brez mikrokrivine \rightarrow nizke izgube!

Kabel: N = nosilni V = vlakna S = slepi



Trak: (ribbon)

4 - 24 vlaken

PMD = ?

Varienje SiO_2 :

PZ1 PZ2

Električni lok $\sim 0,2 \text{ s}$ = čiščenje $\sim 2 \text{ s}$ = zvar

Izgube zvana $\alpha < 0,05 \text{ dB}$

Rod-in-tube

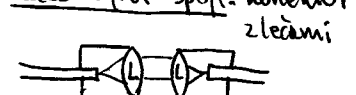
čev $\phi 3 \text{ mm}$

čelatina

vlakno

brez mikrokrivine \rightarrow nizke izgube!

Kabel: N = nosilni V = vlakna S = slepi



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4 - 24 vlaken

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Izgube zvana $\alpha < 0,05 \text{ dB}$

Vlečenje vlakna:

ponik

Sušenje proti PMD $\sim 20 \text{ cm vlakna/obrat}$



Nanašanje primarne zaštite

mekhi akrilat

trši akrilat

Hitrost vlečenja $2 \text{ m/s} - 10 \text{ m/s}$

vlakno + PZ $250 \mu\text{m} \phi$ cena $\sim 8 \text{ \$/km}$

PANDA vlakno:

B_2O_3

SiO_2

jedro GeO_2

Možno dvostrano ohranjanje polarizacije

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Kotno - kriviško (analogni prenos):

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FC-APC SC-APC

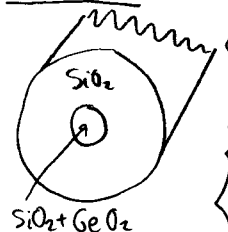
odboj - 70 dB

ZELEN

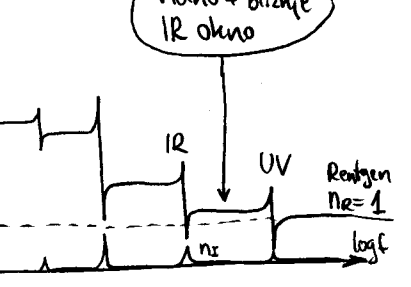
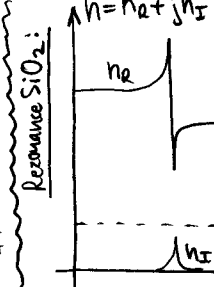
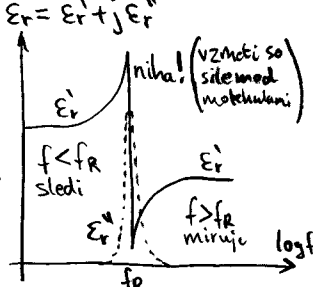
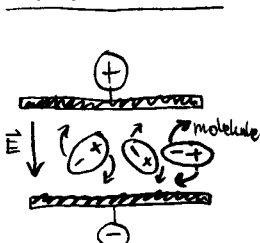
Optične komunikacije # 6

27/4/2014

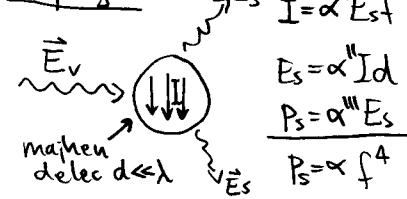
Ponovitev:



Dielektričnost:



Rayleigh:

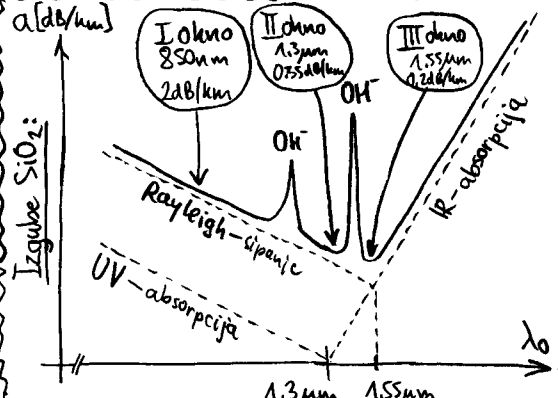


$$I = \alpha^1 E_s f$$

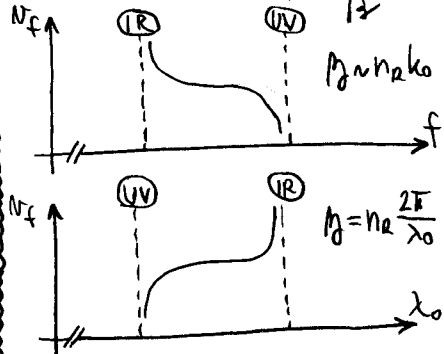
$$E_s = \alpha^1 I d$$

$$P_s = \alpha^3 E_s$$

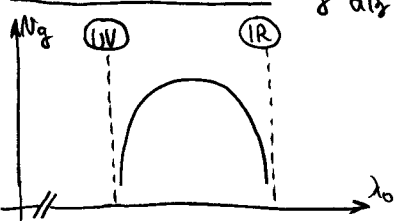
$$P_s \propto f^4$$



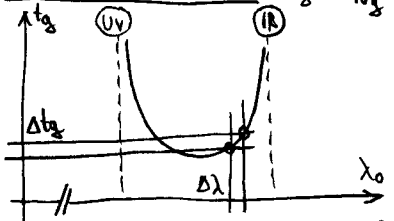
Fazna hitrost:



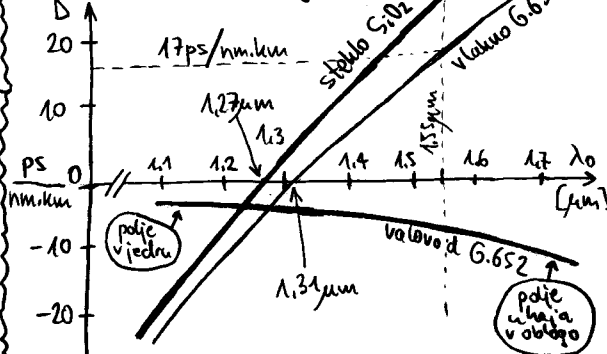
Skupinska hitrost:



Skupinska zakasnitev:



Barvna razpršitev: Δt_g = D Δλ



Zgled: cenovni FP laser Δλ = 10nm, L = 50km, C = 1/(3Δt_g) (strogo!)

λ0 = 1.3μm, D < 2ps/nm.km

Δt_g = D Δλ = 1ns, C = 333 Mbit/s

λ0 = 1.55μm, D = +17ps/nm.km

Δt_g = 8.5ns, C = 39 Mbit/s

Kakovostni TX: Δt_vira << Δt_mad

DFB → EOM → Δf ≈ C

modulacija

$$\lambda_0 = \frac{c_0}{f} \rightarrow \Delta\lambda = \frac{c_0}{f^2} \Delta f = \frac{\lambda_0^2}{c_0} C$$

C = 1/Δt_g (manj strogo!)

$$C = \frac{1}{D \Delta\lambda} \left(\frac{\lambda_0^2}{c_0} C \right)^{-1} L = 50km$$

λ0 = 1.55μm

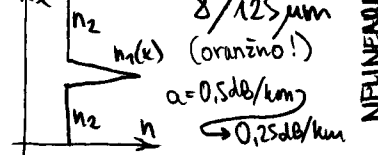
$$C = \sqrt{\frac{c_0}{D \Delta\lambda^2}} = 12.1 Gbit/s$$

Primerjava:

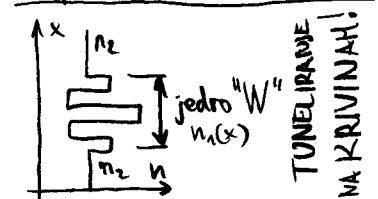
Δt_MME >> Δt_BARVNI > Δt_PMD

monokromatsko vlakno

Dispersion-Shifted Fiber G.653:



Dispersion Flattened Fiber G.654



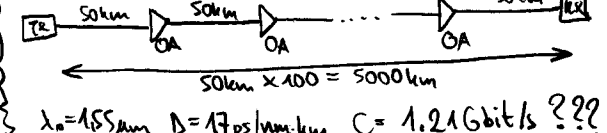
NZDSF vlakna:

D(1.55μm) = 5.7 ps/nm.km

+NZDSF

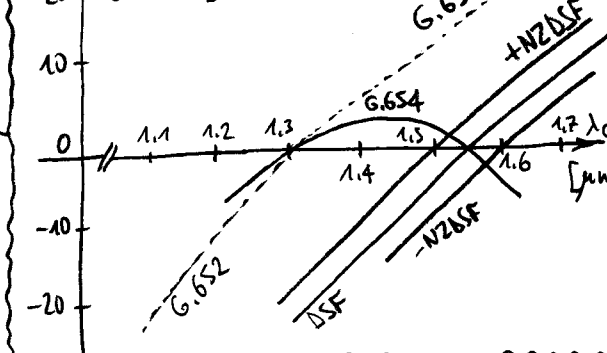
-NZDSF (kompenzacija)

Preko oceanska zveza:

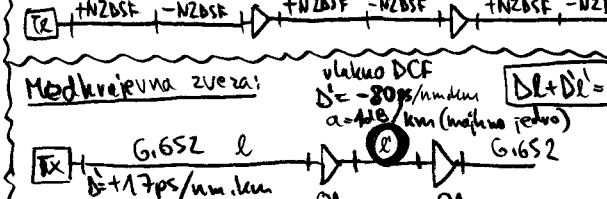


λ0 = 1.55μm, D = 17ps/nm.km, C = 1.21 Gbit/s ???

PRIMERJAVA:



Preko oceanski kabeli:

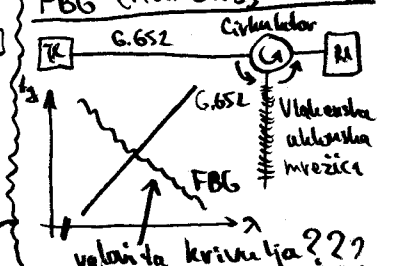


Modkrajnava zveza:

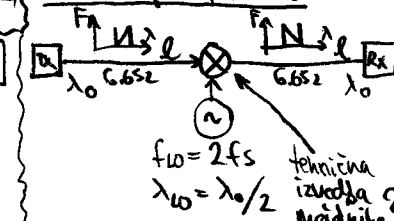


Neuspešne tehnike:

FBG (Fiber Bragg Grating)



Obračunje spektra:



Optične komunikacije #7

3/4/2014

Ponovitev: G.652

Gostota moči:

$$A = \pi a^2$$

$$A_{eff} \approx 70 \mu m^2 = 7 \cdot 10^{-11} m^2$$

$$P = 100 mW$$

$$S = \frac{P}{A_{eff}} = 1.4 GW/m^2 = 140 kW/cm^2$$

Električno polje: $P = 100 mW$

$$S = \frac{|E|^2}{2Z} = \frac{|E|^2}{2Z_0} n_1$$

$$|E| = \sqrt{\frac{2Z_0 S}{n_1}} \quad Z_0 = 377 \Omega \quad n_1 \approx 1.46$$

$$|E| = 850 kV/m = 85 kV/cm$$

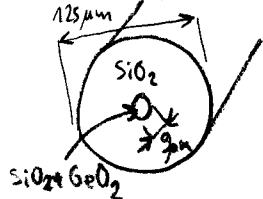
Razredi moči:

$P = 10 W$ uničuje jedro vlakna

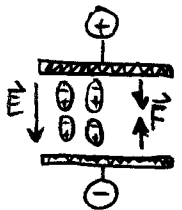
$P = 1 W$ preboj v zrak, max moč v vlaknu

$P = 100 mW$ max moč na konektorjih

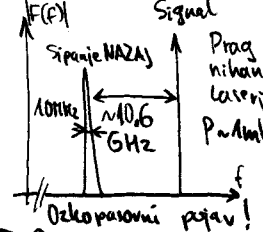
$P = 10 mW$ nevarnost zažigal.



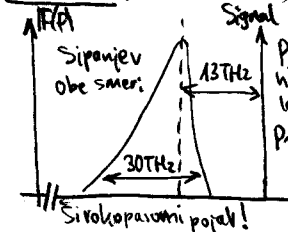
Elektrostrikcija:



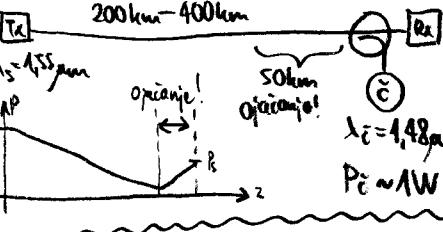
Brillouin: (akustični fononi)



Raman: (optični fononi)



Ramanov oparovalnik: (podmorski kabel)



Nelinearni n:

$$n = n_0 + n_1 E + n_2 E^2 + n_3 E^3 + \dots$$

Pockels

Kerr

Najhina nelinearnost

$$SiO_2 \rightarrow n_0 \approx 1.46$$

$$E_{nguzeni} = 0 \rightarrow n_1 = 0$$

$$n \approx n_0 + n_2 S \quad n_2 \approx 3.2 \cdot 10^{-20} \frac{m^2}{W}$$

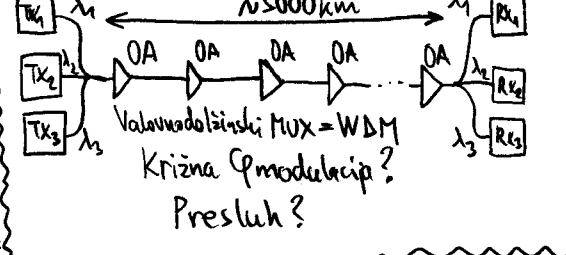
Lastna φ modulacija:

$$P = 100 mW, \quad l = 10 km, \quad \lambda_0 = 155 \mu m$$

$$\Delta \phi = \Delta n \frac{2\pi}{\lambda_0} l = n_2 \frac{P}{A_{eff}} \frac{2\pi}{\lambda_0} l$$

$$\Delta \phi = 3.2 \cdot 10^{-20} \frac{m^2}{W} \frac{100 mW}{70 \mu m^2} \frac{2\pi}{155 \mu m} 10 km = 1.85 rad$$

Preko oceanska zveza:



Dvobinski signali: ω_1, ω_2

1STA POLARIZACIJA

Odkriv preproščeno za $\omega_1, \omega_2, \omega_3$

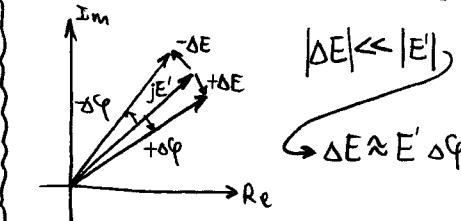
$$E = E_0 \cos \omega_1 t + E_0 \cos \omega_2 t$$

$$P = \alpha |E|^2 = \alpha (E_0 \cos \omega_1 t + E_0 \cos \omega_2 t)^2$$

$$P = \alpha \left(E_0^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega_1 t \right) + 2E_0 E_0 \left(\frac{1}{2} \cos(\omega_1 + \omega_2)t + \frac{1}{2} \cos(\omega_1 - \omega_2)t \right) + E_0^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega_2 t \right) \right)$$

$$P \approx \frac{\alpha}{2} (E_0^2 + 2E_0 E_0 \cos \Delta \omega t + E_0^2) = P_1 + 2\sqrt{P_1 P_2} \cos \Delta \omega t + P_2$$

Križna φ mod → optenjanje faze!



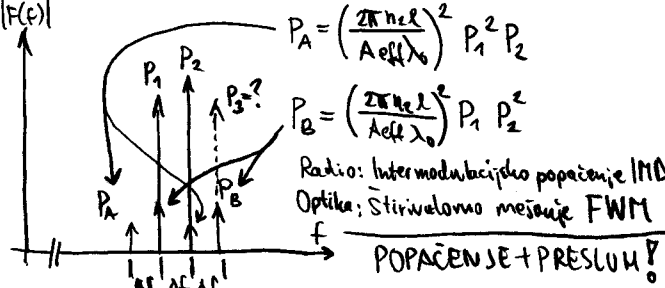
Spekter križne φ mod:

$$E' = E_0 \sin \omega t, \quad P = \alpha |E|^2 \quad (F(c))$$

$$\Delta E = E' \left(\frac{2\pi n_2 l}{A_{eff} \lambda_0} \right) 2\sqrt{P_1 P_2} \cos \Delta \omega t$$

$$\Delta E = E_0 \left(\frac{2\pi n_2 l}{A_{eff} \lambda_0} \right) \sqrt{P_1 P_2} [\sin(\omega + \Delta \omega)t + \sin(\omega - \Delta \omega)t]$$

$$P(\omega + \Delta \omega) = P(\omega - \Delta \omega) = P \left(\frac{2\pi n_2 l}{A_{eff} \lambda_0} \right)^2 P_1 P_2$$



Slabljenje vlakna:

$$\alpha = 0.2 dB/km$$

$$P(z) = P_0 10^{-\frac{\alpha z}{10}} = P_0 e^{-\frac{\alpha \ln 10}{10} z}$$

$$\Delta \phi = \frac{2\pi n_2}{A_{eff} \lambda_0} \int_0^L P(z) dz = \frac{2\pi n_2 P_0}{A_{eff} \lambda_0} \frac{10}{\alpha \ln 10} (1 - e^{-\frac{\alpha \ln 10}{10} L})$$

$$L \rightarrow \infty \Rightarrow L' \approx \frac{10}{\alpha \ln 10} = 21.7 km$$

Vlakno G.653:

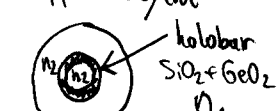
$$A_{eff} \approx 30 \mu m^2$$

$$D = 0.5 ps/nm.km$$

NEUPORABNO V OJAČEVANI ZVEZI

Vlakno LEAF:

$$A_{eff} \approx 80 \mu m^2$$



Učinek $D \neq 0$: fazna neustojanost $\Delta \phi = \beta_s + \beta_m - 2\beta_c$

$$\beta_s = \beta(\omega + \Delta \omega)$$

$$\beta_m = \beta(\omega - \Delta \omega)$$

$$\Delta \beta = \beta(\omega + \Delta \omega) + \beta(\omega - \Delta \omega) - 2\beta(\omega)$$

$$\Delta \beta \approx \Delta \omega^2 \frac{d^2 \beta}{d\omega^2} = \Delta \omega^2 \frac{-\lambda^3}{2\pi c_0} D$$

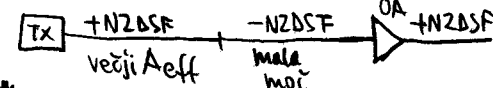
$$t_2 = \frac{L}{N_2} = L \frac{d\beta}{d\omega}; \quad \frac{d\beta}{d\omega} = L \frac{d^2 \beta}{d\omega^2} = \frac{d\beta}{d\lambda_0} \frac{d\lambda_0}{d\omega} = D L \frac{-\lambda^2}{2\pi c_0}$$

Zgled NZDSF:

$$\Delta f = 100 GHz, \quad \lambda_0 = 155 \mu m$$

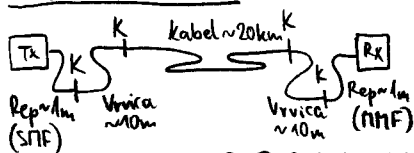
$$D = +5 ps/nm.km$$

$$\Delta \beta = (2\pi \cdot 100 GHz)^2 \frac{-(155 \mu m)^2}{2\pi \cdot 3 \cdot 10^8 m/s} 5 ps/nm.km = -2.51 rad/km$$



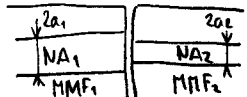
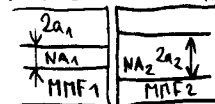
→ kazalna vsota izričuje FWM!

Svetlobna zveza:



Neenaka MMF:

malo izgub $\rightarrow NA_2 > NA_1, a_2 > a_1$



Izgube okoli $10 \log_{10} \left(\frac{a_1 NA_1}{a_2 NA_2} \right)^2$ [dB]
Recipročnost: \rightarrow velja za vsak vod!

Neenaka SMF:

G.652	G.653
9/125	DSF

težave optične nastavitve varilnika?
 $\alpha < 0,5 \text{ dB}$ (neprijetljivost osi svetlobnih vodov)

SMF \rightarrow MMF:

9/125	50/125
NA=0,1	NA=0,2

Storaj brez izgub!

MMF \rightarrow SMF: NEUPORABNO!

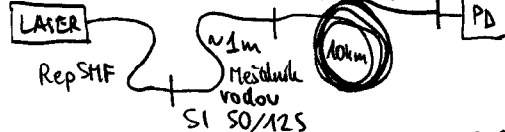
MMF	G.652
-----	-------

Visoko slabljenje! Nezanemljivi spoji!

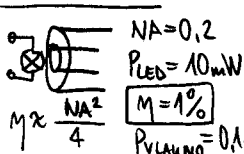
Posebni primer:

G.652 \rightarrow G.651 \rightarrow G.652
V G.651 vzbudimo samo nižje razine \rightarrow **UPORABNO!**

Meritve MMF:



LED \rightarrow MMF:



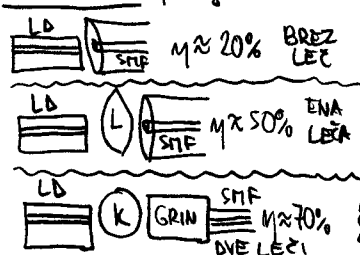
LED \rightarrow SMF:

Spektralna svetlost
 $B_f = \frac{dP}{df d\Omega dA}$
 $d\Omega = \frac{A_{eff}}{r^2} dA = r^2 d\Omega$

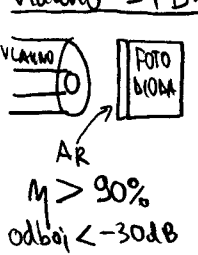
Koharentni sprejem!
 $F(\theta, \phi)$
 $A_{eff} = \frac{\lambda^2}{4\pi} D(\theta, \phi) = \frac{\lambda^2 |F|^2}{\int |F|^2 d\Omega}$

$P = \int_{4\pi} B_f d\Omega \frac{1}{r^2} \frac{\lambda^2 |F|^2}{\int |F|^2 d\Omega} r^2 d\Omega$
 $B_f = \text{konst.}$
 $P = B_f d\Omega \lambda^2$
 $M < 0,1\%$
 $P_{LED} = 10 \text{ mW} \rightarrow P_{SMF} = 3 \dots 10 \mu\text{W}$

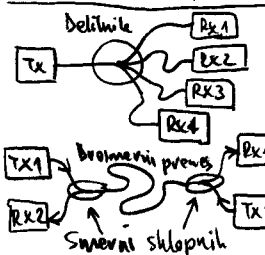
LD \rightarrow SMF: prilagoditev rodov?



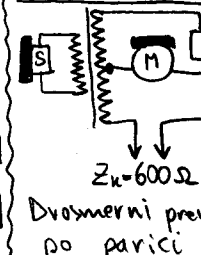
Vlakno \rightarrow PD:



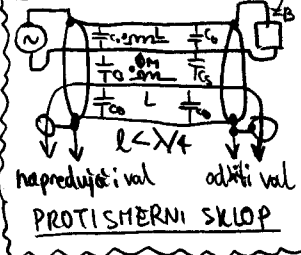
Delitniki in sklopniki:



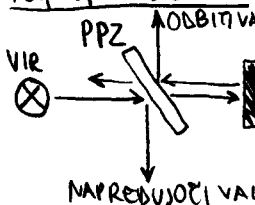
Telefonske vilice:



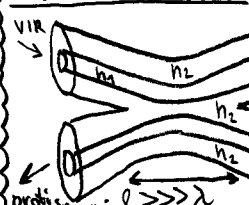
Radialni (kvadratni) sklopniki:



Polprepusno zrcalo:



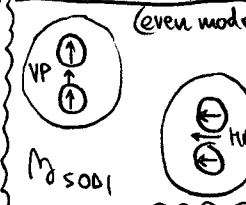
Vlakenski sklopniki:



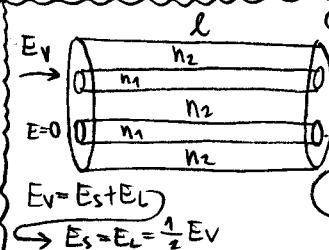
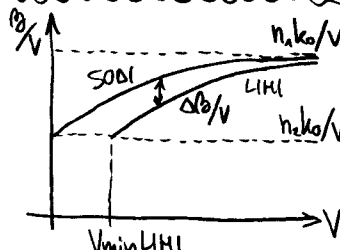
LI > 1000 λ, βs01 ≠ βs02

Blagi prehod
Samo sosednji sklop
Sosednji

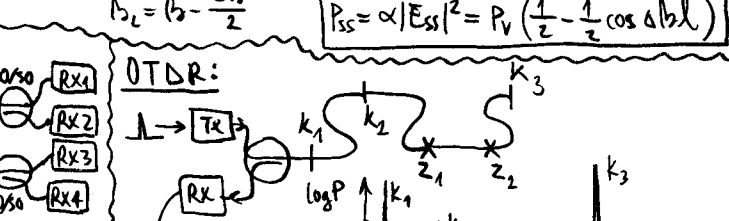
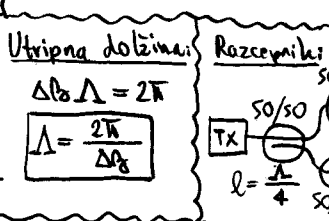
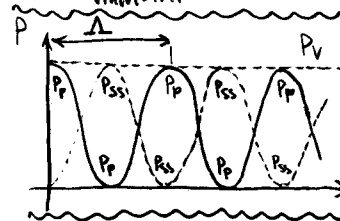
SODI (SOFARNI) ROD:



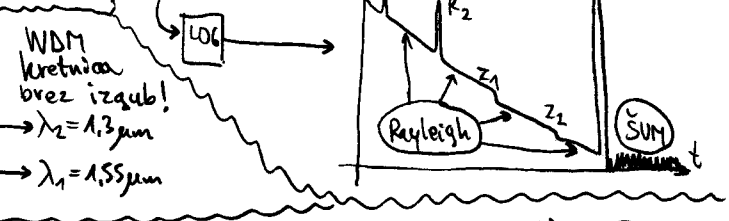
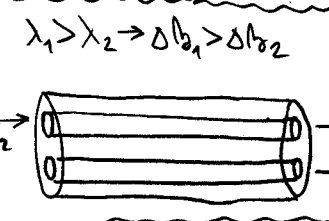
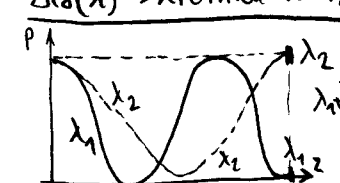
LIHI (PROTIFAZA) ROD:



PREPOST
 $E_p = E_s e^{-i\beta_s l} + E_r e^{i\beta_s l} = E_v e^{-i\beta_s l} \cos \frac{\Delta\beta l}{2}$
 $E_s = E_s e^{-i\beta_s l} - E_r e^{i\beta_s l} = -j E_v e^{-i\beta_s l} \sin \frac{\Delta\beta l}{2}$
 $E_v = E_s + E_r$
 $E_s = E_r = \frac{1}{2} E_v$
 $\beta_s = \beta_0 + \frac{\Delta\beta}{2}$
 $\beta_r = \beta_0 - \frac{\Delta\beta}{2}$
 $P_p = \alpha |E_p|^2 = P_v \left(\frac{1}{2} + \frac{1}{2} \cos \Delta\beta l \right)$
 $P_{ss} = \alpha |E_s|^2 = P_v \left(\frac{1}{2} - \frac{1}{2} \cos \Delta\beta l \right)$
kvadrant!

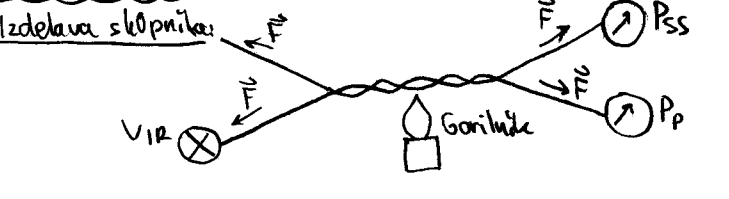
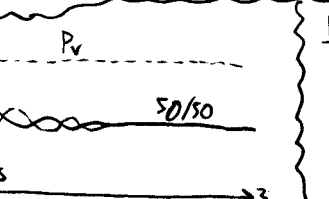


Δβ(λ) \rightarrow kretnica WDM:



MMF sklopni:

Vsak par rodov različni Δβ
Zelo občutljiv od porazdelitve rodov

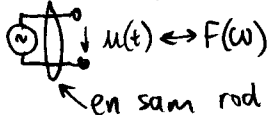


Optične komunikacije # 9

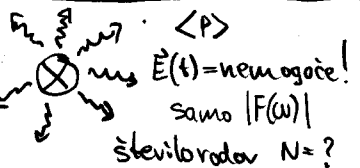
17/4/2014

Električni vir $< 1 \text{ THz}$

$\langle P \rangle$

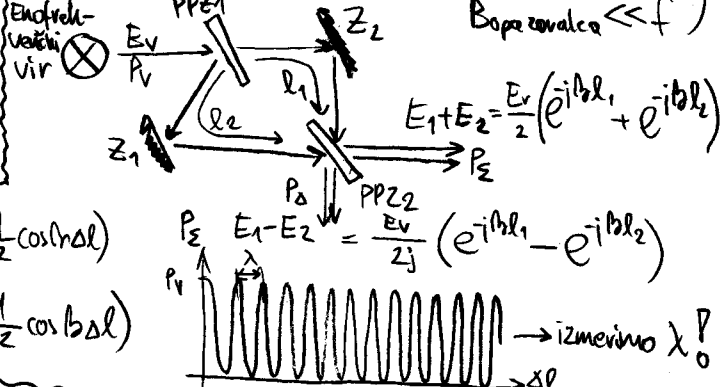


Svetlobni vir $f \approx 300 \text{ THz}$

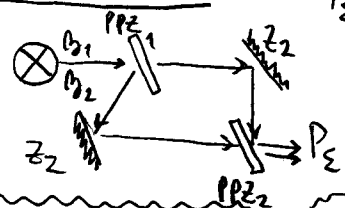


Interferometer:

(samo počasna meritev moči)
Bopozoralec $\ll f$



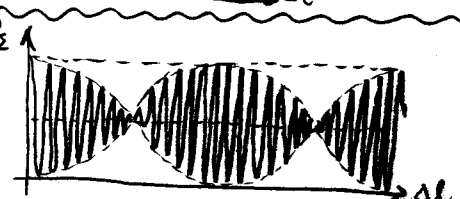
Dvofrekvenčni vir:



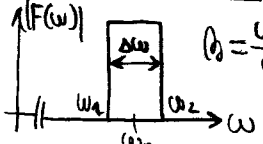
$$P_z = P_1 \left(\frac{1}{2} + \frac{1}{2} \cos \beta \Delta l \right) + P_2 \left(\frac{1}{2} + \frac{1}{2} \cos \beta \Delta l \right)$$

Zgled: $P_1 = P_2 = P_v/2$ (HeNe laser naleten)

$$P_z = P_v \left(\frac{1}{2} + \frac{1}{2} \cos \frac{\beta_1 + \beta_2}{2} \Delta l \cos \frac{\beta_1 - \beta_2}{2} \Delta l \right)$$

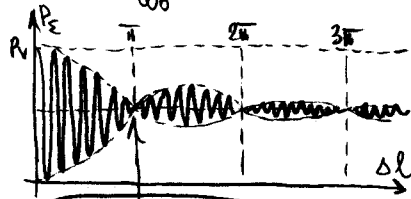


Zverni spekter $\Delta \omega$:



$$P_v = \frac{dP_v}{d\omega} \Delta \omega \rightarrow P_z = \int_{\omega_1}^{\omega_2} \frac{dP_v}{d\omega} \left(\frac{1}{2} + \frac{1}{2} \cos \frac{\omega}{c_0} \Delta l \right) d\omega = \frac{P_v}{\Delta \omega} \int_{\omega_1}^{\omega_2} \left(\frac{1}{2} + \frac{1}{2} \cos \frac{\omega}{c_0} \Delta l \right) d\omega = \frac{P_v}{\Delta \omega} \left(\frac{\Delta \omega}{2} + \frac{c_0}{2\Delta l} \sin \frac{\omega \Delta l}{c_0} \right)$$

$$P_z = P_v \left(\frac{1}{2} + \frac{c_0}{2\omega \Delta l} \left(\sin \frac{\omega_2 \Delta l}{c_0} - \sin \frac{\omega_1 \Delta l}{c_0} \right) \right) = P_v \left(\frac{1}{2} + \frac{1}{2} \cos \left(\frac{\omega_0 \Delta l}{c_0} \right) \cdot \frac{\sin \frac{\Delta \omega \Delta l}{2c_0}}{\frac{\Delta \omega \Delta l}{2c_0}} \right)$$



$$\sin \frac{\Delta \omega \Delta l}{2c_0} = 0$$

$$\frac{\Delta \omega \Delta l}{2c_0} = \pi = \frac{2\pi \Delta f \Delta l}{2c_0}$$

vzdolžna koherenčna dolžina d

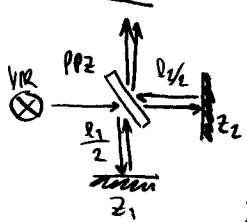
$$d = \frac{c_0}{\Delta f}$$

Valovna dolžinska širina:

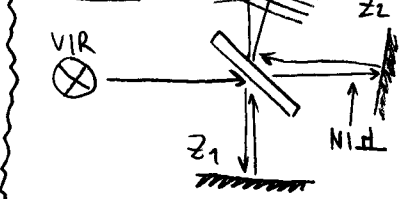
$$\lambda = \frac{c_0}{f} \rightarrow \frac{d\lambda}{df} = -\frac{c_0}{f^2} \rightarrow |\Delta \lambda| = \frac{c_0}{f^2} |\Delta f| = \frac{\lambda^2}{c_0} |\Delta f|$$

$$\frac{d\lambda}{df} = -\frac{c_0}{f^2} \rightarrow d = \frac{c_0}{\Delta f} = \frac{\lambda^2}{\Delta \lambda}$$

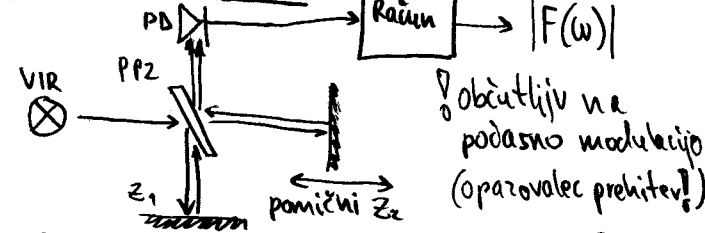
Michelson:



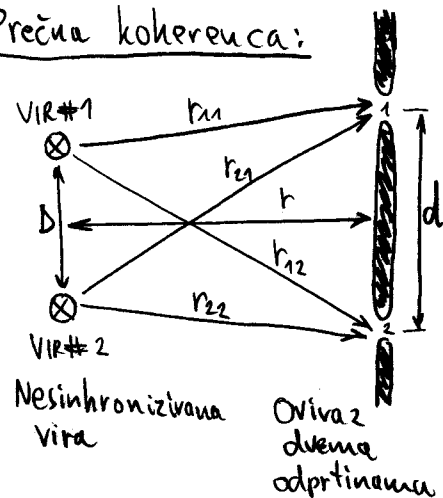
Neporavnan Michelson:



Interferometrijski SA:



Prečna koherenca:



Interferenčne proge izhajajo (vir #1 in vir #2 se prekrivata), ko velja $(r_{12} - r_{11}) - (r_{22} - r_{21}) = \frac{\lambda}{2}$

$$d, D \ll r \rightarrow r_{12} = r_{21} = \sqrt{r^2 + \left(\frac{d+D}{2} \right)^2} \approx r + \frac{(d+D)^2}{8r}$$

$$r_{11} = r_{22} = \sqrt{r^2 + \left(\frac{d-D}{2} \right)^2} \approx r + \frac{(d-D)^2}{8r}$$

$$\frac{\lambda}{2} = r + \frac{(d+D)^2}{8r} - r - \frac{(d-D)^2}{8r} = r + \frac{(d+D)^2}{8r} - r - \frac{(d-D)^2}{8r} = \frac{2dD + 2dD + 2dD + 2dD}{8r} = \frac{dD}{r}$$

$$d = \frac{\lambda r}{2D}$$

prečna koherenčna dolžina d

Enovredni vir: $d_{prečna} \rightarrow \infty$

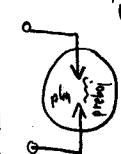
žarnica z nitko:

→ TOPLLOTNI VIR



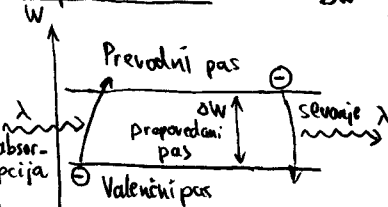
~ belišum
~ nizka prečna koherenca
 $\tau = 1\text{ms} - 100\text{ms}$

Tlilka, oblačnica: $\Delta W = hf = \frac{hc}{\lambda}$



Ravni energije
 $\tau \approx 1\text{ms} - 100\text{ms}$
 $\lambda = \frac{hc}{\Delta W}$
→ sevalni prehodi
→ nesvalni prehodi
Tlilka → majhen Doppler, Oblačnica → velik τ , trki

Polprevodniki: $\lambda = \frac{hc}{\Delta W}$



sevalni prehod → foton
nesvalni prehod → fonon

$M_{Si} \approx 0,01\%$

$M_{GaAs} \approx 50\%$

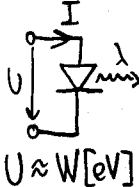
Merska enota eV:

$$h = 6.626 \cdot 10^{-34} \text{ Js}$$

$$W = hf = \frac{hc}{\lambda} = |Q_e| U \quad Q_e = -1.6 \cdot 10^{-19} \text{ As}$$

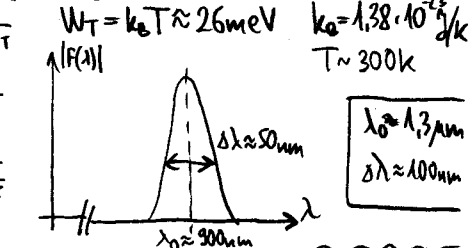
$$W[\text{eV}] = \frac{W[\text{J}]}{|Q_e|} = \frac{hc}{\lambda |Q_e|} = \frac{1.24 \text{ eV} \cdot \mu\text{m}}{\lambda[\mu\text{m}]}$$

Spekter LED:

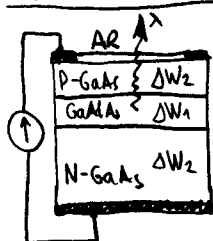


$$U \approx W[\text{eV}]$$

$$N_e = \alpha e^{-\frac{W}{kT}}$$



Heterostruktural ED:



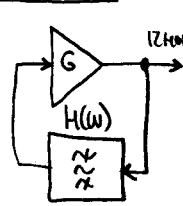
$\Delta W_1 < \Delta W_2$
Ni absorpcije v oblagah!

$$\tau = 10\text{ns} - 1\mu\text{s}$$

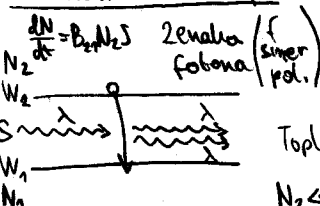
Nehoherenčni vir:

6651
 $M_{MHF} \approx 1\%$
6652
 $M_{SHF} < 0,1\%$
slab stolpni izvoristek

Oscilator:



Stimulirano sevanje:



$$\text{Absorpcija: } \frac{dN}{dt} = B_{12} N_1 S$$

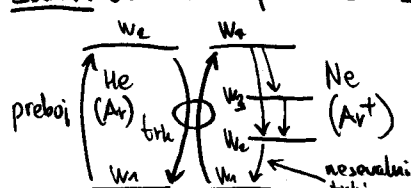
$$\text{Spontano sevanje: } \frac{dN}{dt} = A_{21} N_2$$

$$\text{Fizika: } B_{21} = B_{12} \frac{\Delta W}{\omega}$$

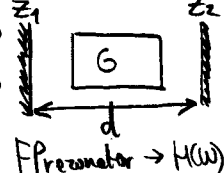
$$\text{Toplotno ravnovesje: } \frac{N_1}{N_2} = e^{\frac{W}{kT}}$$

$N_2 \ll N_1 \rightarrow$ stimulirano sevanje je zanemarljivo majhno

Laser: obratna naseljenost $N_2 > N_1$



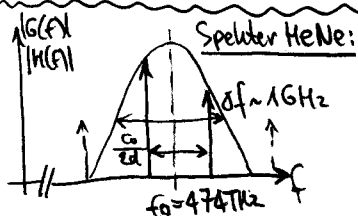
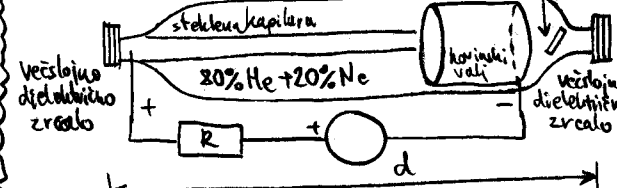
Oscilator:



rodovi TEM00m

$$f = m \frac{c_0}{2d}$$

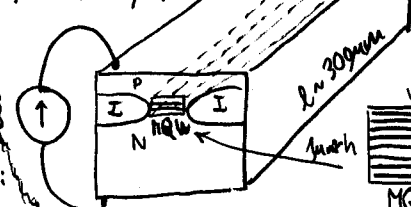
HeNe laser: $G/L \approx 1\text{dB/m}$



Spekter HeNe:

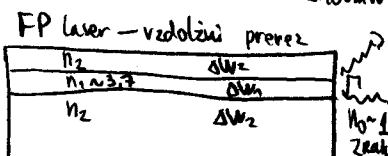
Polprevodniški laser:

$$G/L \approx 10^4 \text{ dB/m}$$



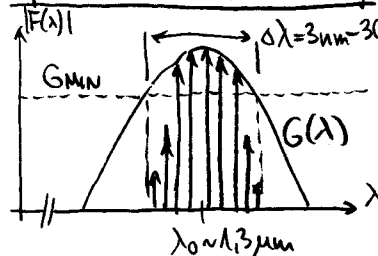
$W > 10\mu\text{m} \rightarrow$ prečni rodovi, močnejši laser

$W < 10\mu\text{m} \rightarrow$ samo vzdolžni rodovi, TK laser $< 100\text{mW}$

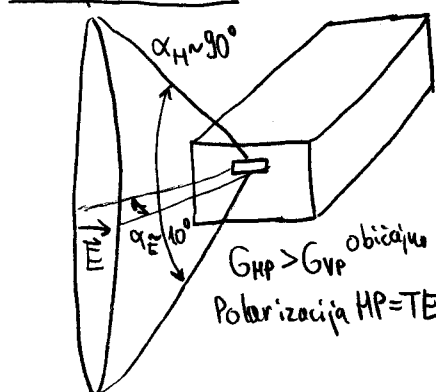


$n_1 > n_2 \rightarrow$ valovod n_1/n_2
 $\Delta W_1 < \Delta W_2 \rightarrow$ ni absorpcije v oblagah n_2

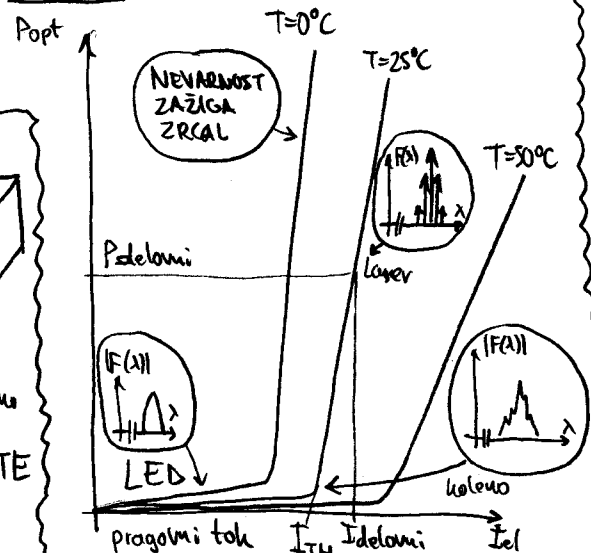
Spekter InGaAsP-FP laserja:



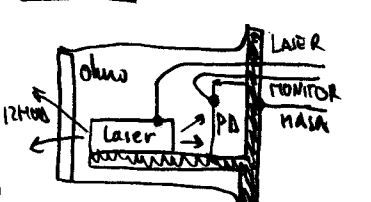
Sevanje FP laserja:



Modulacijska krivulja:



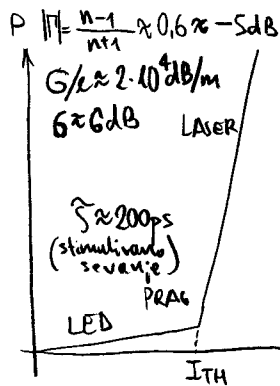
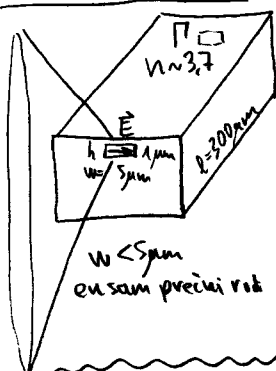
Ohišje laserja:



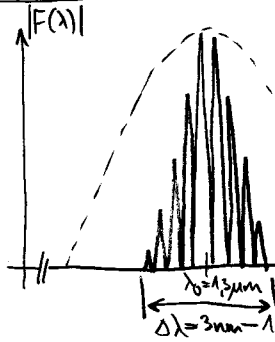
Snop nazaj uporabimo za monitoring fotodiode!

	ITH	Idelovni
1980	80mA	100mA
1995	15mA	25mA
danes	1mA	10mA

Ponovitev: FP laser



Spekter FP laserja:



$$\lambda_0 = 1,3 \mu\text{m} \rightarrow f_0 = \frac{c_0}{\lambda_0} = 230 \text{ THz}$$

$$G(\lambda) = \text{spekter LED}$$

$$f = m \frac{c_0}{2Ln} \text{ za Terboom}$$

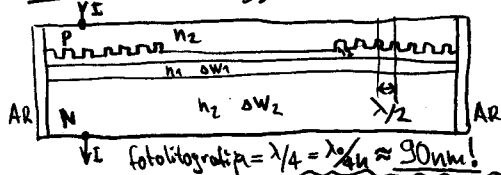
$$\Delta f = \frac{c_0}{2Ln} = 135 \text{ GHz}$$

$$\Delta f' = \frac{\Delta \lambda c_0}{\lambda^2} = 1,8 \text{ THz}$$

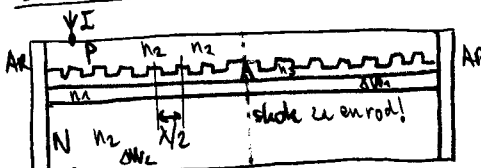
$$N_{\text{modov}} = \frac{\Delta f'}{\Delta f} = 13 \text{ modov}$$

preskakanje med modovi → šum!

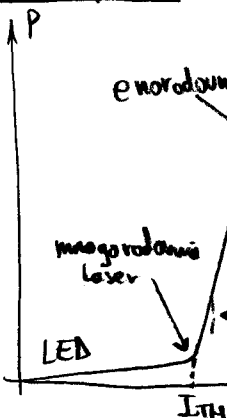
Distributed Bragg Reflector = DBR



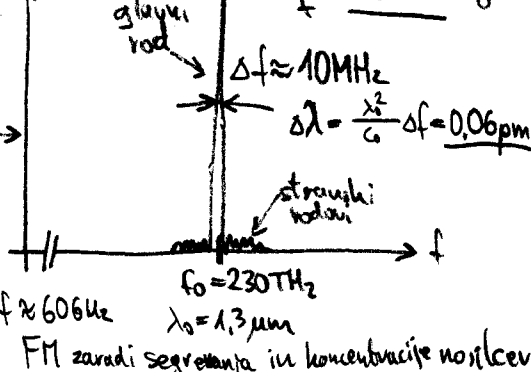
Distributed Feed-Back = DFB



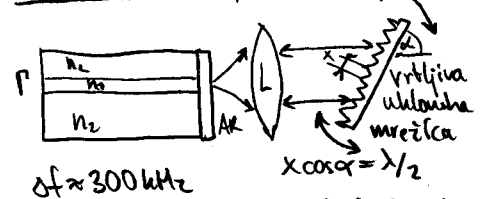
Modulacija DFB1



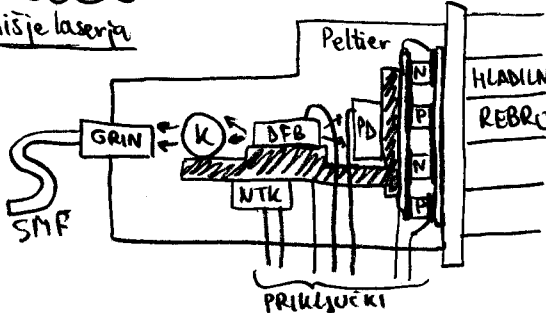
NF(f)



External Cavity = EC Mehanka =



Ohišje laserja



Koherenčna dolžina

$$L_{\text{zdolžina}} d = \frac{c_0}{\Delta f}$$

FP $\Delta f = 1,8 \text{ THz} \rightarrow d = 170 \mu\text{m}$
 DFB $\Delta f = 10 \text{ MHz} \rightarrow d = 30 \text{ m}$
 EC $\Delta f = 300 \text{ kHz} \rightarrow d = 1 \text{ km}$

Ločitev oscilatorji:

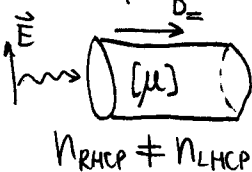
- neregularni optični valnik
- neregularni pasivni gradnik = IZOLATOR

YIG ferit v \vec{B}_0 :

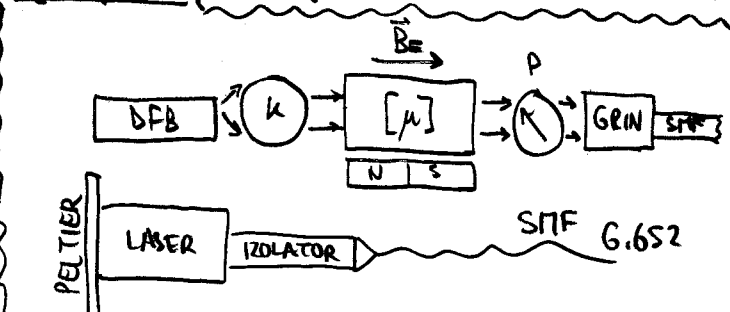
$$[\mu] = \begin{bmatrix} \mu_1 & j\mu_2 & 0 \\ -j\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix}$$

neregularni tenzor!

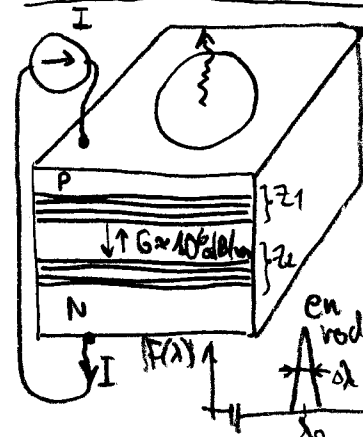
Faraday: \vec{B}_0



Vgradnja DFB1



Vertical Cavity Surface Emitting Laser = VCSEL



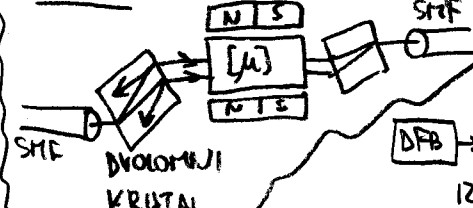
SMF 9/125 ali MMF 50/125

$$\lambda = 850 \text{ nm} \text{ ali } \lambda = 1,3 \mu\text{m}?$$

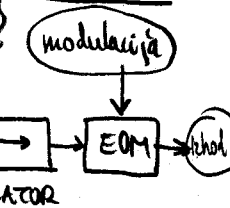
sklop brez leč



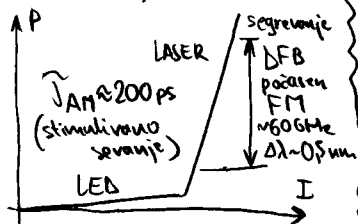
Polarizacijsko neodvisni izolator



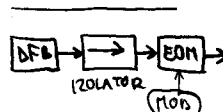
Zunanji modulator



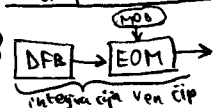
Ponovitev: nepovredna modulacija FP/DFB



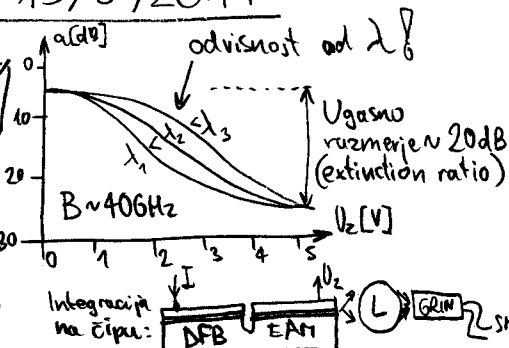
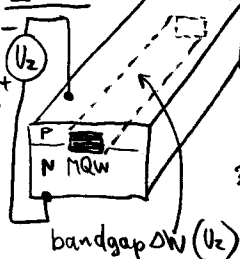
Vrhuški Tx:



Srednje kakovosten Tx:



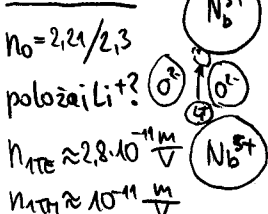
EAM:



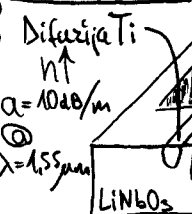
Kerr in Pockels:

$n(E) = n_0 + n_1 E + n_2 E^2 + \dots$
 Kerr = $n_2 E^2$
 Pockels = $n_1 E$
 $E = E_m + E_0$
 $E^2 = (E_m + E_0)^2 = E_m^2 + 2E_m E_0 + E_0^2$

LiNbO₃:

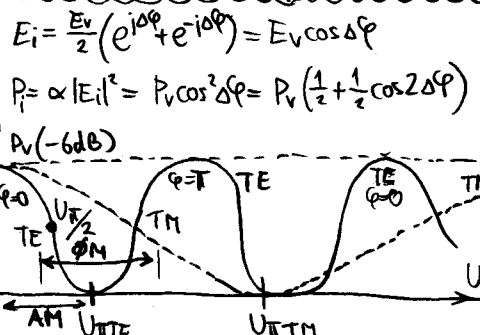
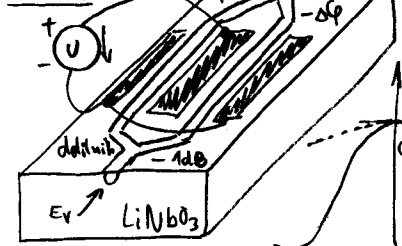


Valovod LiNbO₃:

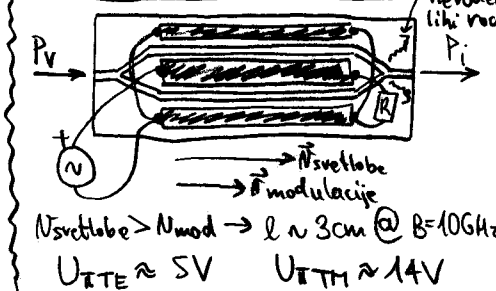


$d = 10 \mu m$
 $U = 5V$
 $E_m = \frac{U}{d} = 5.10^5 \frac{V}{m}$
 $\Delta n = n_1 E_m = 1.4 \cdot 10^{-5} (TE)$
 $l = 5 cm$
 $\Delta \phi = \Delta n l / \lambda = 0.84 rad = \text{fazni modulator}$

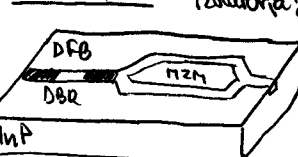
MZM:



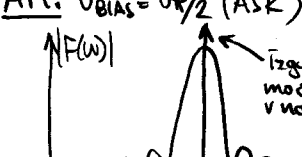
Elektrode na potujoči val:



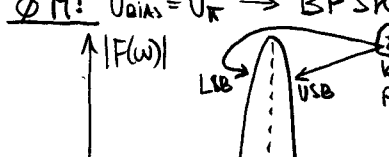
DFB + MZM: brez izolatorja!



AM: U_{bias} = U_π/2 (ASK)

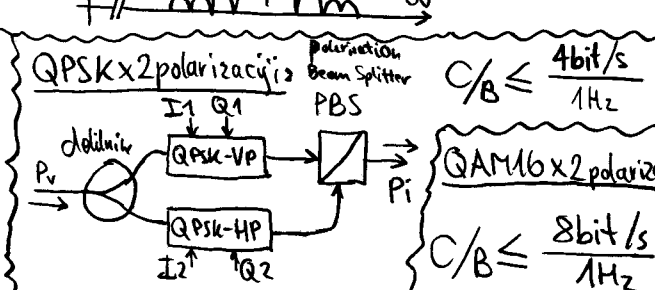
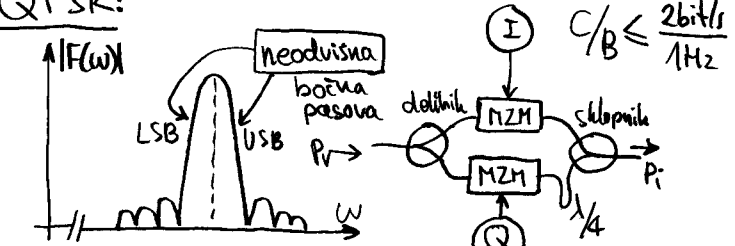


QPM: U_{bias} = U_π → BPSK



Spektralna učinkovitost:
 $C/B \leq \frac{1 \text{ bit/s}}{1 \text{ Hz}}$

QPSK:



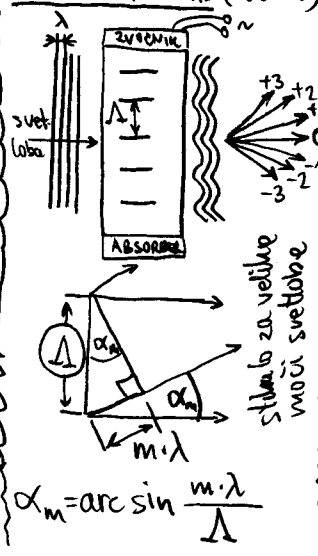
Zvok: (ultrazvok)

plini $f < 100 \text{ kHz}$
 tekočine $f < 100 \text{ MHz}$
 trdne snovi $f < 10 \text{ GHz}$

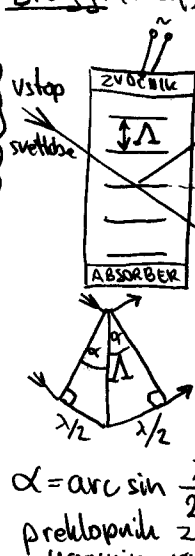
zgošnje/rezredčine

modulacija $n(x)$
 uklonska mrežica za svetlobo $\approx \lambda$
 stikala, preklonilni akustoptična sita

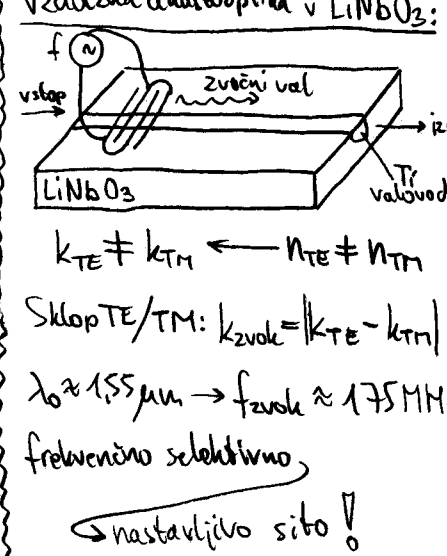
Raman-Nath: (uklon)



Bragg: (odboj)

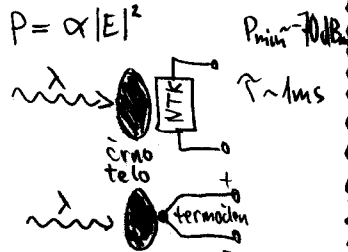


Vzdržna akustoptika v LiNbO₃:

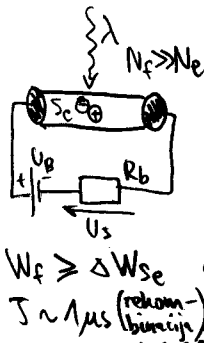


Polprevodniki: $f_{max} \approx 1 \text{ THz}$
GaAs Schottky

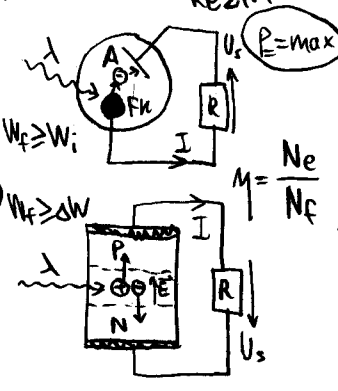
Toplotni sprejemnik:



Fotoupor: Se (1873)



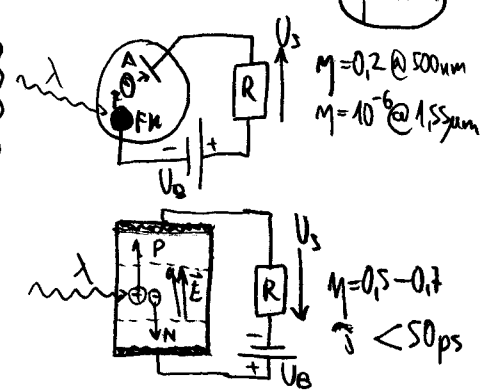
Fotodioda:



FOTOVOLTAINI REŽIM

FOTOUPOROVNI REŽIM

REŽIM ($M = \max$)



Ponovitev: $W [\text{eV}]$

$$W [\text{eV}] = \frac{W [J]}{|Q_e|} = \frac{h c_0}{|Q_e| \lambda}$$

$$h = 6,626 \cdot 10^{-34} \text{ Js}$$

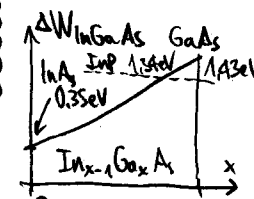
$$Q_e = -1,6 \cdot 10^{-19} \text{ As}$$

$$W [\text{eV}] = \frac{1,24 \text{ eV} \cdot \mu m}{\lambda [\mu m]}$$

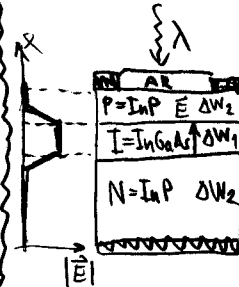
Bandgap:

$$\Delta W_{Si} = 1,1 \text{ eV}$$

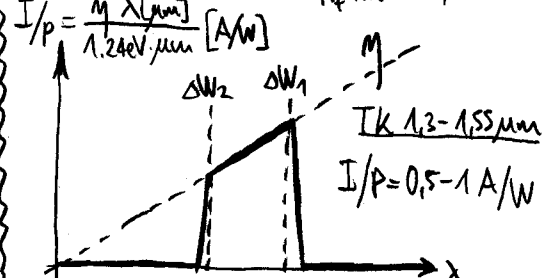
$$\Delta W_{Ge} = 0,67 \text{ eV}$$



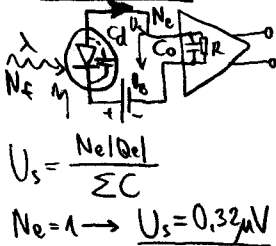
Hetero struktura:



$$\text{Odzivnost: } I/p = \frac{dQ/dt}{dW/dt} = \frac{N_e Q_e \lambda}{N_f h c_0} = \eta \frac{Q_e}{h c_0} \lambda$$



Občutljivost RX: $\Sigma C = C_d + C_0 \approx 0,5 \text{ pF}$



Znatišum: Poisson

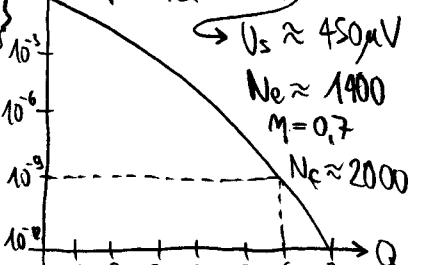
$\langle N_e \rangle$ povprečno število elektronov
 $p(N_e) = \frac{N_e!}{N_e!} e^{-\langle N_e \rangle}$
 $BER = p(0) = 10^{-9}$
 $\langle N_e \rangle = 21 / U_s = 6,7 \mu V$

Toplotni šum: $T = 300 \text{ K}$

$P_n = B k_B T$ $k_B = 1,38 \cdot 10^{-23} \text{ J/K}$
 $B = \frac{1}{2 \pi R \Sigma C}$ $U_{nff} = \sqrt{P_n R}$
 $U_{nff} = \sqrt{\frac{k_B T}{2 \pi \Sigma C}} \approx 36 \mu V_{eff}$
Znati $U_{nff} = \frac{10 \mu V}{\Sigma C} \ll U_{nff, toplotni}$

Razmerje $S/N = Q = \frac{\langle U_n \rangle - \langle U_0 \rangle}{\sigma_1 + \sigma_0}$

$BER = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right)$
 $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du$



Zaled: zveza C=16 Gbit/s

50% enic $\rightarrow \langle N_f \rangle = \frac{N_f}{2} = 1000$

$\frac{d\langle N_f \rangle}{dt} = \langle N_f \rangle \cdot C = 10^{12} \text{ fotonov/s}$

$P = W_f \frac{d\langle N_f \rangle}{dt} = \frac{h c_0}{\lambda} \frac{d\langle N_f \rangle}{dt} = \frac{W_s}{6,5 \cdot 10^{13}} \frac{d\langle N_f \rangle}{dt}$
 $\lambda = 1,3 \mu m$

$P = 1,53 \cdot 10^{-7} \text{ W} = -38,2 \text{ dBm}$

Domet: $P_{rx} = 10 \text{ mW} = +10 \text{ dBm}$

točka-točka

$P_{rx}/P_{tx} = 48,2 \text{ dB}$

$\alpha/k = 0,35 \text{ dB/km}$

$l = 137 \text{ km}$

(16 Gbps)

$P_{rx}/P_{tx} = 48,2 \text{ dB}$

$\alpha/k = 0,35 \text{ dB/km}$

$l = 137 \text{ km}$

(16 Gbps)

PON 100 Mbps



Recep -3 dB \rightarrow -3,5 dB

64 upodobnikov

6 razvepov \rightarrow -2,4 dB

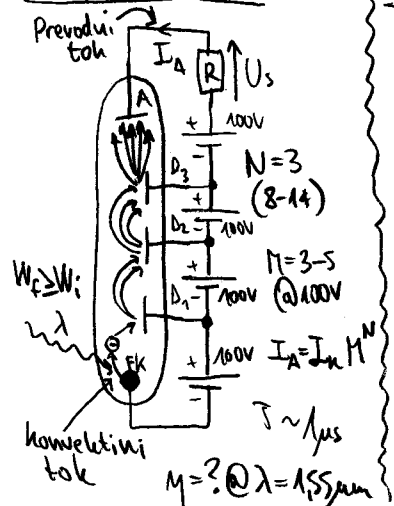
64 upodob. x 100 Mbps = 6,4 Gbps

(-8 dB)

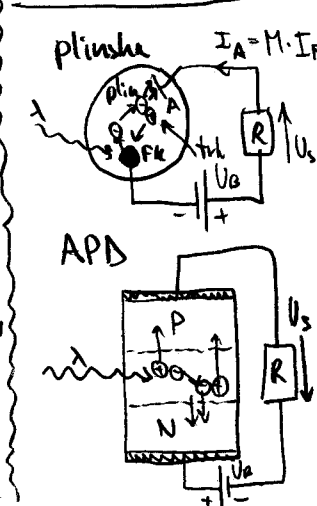
domet = 48 dB - 8 dB - 2,4 dB = 37,6 dB

= 1,9 dB !!! MAJO REZERVO!

Fotopomnoževalka:

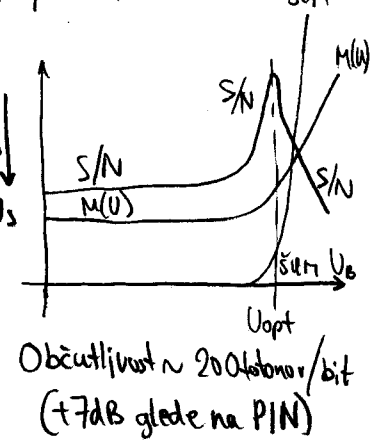
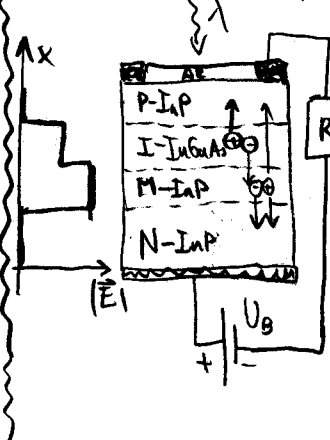


Plazovne fotodioda:



Izvedba APD:

Ge	1,3 μm	M=10	$U_b = 30 \text{ V}$
Si	0,85 μm	M=100	$U_b = 150 \text{ V}$
InGaAsP	1,55 μm	M=20	$U_b = 70 \text{ V}$



Občutljivost $\sim 20 \text{ fotonov/bit}$
(+7 dB glede na PIN)

Ponovitev: \sum

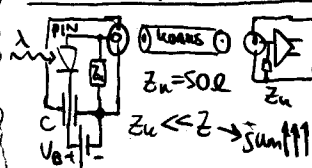


PIN-FET ~ 1000 fotony/bit

APD-FET ~ 200 fotony/bit

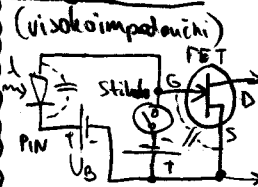
hlajen APD ~ 60 fotony/bit
(samo Si vidna svetloba)

Nizkoimpedančni RX:



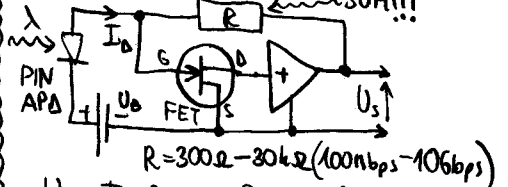
$Z_u \ll Z_L \rightarrow \sum$!!!
širokopasovna merilna
tehnika $\rightarrow \sum$!!!
 $10^4 - 10^6$ fotony/bit

Integracijski RX:



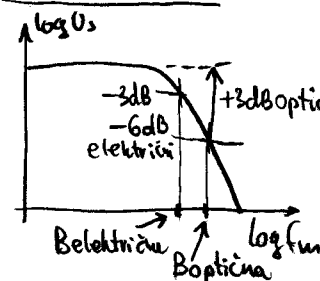
(visokoimpedančni)
teoretska občutljivost!
težavo kamiljenje
stihala (reset)?

Transimpedančni RX:



$R = 300\Omega - 30k\Omega$ (100nbp/s - 106bp/s)
 $U_s = I_D \cdot R_T$ $R_T \sim R$, $R_T < R$
Moduli: PIN-FET ali APD-FET
TRANSHIPEDANCA
 \rightarrow optična B!

Pasovna širina:



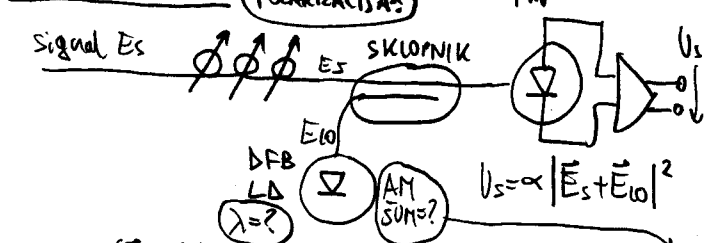
$$U_s = I_D R_T = R_T (I/P) P = R_T (I/P) A \frac{|E|^2}{2\epsilon_0}$$

$$U_s = \alpha |E_{opt}|^2$$

$$P_{el} = \frac{U_s^2}{R_b} = \alpha' P_{opt}^2$$

Kvadratni odziv
detektorja moči!

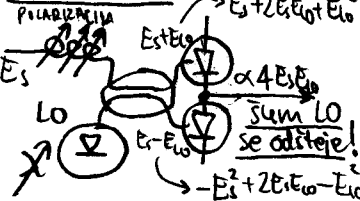
Koharentni RX:



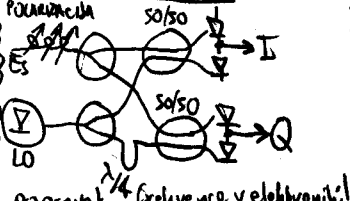
$$U_s = \alpha (\vec{E}_s + \vec{E}_0)(\vec{E}_s + \vec{E}_0)^* = \alpha (|\vec{E}_s|^2 + \vec{E}_s \vec{E}_0^* + \vec{E}_s^* \vec{E}_0 + |\vec{E}_0|^2)$$

običajno $|\vec{E}_s| \ll |\vec{E}_0|$
dobitek $\approx 2|\vec{E}_0|/|\vec{E}_s|$
MEJANJE
FREKVENCA=?
POLARIZACIJA=?

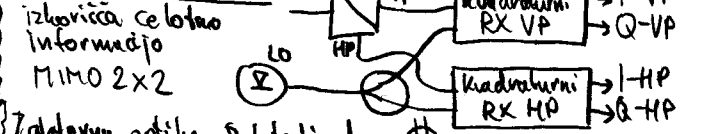
Balanci RX:



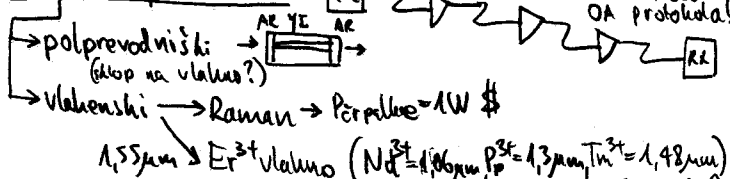
Kvadraturni RX:



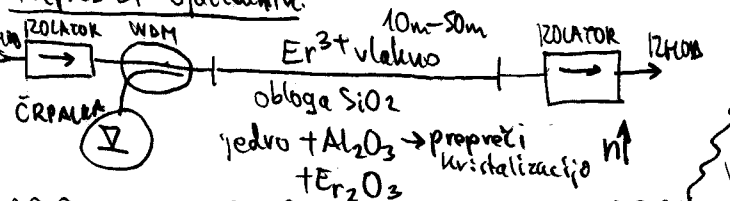
Dvopolarizacijski RX:



Optični ojačevalnik:



Preprosti Er^{3+} ojačevalnik:



ASE šum ojačevalnika: (za vsakod valovanja)

$$P_{ASE} = \mu(G-1)hf\Delta f \quad \mu = \frac{N_2}{N_2 - N_1}$$

Zgled: $\lambda_c = 980nm \rightarrow \mu \approx 1$

$$G = 40dB = 10^4 = 10000$$

$$h = 6.626 \cdot 10^{-34} Js$$

$$f = 194THz (\lambda = 1.55\mu m)$$

$$\Delta f = 4THz (\text{širina } Er^{3+} \text{ v } SiO_2)$$

$$P_{ASE} = 5.1mW!!! \text{ za en rod}$$

$$VP+HP, napretnazuj \rightarrow 4P_{ASE} = 20.6mW$$

$$P_o = P_{ASE} \frac{\lambda_{ASE}}{\lambda_c} = 33mW!!!$$

Definicija šumnega števila:

$$F[dB] = 10 \log_{10} \frac{(S/N)_{VHOD}}{(S/N)_{IZHOD}} = 10 \log_{10} \frac{\frac{P_s}{\frac{1}{2}hf\Delta f}}{\frac{G P_s}{\frac{1}{2}hf\Delta f P_{ASE}}} = 10 \log_{10} 2\mu$$

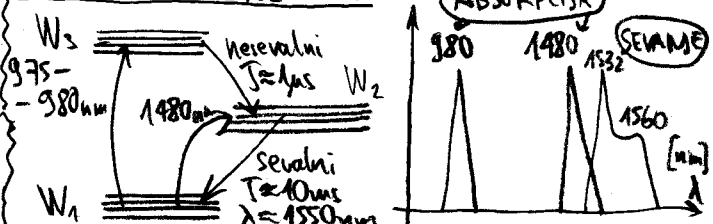
Zgledi F:

$$Er^{3+} \text{ v } SiO_2 + 980nm \rightarrow F = 3dB - 3.5dB$$

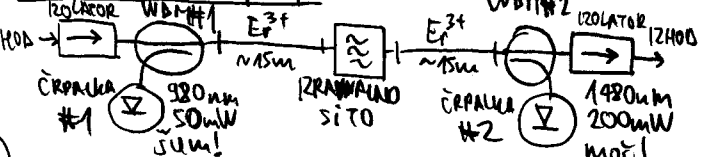
$$Er^{3+} \text{ v } SiO_2 + 1480nm \rightarrow F = 4dB - 5dB$$

$$\text{Aslprevedniški} \rightarrow F = 6dB - 9dB \text{ (izgube širine čip-vlakna)}$$

Lastnosti Er^{3+} v SiO_2 stekla:



Dvosmerno čipanje:

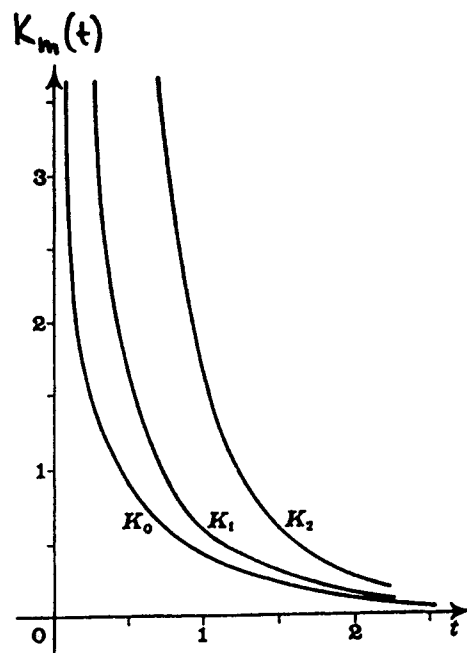
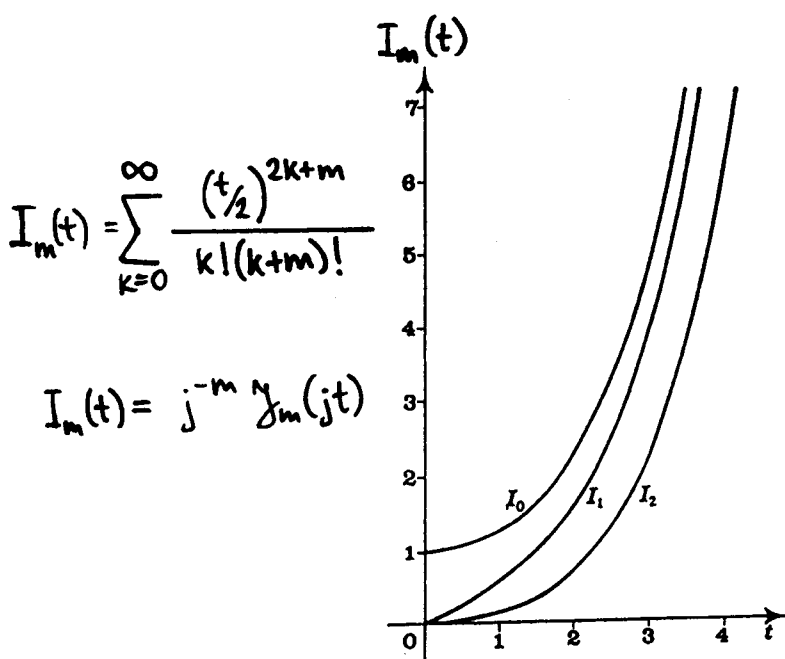
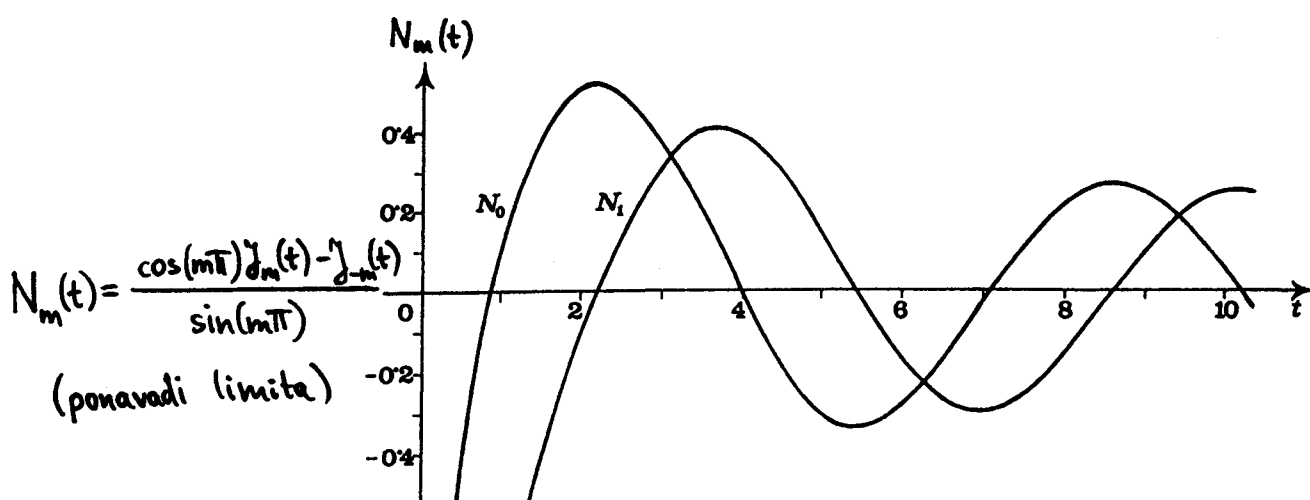
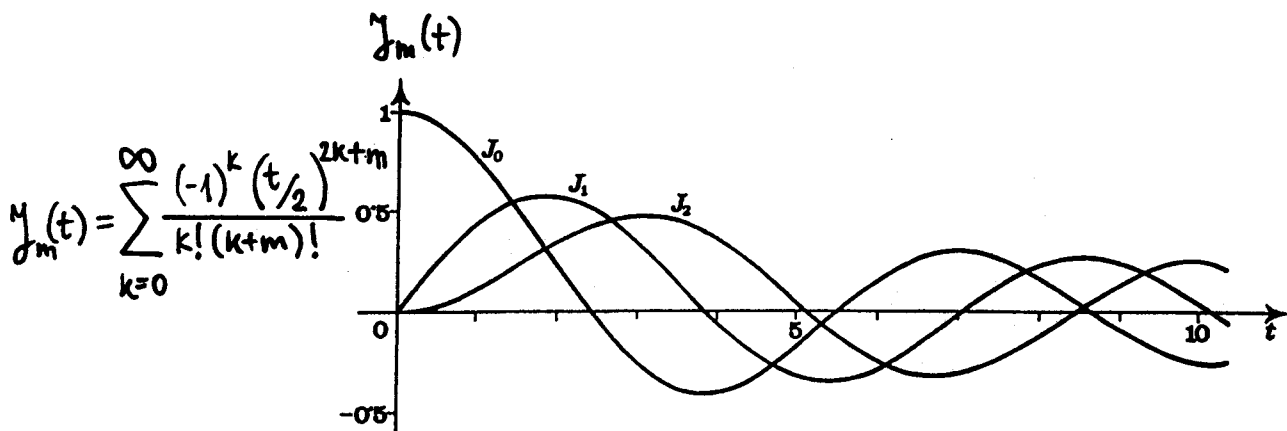


$$\text{Zračni šum } P_z = \frac{1}{2} hf \Delta f$$

Optične komunikacije #15 - 5/6/2014

1. Kratka zgodovina Etherneta, Robert Metcalfe.
2. Thick Ethernet 10BASE5, komplicirano in drago omrežje, jabber limit.
3. Oznake Ethernet inačic.
4. Zasnova Ethernet okvirja.
5. Thin Ethernet 10BASE2, ceneno omrežje z BNC vtičnicami.
6. Računalniški duh uide iz steklenice, zmagovita pot TCP/IP in Etherneta.
7. TCP/IP Ethernet okvirji in omrežja.
8. Address Resolution Protocol (ARP).
9. Neoklopljena sukana parica (UTP), zvrsti UTP/STP vodnikov.
10. Vtikač in trafo vtičnica RJ45.
11. Linijska kodiranja Manchester, 4B5B in MLT3.
12. Delovanje 10BASE-T in 100BASE-TX.
13. OSI ravni, TCP/IP/Ethernet/UTP sklad protokolov.
14. Nadzor pretoka (Flow control), backpressure in pause frame.
15. Različice Media-Independent Interface (MII).
16. Reduced Media-Independent Interface (RMII).
17. 100BASE-TX 3R regenerator (Extender).
18. 100BASE-TX/100BASE-FX Media Converter.
19. Hub v središču zvezde UTP kablov za način delovanja half-duplex.
20. Aktivno Ethernet stikalo, uporaba v domačem usmerjevalniku.
21. Virtual Local Area Network (VLAN).
22. Zgodovina optičnega Etherneta.
23. Linijsko kodiranje v optičnem Ethernetu.
24. Različice 1Gbps Media Converter-jev.
25. Ethernet standardi 40Gbps in 100Gbps.
26. Uspehi in neuspehi Etherneta, kaj je to Ethernet danes?
27. Vprašanja študentov o Ethernetu, opis delovanja PoE.
28. Predstavitev izbirnih predmetov modula K.

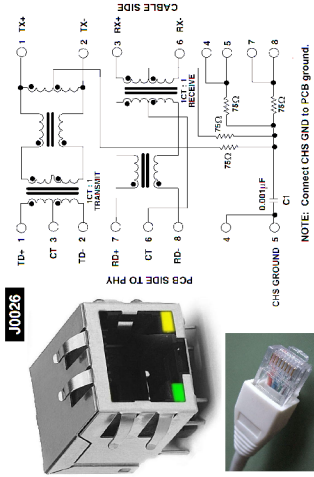
Valjne funkcije:



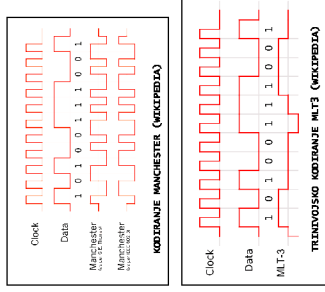


Zvrst	Cat1	Cat2	Cat3	Cat4	Cat5	Cat5e	Cat6	Cat6a	Cat7	Cat7a
Izvedba	UTP	UTP	UTP	UTP	UTP	UTP	UTP	UTP	UTP	S/FTP
B [MHz]	0.4	4	16	20	100	100	250	500	600	1000
10BASE-T	-	-	-	-	-	-	-	-	-	-
100BASE-T	-	-	-	-	-	-	-	-	-	-
1000BASE-T	-	-	-	-	-	-	-	-	-	-
10GBase-T	-	-	-	-	-	-	-	-	-	-
10GBase-P	-	-	-	-	-	-	-	-	-	-

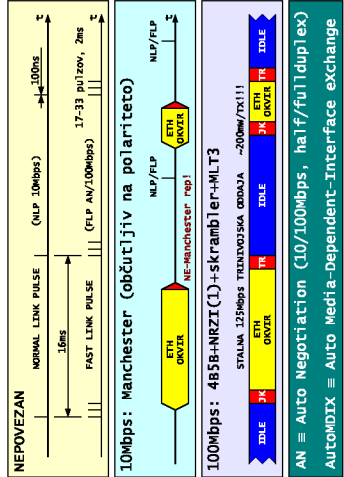
13 - Zvrstni UTP/STP vodniki



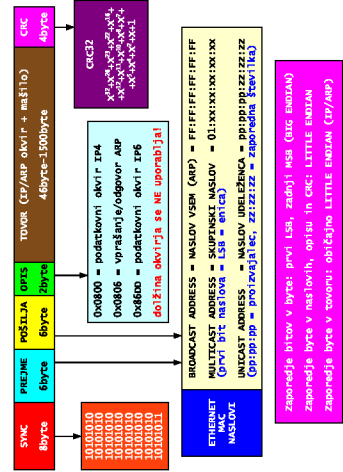
14 - Vtičnik in trafo vtičnica RJ45



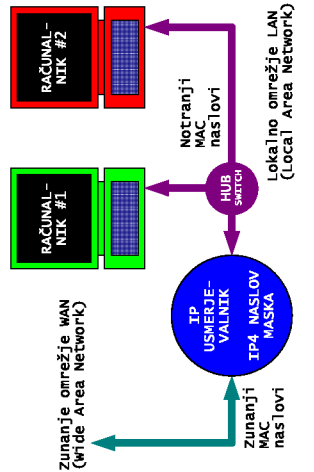
15 - Manchester, 4858 in MLT3



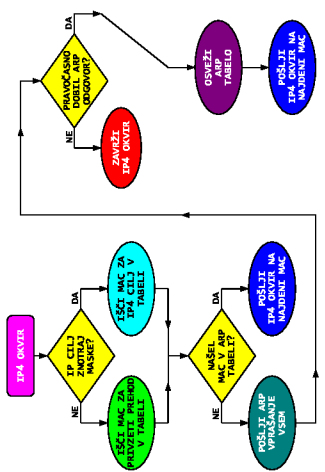
16 - Delovanje 10BASE-T in 100BASE-TX



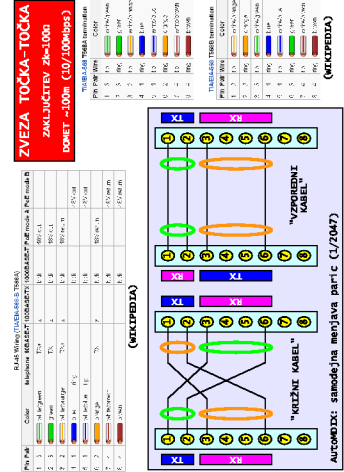
9 - TCP/IP Ethernet okvirji



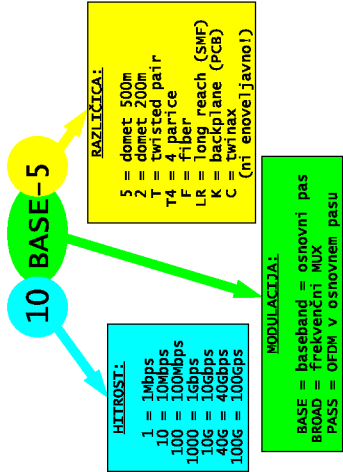
10 - TCP/IP Ethernet omrežja



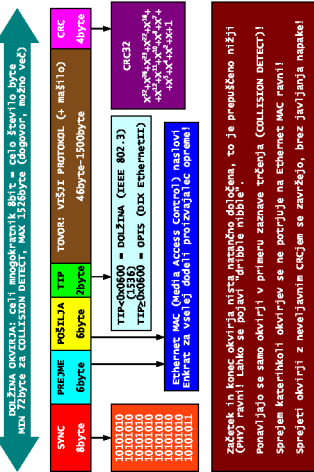
11 - Address Resolution Protocol (ARP)



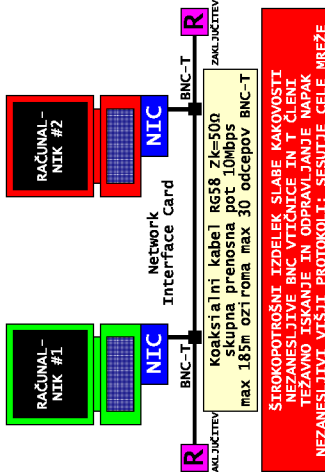
12 - Neoklopljena sukana parica (UTP)



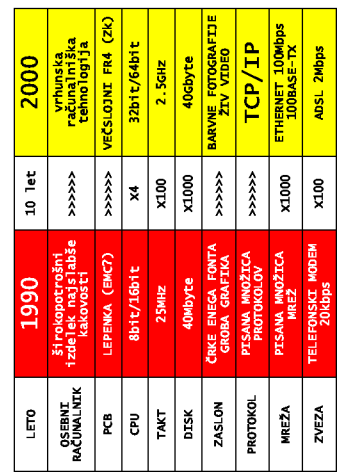
5 - Oznake Ethernet in način



6 - Zasnova Ethernet okvirja



7 - Thin Ethernet 10BASE2

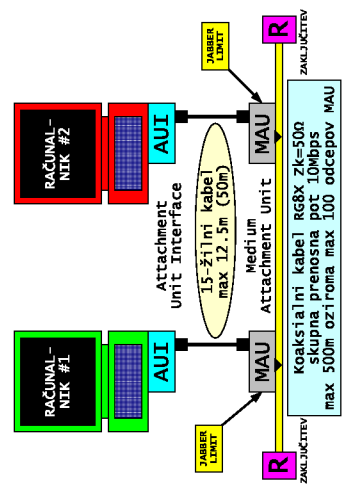


8 - Računalniški duh uide iz steklenice

pr. n.š. - svetlobni signali (naprava in protokol)
-1830 - električni telegraf (naprava) več izumiteljev
-1865 - mednarodna telegrafska abeceda (standard)
-1880 - analoga komunikacija (naprava) Bell-ov telefon
-1900 - radijska zveza (naprava) Marconi
-1912 - elektronsko ojačanje (obdelava) Meissner
-1930 - frekvenčni prostor (naprava) Armstrong
-1948 - teorija informacije (protokol) Shannon
-1957 - umetni satelit (naprava) hladna vojna
-1965 - svetlobno vlakno (naprava) čisti stihicij / siol
-1970 - paketni prenos (protokol) mikrorazdaljnik
-1980 - sklad protokolov (protokol) OSI ravnj
-1990 - svetovni splet (standard) HTTP
-2000 - združljivost in odpornost na napake (naprava)
-2000 - Peer-to-Peer omrežja (protokol) skype
-2000 - WLAN-WiFi (standard) neličniciran in globalni
-15.06.2018 - izklop javnega telekomunikačnega omrežja v ZDA
1 - Mejniki v zgodovini telekomunikacij

1971: radijsko paketno omrežje ALOHNet (U. Hawaii)
1973: Robert Metcalfe in sodilavci (Xerox)
1973: skupna prenosna pot = "ETHER" = koks 2.94Mbps
Sodostop CSMA/CD = Carrier-Sense Multiple Access / Collision Detect
1972: univerza Harvard zavrne Metcalfe-jev doktorat
1979: Metcalfe ustanovi podjetje 3com za Ethernet opremo
1990: managerji odstranijo Metcalfe-ja na vrhuncu uspeha 3com
2 - Kaj je bil Ethernet pred 40 leti (1973)?

1973 - prvo omrežje (2.94Mbps) na skupnem vodilu "Ether",
8-bitni naslovi, CSMA/CD sodostop (Xerox, ZDA)
1980 - 10Mbps, Manchester, 48-bitni MAC naslovi, 16-bitni opis vsebine, dix EthernetII (Digital-Intel-Xerox)
1982 - 10Mbps 10BASE5 Thick Ethernet, MAU priključ na vodilo RG58 (debel koks) z donetom 500m
1985 - 10Mbps 10BASE2 Thin Ethernet, BNC priključ na vodilo RG58 (tanek koks) z donetom 185m
1990 - 10Mbps 10BASE-T, dve parici (UTP), donet 100m točka-točka, omrežje zvezda do Ethernet hub
1995 - 100Mbps 100BASE-TX, MLT3, dve parici (UTP), donet 100m točka-točka, omrežje zvezda do ethernet stikala (switch), full-duplex, auto-negotiation
1999 - 1Gbps 1000BASE-T, štiri parice (UTP), 100m
2003 - PoE (UTP) in 10Gbps ETH po svetlobnem vlaknu
2010 - prvi standardi za 40Gbps in 100Gbps Ethernet
3 - Kratka zgodovina Etherneta



4 - Thick Ethernet 10BASE5

