

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

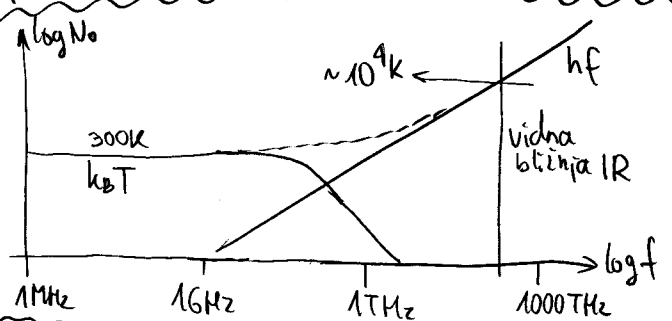
m = nabor znakov

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

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

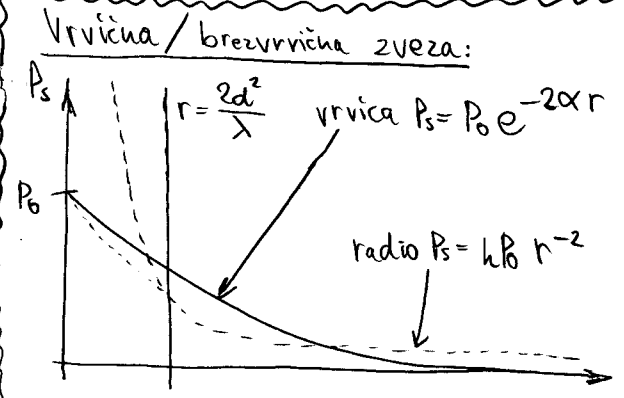
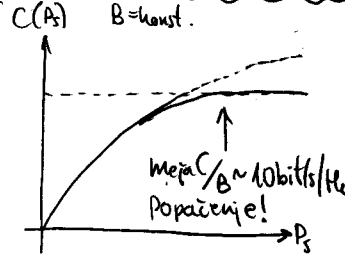
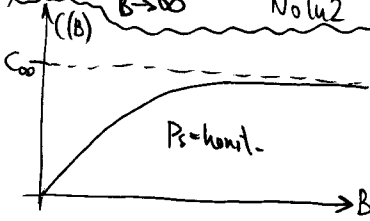
$$B = \frac{1}{2T} \quad C = B \log_2 \left(1 + \frac{P_s}{P_n} \right)$$

Moč šuma: toplotni šum: $N_0 = k_B T \quad k_B = 1,38 \cdot 10^{-23} \text{ J/K}$
 $P_N = B N_0$
 Zrnatni šum: $N_0 = hf \quad h = 6,626 \cdot 10^{-34} \text{ Js}$

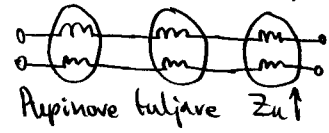
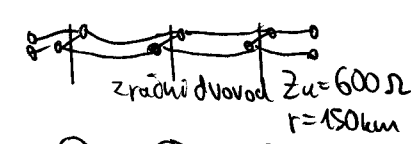


$$C = B \log_2 \left(1 + \frac{P_s}{N_0 B} \right)$$

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



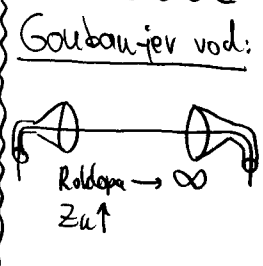
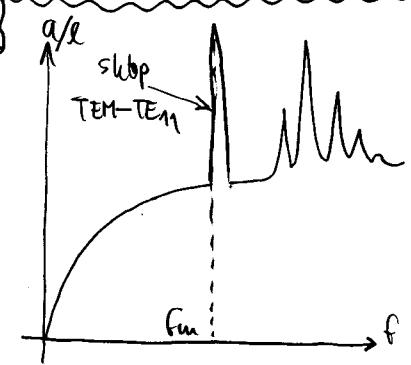
Domet telefona: prenosna parica $Z_u = 100 \Omega$
 $r = 25 \text{ km}$



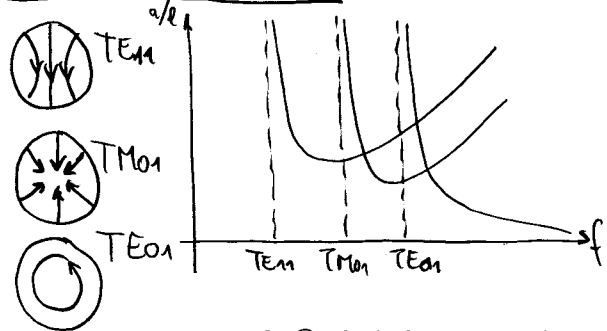
Dvovod: $Z_u = \sqrt{\frac{L/e}{C/e}}$
 $\alpha = \frac{R/e}{2Z_u}$

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

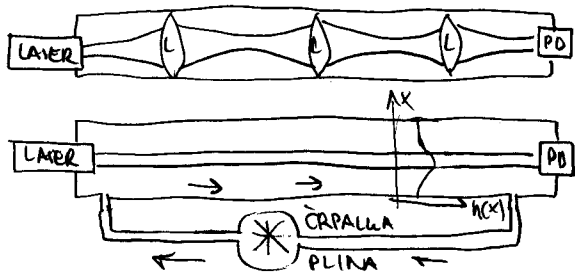
Višji redovi: $f_{\text{m}} = \frac{c_0 / TE_r}{\pi (R_{\text{zila}} + R_{\text{kabla}})}$



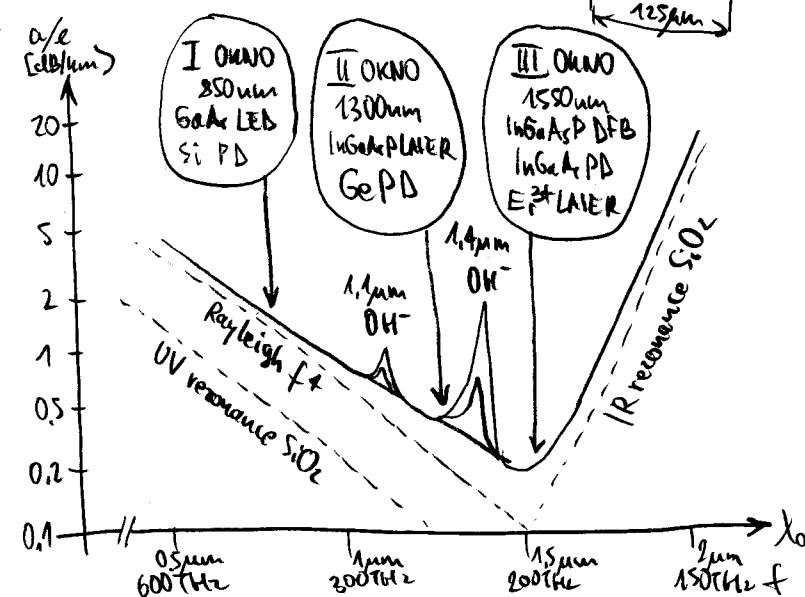
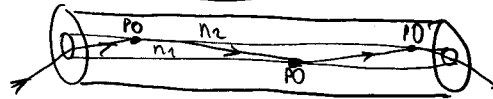
Okrogli kovinski valovod:



Laserske zveze:



Svetlobno vlakno: $n_1 > n_2$



Ponovitev elektrodinamike:

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

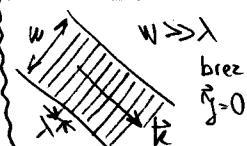
$(x, y, z) \rightarrow \vec{\nabla} = \vec{1}_x \frac{\partial}{\partial x} + \vec{1}_y \frac{\partial}{\partial y} + \vec{1}_z \frac{\partial}{\partial z}$

$\text{rot } \vec{H} = \vec{\nabla} \times \vec{H} = \begin{vmatrix} \vec{1}_x & \vec{1}_y & \vec{1}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix}$

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

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

Zarok = ravninski val



Ugiban rešitev:

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

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

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

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

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

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

$\vec{k} \equiv$ valovni vektor [rd/m]
 $k \equiv$ valovno število [rd/m]
 $k = |\vec{k}| = \omega \sqrt{\mu \epsilon}$

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

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

$\vec{k} \times (\vec{k} \times \vec{E}) = \vec{k}(\vec{k} \cdot \vec{E}) - k^2 \vec{E}$

Preostanek: $\vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^* = \vec{1}_k \frac{|\vec{E}|^2}{2Z} \hat{z}$

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

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

Prazen prostor: ϵ_0, μ_0

$c_0 = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 2,9979 \dots \cdot 10^8 \text{ m/s} \approx 3 \cdot 10^8 \text{ m/s}$
 DEFINICIJA METRA

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

$\epsilon_0 = \frac{1}{\mu_0 c^2} \approx \frac{1}{4\pi \cdot 10^7 \text{ Vs/m}} \text{ As}$
 $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 120\pi \Omega = 377 \Omega$

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

$\epsilon_r \geq 1, \mu_r \geq 1$ (BREZ 126008)

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

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

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

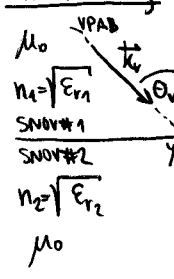
Dielektrik = neferomagnetik

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

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

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

Lom in odboj:

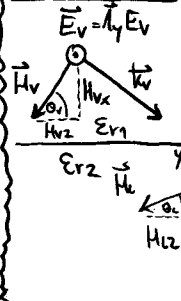


$\vec{k}_r = \vec{1}_x k_{rx} + \vec{1}_z k_{rz}$
 $\vec{k}_i = \vec{1}_x k_{ix} + \vec{1}_z k_{iz}$
 $|\vec{k}_r| = |\vec{k}_i| = k_1$
 $|\vec{k}_t| = k_2$

$k_{rx}^2 = k_{ix}^2$
 $k_{rz}^2 = k_{iz}^2$
 $\sin \theta_r = \frac{k_{rz}}{k_1} = \frac{k_{iz}}{k_1} = \sin \theta_i$

$\sin \theta_t = \frac{k_{tz}}{k_2} = \frac{k_{iz}}{k_2}$
 $\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}$

Odbojnost TE:



Prestopni pogoji: $D_v = D_0 = 0$

1) $E_v + E_0 = E_L$

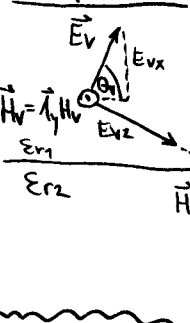
2) $H_{vx} + H_{0x} = H_{Lx}$ (linearno odvisna!)

3) $H_{vz} + H_{0z} = H_{Lz}$

$-E_v \cos \theta_i + \frac{E_0}{Z_1} \cos \theta_0 = -\frac{E_L}{Z_2} \cos \theta_L$

$(E_v - E_0) n_1 \cos \theta = (E_v + E_0) n_2 \cos \theta_L$

Odbojnost TM:



Prestopni p: 1) $H_v + H_0 = H_L$

2) $(E_{vx} + E_{0x}) \epsilon_{r1} = E_L \epsilon_{r2}$

3) $E_{vz} + E_{0z} = E_L z$

$E_v \cos \theta_v - E_0 \cos \theta_0 = (E_v + E_0) \frac{Z_2}{Z_1} \cos \theta_L$

$(E_v - E_0) n_2 \cos \theta = (E_v + E_0) n_1 \cos \theta_L$

$\Gamma_{TM} = \frac{E_0}{E_v} = \frac{n_2 \cos \theta - n_1 \cos \theta_L}{n_2 \cos \theta + n_1 \cos \theta_L}$

$\Gamma_{TE} = \frac{E_0}{E_v} = \frac{n_1 \cos \theta - n_2 \cos \theta_L}{n_1 \cos \theta + n_2 \cos \theta_L}$

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

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

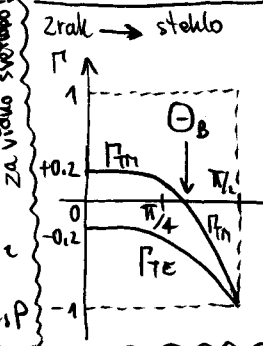
$\Gamma_{TM} = \frac{(n_2/n_1)^2 \cos \theta - \sqrt{(n_2/n_1)^2 - \sin^2 \theta}}{(n_2/n_1)^2 \cos \theta + \sqrt{(n_2/n_1)^2 - \sin^2 \theta}}$

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 SF₆
- $n=3,5-4$ Si, GaAs polprevodniki InGaAsP

Odbojnost TE in TM:



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

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

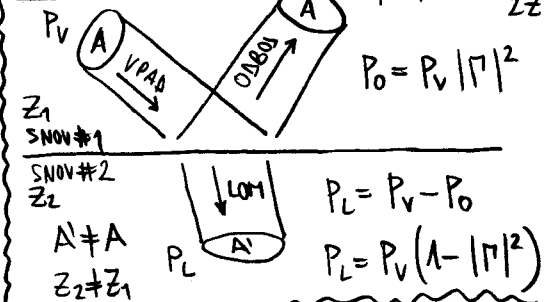
$(n_2/n_1)^4 \cos^2 \theta_B = (n_2/n_1)^2 - \sin^2 \theta_B$

$(n_2/n_1)^2 \alpha \rightarrow (\alpha^2 - 1) \cos^2 \theta_B = \alpha - 1$

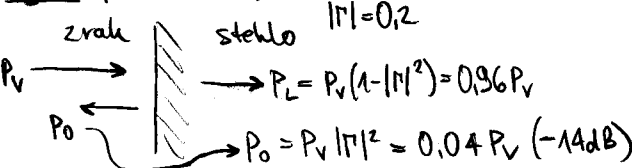
$\cos^2 \theta_B = \frac{1}{\alpha + 1}, \sin^2 \theta_B = \frac{\alpha}{\alpha + 1}$

$\tan^2 \theta_B = \alpha \rightarrow \theta_B = \arctan n_2/n_1$

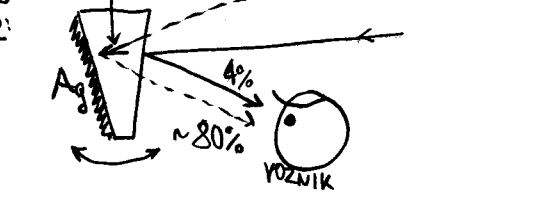
Delitev moči:



Zalob: pravokotni vpad na steklo



Vzratno ogledalo:



Optične komunikacije # 3

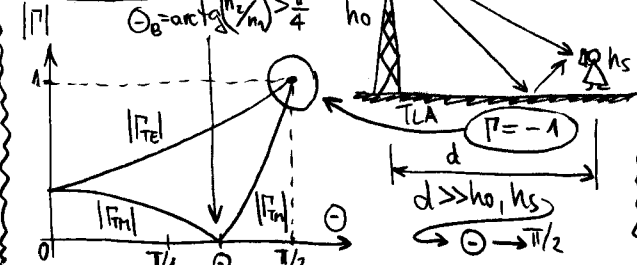
6/3/2014

Ponovitev: Fresnel-ovi odbojnosti

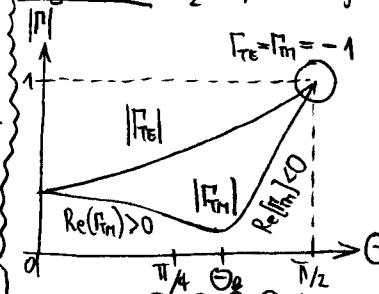
$$\Gamma_{TE} = \frac{\cos\theta - \sqrt{(n_2/n_1)^2 - \sin^2\theta}}{\cos\theta + \sqrt{(n_2/n_1)^2 - \sin^2\theta}}$$

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

Zgled $n_2 > n_1$:

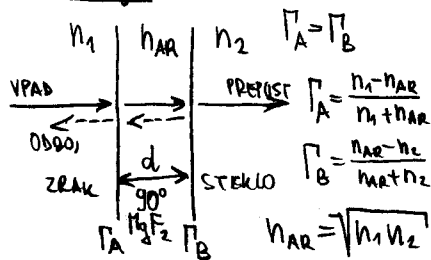


Izgubni n_2 : $\epsilon_2 \neq 0, n_2 = n_2' + jn_2''$

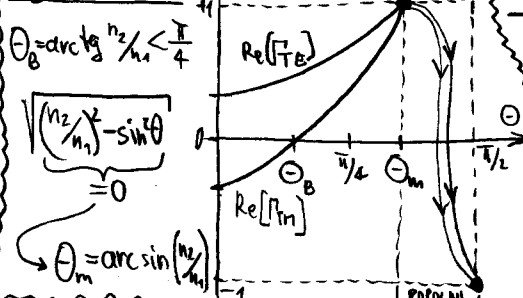


AR sloj:

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

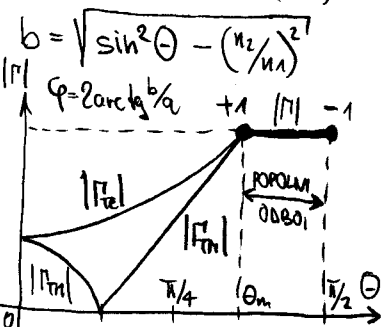


Zgled $n_2 < n_1$:



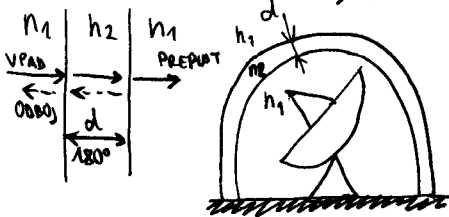
$$\Gamma = \frac{a - jb}{a + jb}$$

$$a_{TE} = \cos\theta \quad a_{TM} = (n_2/n_1) \cos\theta$$

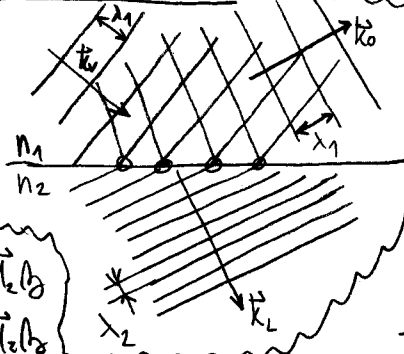


Prozoren pokrov:

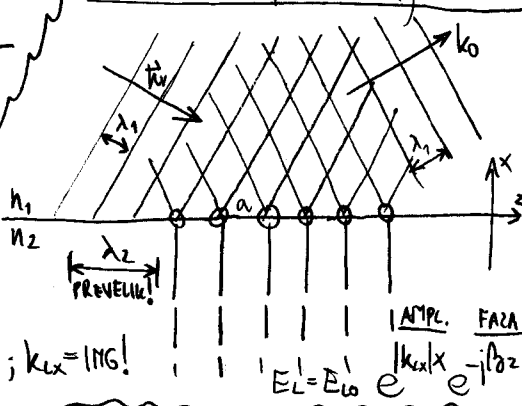
$$d = \lambda_2 / 2$$



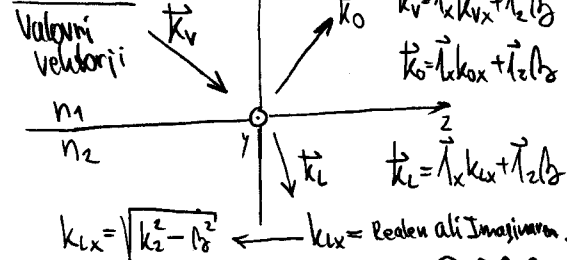
Lom + odboj $n_2 > n_1$:



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



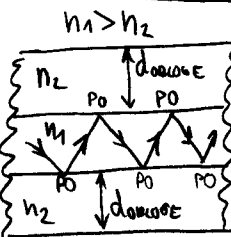
Ponovitev:



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

$$\sin\theta_L = \frac{\lambda_2}{a} > 1 \rightarrow \theta_L = ?; k_Lx = i\text{NG!}$$

Dielektrični valovod:

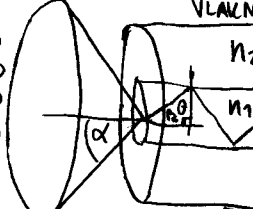


Relativna razlika n:

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

$\Delta \ll 1 \rightarrow$ šibkolomno vlakno

Numerična apertura NA:



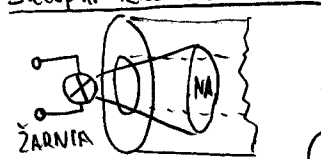
$$\sin\theta_m = n_2/n_1$$

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

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

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

Sklopni izkoristek vira:



$$\eta = \frac{P_{VLAKNO}}{P_{ZARNICA}} = \frac{\Omega}{4\pi}$$

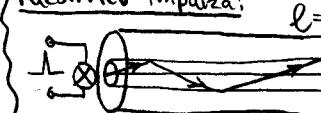
$$\Omega = \frac{A}{r^2} = \frac{2\pi r h}{r^2} = 2\pi(1 - \cos\alpha)$$

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

Zgled: $NA = 0,2 \rightarrow \eta = 0,01 = 1\%$

Šibkolomno: $NA \approx n_1 \sqrt{2\Delta} \rightarrow \Delta = \frac{1}{2} \left(\frac{NA}{n_1}\right)^2 = 0,009$

Razširitev impulza:

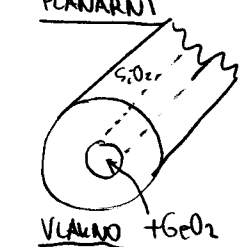
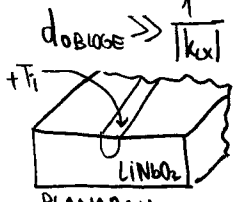


$$Ravni žarek: t_1 = \frac{n_1 L}{c_0} \quad n_1 \approx 1,5 \quad \Delta \approx 0,009$$

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

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

$$\Delta t \approx \frac{n_1 L}{c_0} \Delta = \frac{1,5 \cdot 10^4 \text{ m} \cdot 0,009}{3 \cdot 10^8 \text{ m/s}} = 0,45 \mu\text{s}$$



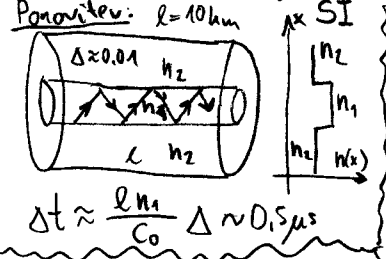
$$C = \frac{1}{T}; T > 3\Delta t$$

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

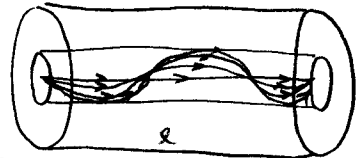
???

1D valovod

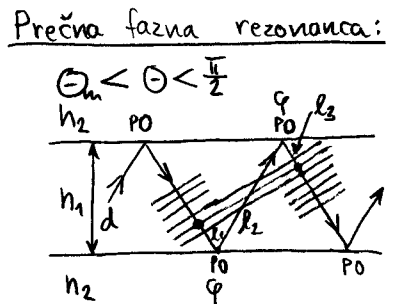
Ponovitev:
 $\Delta = \frac{n_1 - n_2}{n_1} \ll 1$
 $NA = \sqrt{n_1^2 - n_2^2}$
 $NA \approx n_1 \sqrt{2\Delta}$
 $NA = \sin \alpha \approx \frac{1}{2F\#}$



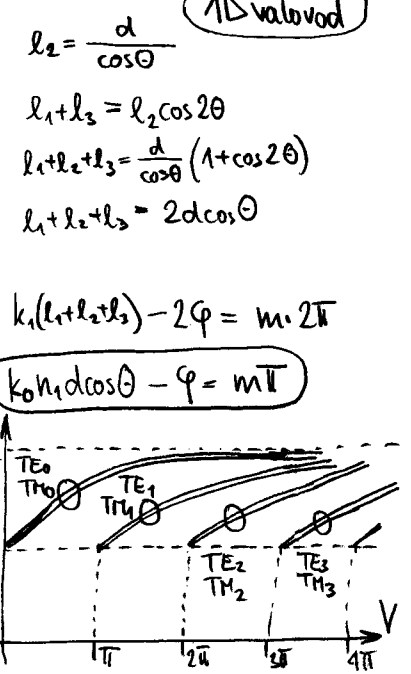
GI vlakno
 50/125 G.651 (ITU)
 62.5/125 H (rač.)
 $\Delta \sim 0.01, NA \sim 0.2$



$\Delta t \approx \frac{L n_1}{c_0} \Delta \sim 0.5 \mu s$
 $\Delta t \approx \frac{L n_1}{c_0} \Delta^2$
 $L = 10 km \rightarrow \Delta t \sim 5 ns$

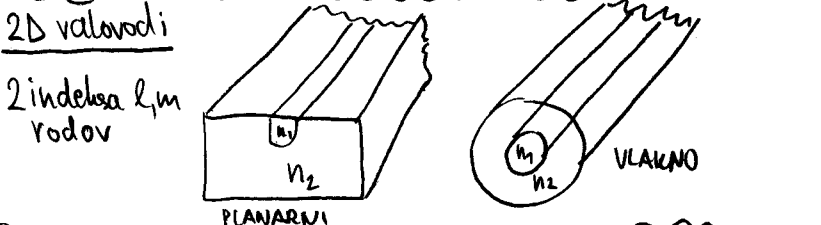
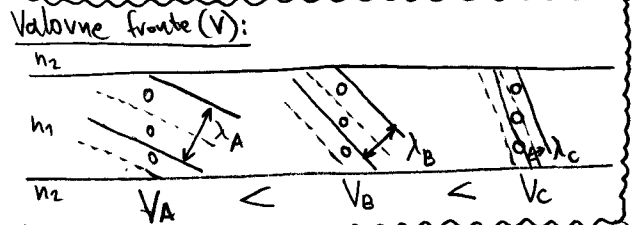
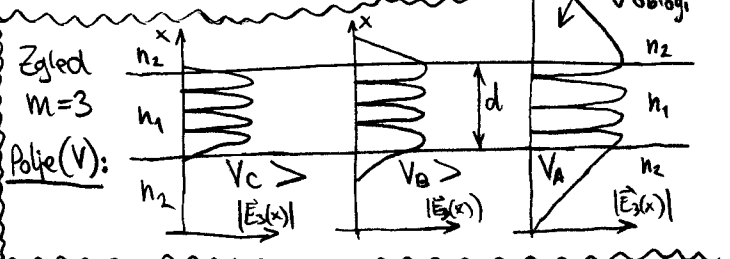
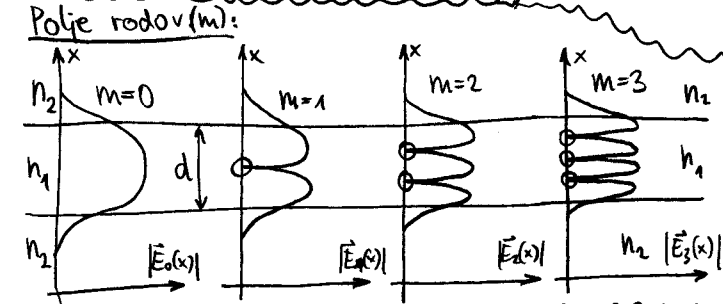
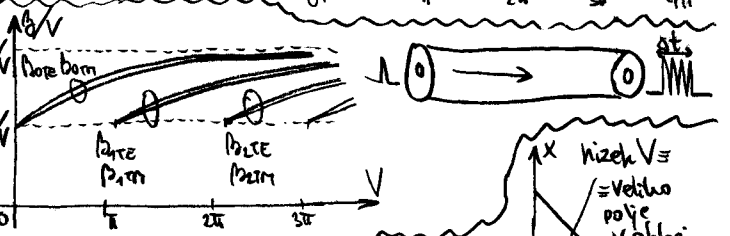


Prečna fazna rezonanca:
 $\theta_m < \theta < \frac{\pi}{2}$
 $\Gamma = \frac{a-jb}{a+jb} \rightarrow \varphi = 2 \arctan \frac{b}{a}$
 $\alpha_{TE} = \cos \theta \quad \alpha_{TM} = (\frac{n_2}{n_1})^2 \cos \theta$
 $b = \sqrt{(\frac{n_2}{n_1})^2 - \sin^2 \theta}$
 $\cos \theta = \sqrt{1 - \sin^2 \theta}$ Normirana frekvenca!
 $\cos \theta_m = \sqrt{1 - (\frac{n_2}{n_1})^2}$
 $k_0 n_1 d \cos \theta_m = k_0 d NA = V$

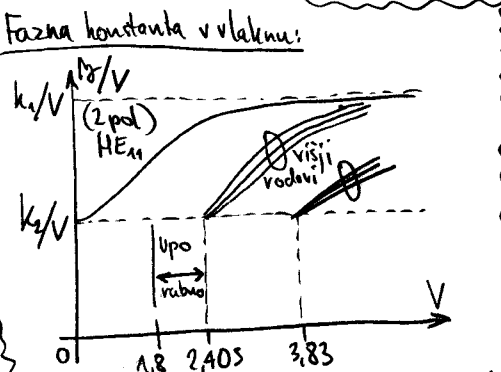


Zaled: $d = 1 \mu m, \lambda = 633 \text{ nm}$
 $n_1 = 1.5 \approx \text{steklo}$
 $n_2 = 1 \approx \text{zrak}$
 $V = \frac{2\pi}{\lambda_0} d NA = \frac{2\pi \cdot 10^{-6} \text{ m}}{633 \cdot 10^{-9} \text{ m}} \cdot \sqrt{2.25 - 1} \approx 1000$
 $m < \frac{V}{\pi} = 3533 \text{ rodov TE+TM!}$

Fazna konstanta:
 $k_x = \sqrt{k_1^2 - k_z^2}$
 $k_y = k_1 \sin \theta$



Rodovi v vlaknu:
 Cikcak $TE_{l,m}, TM_{l,m}$
 Vijacni $HE_{l,m}, EH_{l,m}$



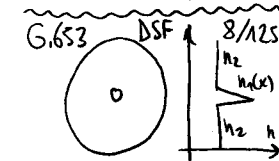
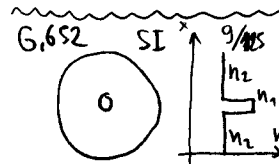
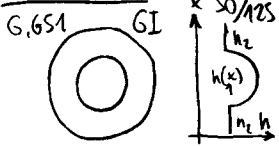
Polje HE11: → šibkolomno $HE_{11} = LP_{01}$
 Tunneliranje na krivinski pahljača se odpira
 sevanje $> \lambda_2$

EM rešitev: $\Delta E_z + k^2 E_z = 0$
 jedro: $E_z, H_z = C_1 J_m(k_1 r) \begin{cases} \sin m\varphi \\ \cos m\varphi \end{cases} e^{-j\beta z}$
 oblogo: $E_z, H_z = C_2 K_m(k_2 r) \begin{cases} \sin m\varphi \\ \cos m\varphi \end{cases} e^{-j\beta z}$
 $E_z, H_z \rightarrow E_{z1}, H_{z1}, E_{z2}, H_{z2}$
 + prestopni pogoji

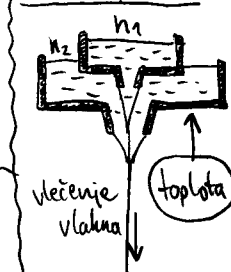
Vlakno G.652 $2a = 9 \mu m - 10 \mu m$
 9/125 ali 10/125
 $NA \sim 0.1$
 $\lambda_0 = \frac{2\pi a NA}{2.405}$
 $\lambda_0 \sim 1.25 \mu m$

$V > 1.8$
 Uporabni pas $HE_{11} \rightarrow 1.8 < V < 2.405$
 $G.652 \rightarrow 1.67 \mu m > \lambda_0 > 1.25 \mu m$

Ponovitev:



Talilni posodi:

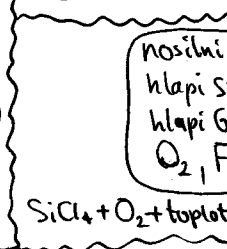


$\alpha \sim 1000 \text{ dB/km}$
(umazanija posod)

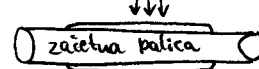
izdelava plastičnih vlaken

Čiste surovine:

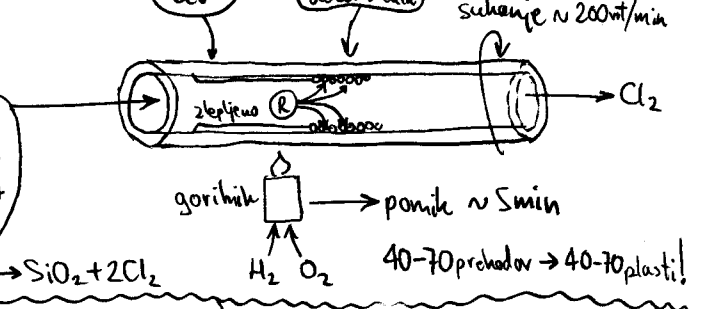
- SiCl_4 = tekočina
- GeCl_4 = tekočina
- O_2 = plin
- F_2 = plin
- POCl_3 = tekočina



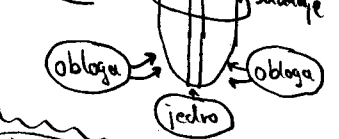
OCVD:



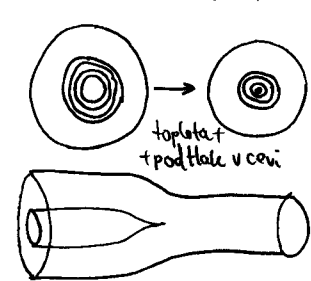
MCVD:



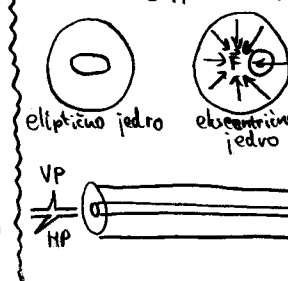
VAD:



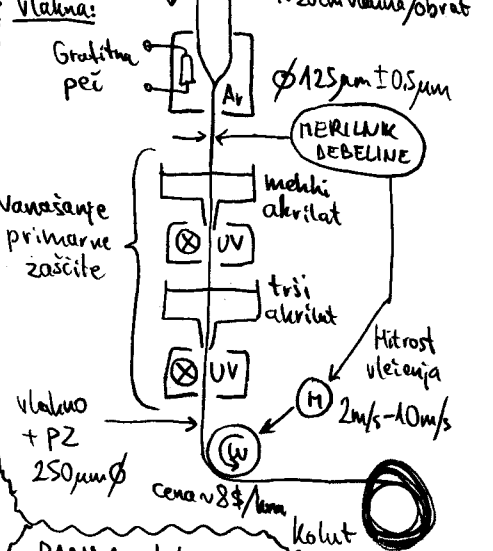
Kolaps: cev \rightarrow preform



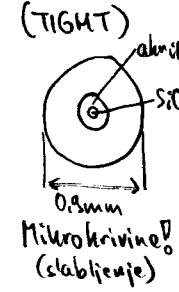
PMD: $\beta_{VP} \neq \beta_{HP}$



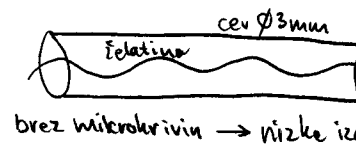
Vlečenje vlakna:



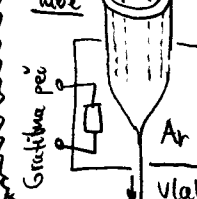
Tesna zaščita: (TIGHT)



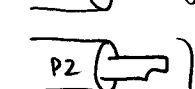
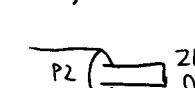
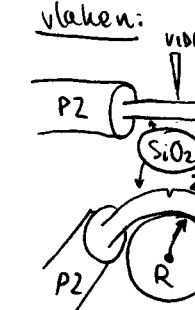
Ohlapna zaščita: (LOOSE)



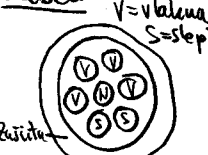
Rod-in-tube



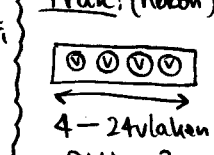
Rezanje SiO_2 vlaken:



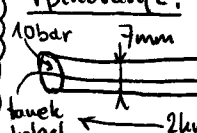
Kabel: N=nosilni, V=vlakna, S=stepli



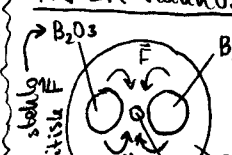
Trak: (ribon)



Vpikovanje:



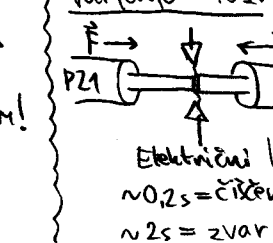
PANDA vlakno:



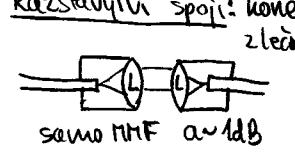
MOŽNO DVOLOMNHO ohranjanje polarizacije

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

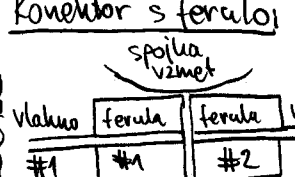
Varienje SiO_2 :



Razstavljivi spoji: konektor zlečami



Konektor s ferulo



ϕ ferule: 4mm

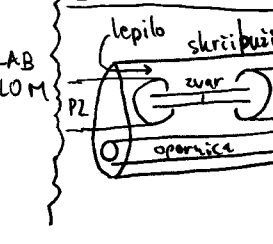
2,5mm \checkmark

2mm

1,27mm \checkmark

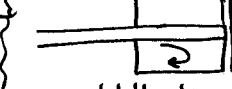
$\pm 0,5 \mu\text{m}$

Zaščita zvara:

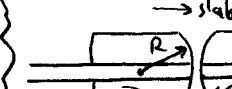


Brušenje ferule:

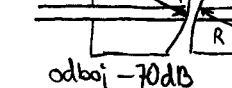
Ravno (MMF): umazanija?



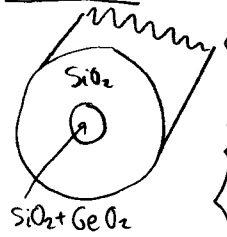
Kriviško (SMF): \rightarrow slabljenje 0,2dB



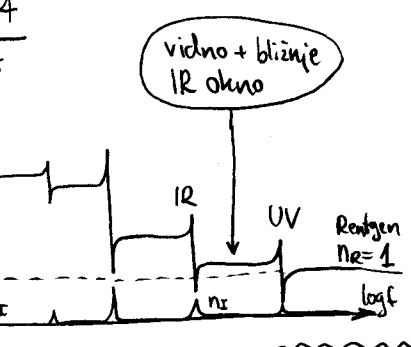
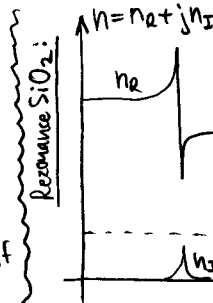
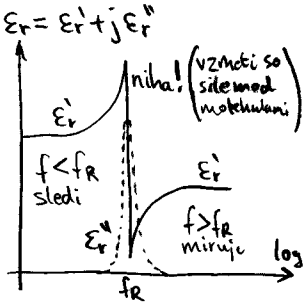
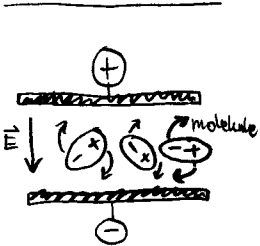
Kotno-kriviško (analogni prenos): odboj \rightarrow slabljenje $\sim 0,5 \text{ dB}$



Ponovitev:



Dielektričnost:

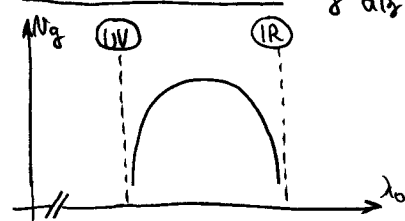


vidno + bližnje IR okno

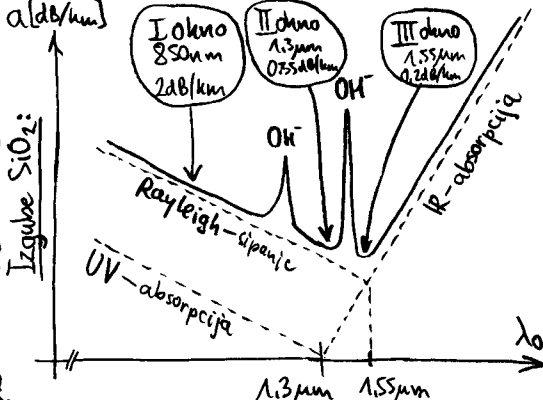
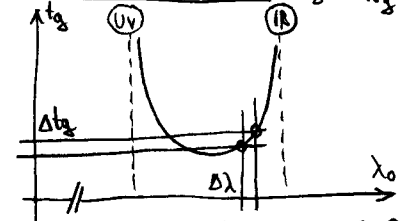
Rayleigh:

$I = \alpha^1 E_s f$
 $E_s = \alpha^2 I d$
 $P_s = \alpha^3 E_s$
 $P_s \propto f^4$

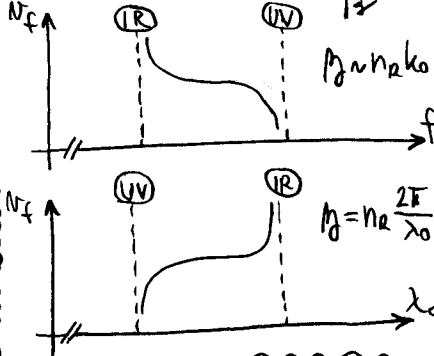
Skupinska hitrost:



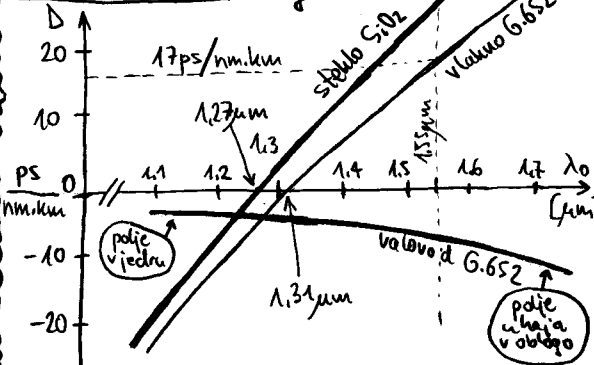
Skupinska zakasnitev:



Fazna hitrost:



Barvna razpršitev: Δtg = D Δλ

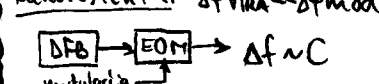


Zgled: cenon FP laser Δλ = 10nm
 l = 50km C = 1/3Δtg (strogo!)

λ0 = 1.3μm |D| < 2ps/nm.km
 Δtg = DΔλ = 1ns C = 333Mbit/s

λ0 = 1.55μm D = +17ps/nm.km
 Δtg = 8.5ns C = 39Mbit/s

kakovosten TX: Δtvira < Δtmod



λ0 = c0/f → Δλ = c0/f^2 Δf = λ0^2/c0 C

C = 1/Δtg (manj strogo!)

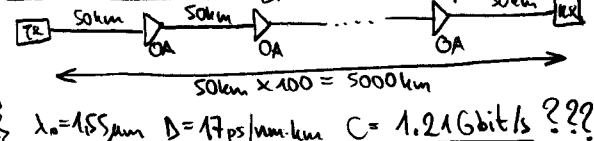
C = 1/DΔ (λ0^2/c0 C)^-1 l = 50km λ0 = 1.55μm

C = sqrt(c0/DΔλ^2) = 12.1Gbit/s

Primerjava:

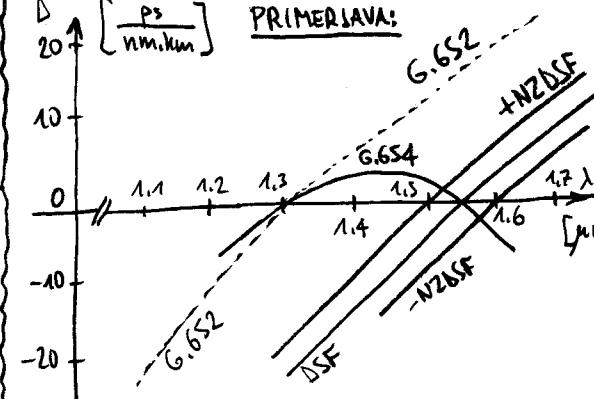
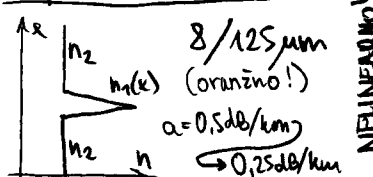
ΔtNMF >> ΔtBARVNI > ΔtPMD
 mnogomodna vlakna (PMD)

Preko oceanska zveza:

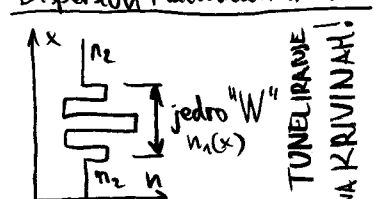


λ0 = 1.55μm D = 17ps/nm.km C = 1.21Gbit/s ???

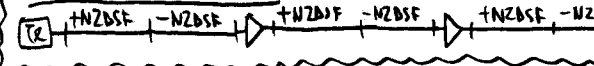
Dispersion Shifted Fiber G.653:



Dispersion Flattened Fiber G.654:



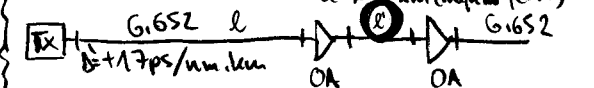
Preko oceanski kabeli:



NZDSF vlakna:

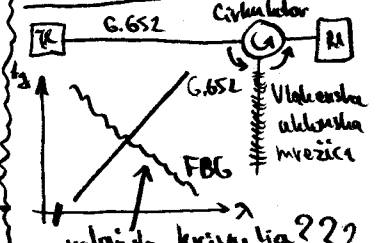
D(1.55μm) = 5.17ps/nm.km
 +NZDSF
 -NZDSF (kompensacija)

Medkrajinska zveza:

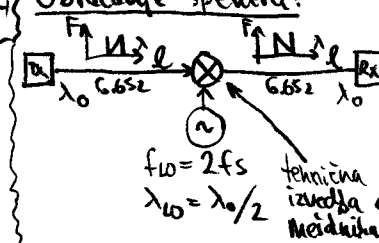


Neuspešne tehnike:

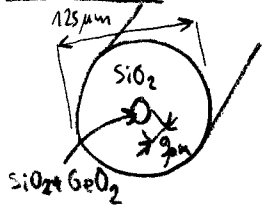
FBG (Fiber Bragg Grating)



Obračunje spektra:



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: $P = 100 mW$

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

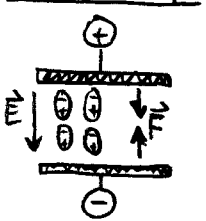
$$|E| = \sqrt{\frac{2Z_0 S}{n_1}} \quad n_1 \approx 1.46$$

$$|E| = 850 kV/m = 8.5 kV/cm$$

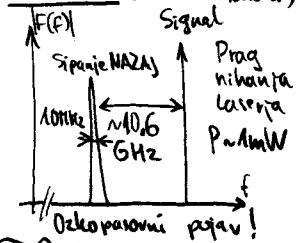
Rezervi moči:

$P = 10W$ uničuje jedra vlakna
 $P = 1W$ preboj v zraklu, max mož v vlaknu
 $P = 100 mW$ max moč na konektorjih
 $P = 10 mW$ nevarnost zažiga km.

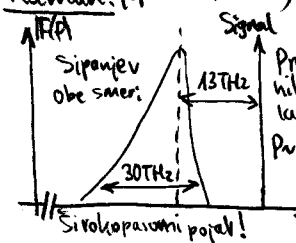
Elektrostrikcija:



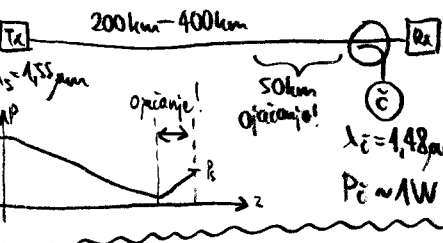
Brillouin: (akustični fononi)



Raman: (optični fononi)



Ramanov opačevalnik: (podmorski kabel)



Nelinearni n:

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

Pockels Kerr Najhna nelinearnost

$SiO_2 \rightarrow n_0 \approx 1.46$

Engjejni = 0 $\rightarrow n_1 = 0$

$n_2 \approx 3.2 \cdot 10^{-20} \frac{m^2}{W}$

Lastna φ modulacija:

$$P = 100 mW$$

$$l = 10 km$$

$$\lambda_0 = 155 \mu m$$

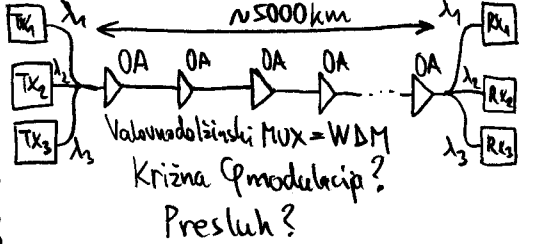
$$A_{eff} = 70 \mu m^2$$

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

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

Visoko: $\frac{l}{\lambda_0}$

Prekoceasna zveza:



Dvobinski signali: ω_1, ω_2

ISTA POLARIZACIJA

Odkriv prepacšen za $2\omega_1, \omega_1 + \omega_2, 2\omega_2$

razlika $\Delta\omega = \omega_1 - \omega_2 \ll \omega_1, \omega_2$

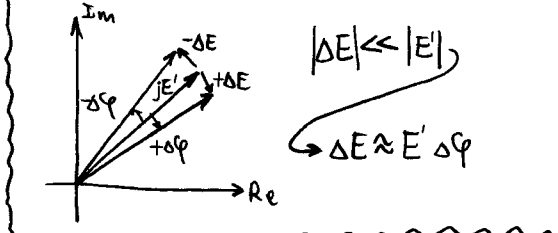
$$E = E_{01} \cos \omega_1 t + E_{02} \cos \omega_2 t$$

$$P = \alpha |E|^2 = \alpha (E_{01} \cos \omega_1 t + E_{02} \cos \omega_2 t)^2$$

$$P = \alpha \left(E_{01}^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega_1 t \right) + 2E_{01}E_{02} \left(\frac{1}{2} \cos(\omega_1 + \omega_2)t + \frac{1}{2} \cos(\omega_1 - \omega_2)t \right) + E_{02}^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega_2 t \right) \right)$$

$$P \approx \frac{\alpha}{2} (E_{01}^2 + 2E_{01}E_{02} \cos \Delta\omega t + E_{02}^2) = P_1 + 2\sqrt{P_1 P_2} \cos \Delta\omega t + P_2$$

Križna φ mod \rightarrow opletanje faze!



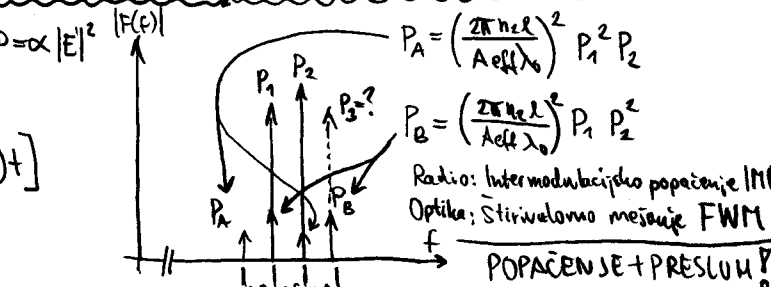
Spekter križne φ mod:

$$E' = E_0 \sin \omega t, P = \alpha |E|^2$$

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

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

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



Slabljenje vlakna:

$$\alpha = 0.2 dB/km$$

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

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

$$z \rightarrow \infty \Rightarrow \Delta\phi \approx \frac{10}{\alpha \ln 10} = 21.7 km$$

Voineki $D \neq 0$: fazna neustojavnost $\Delta\beta = \beta_s + \beta_m - 2\beta_c$

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

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

$$\beta_c = \beta(\omega)$$

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

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

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

Vlakno G.653:

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

$$D = 0 ps/nm.km$$

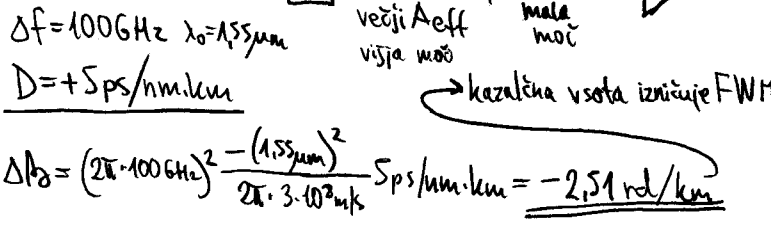
NEUPORABNO V OJAČEVANI ZVEZI

Vlakno LEAF:

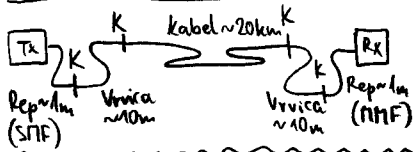
$$A_{eff} \approx 80 \mu m^2$$

kolobar $SiO_2 + GeO_2$

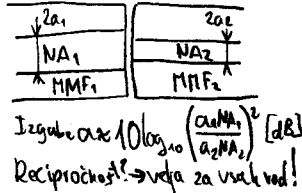
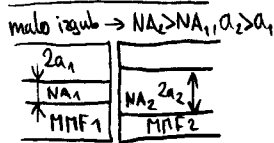
žgled + NZDSF:



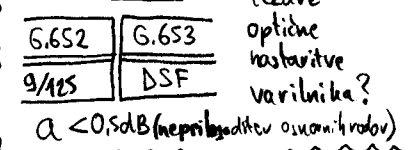
Svetlobna zveza:



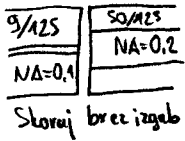
Neenaka MMF:



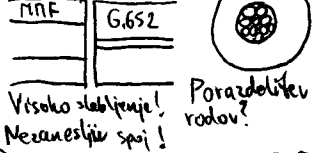
Neenaka SMF:



SMF \rightarrow MMF:



MMF \rightarrow SMF: NEUPORABNO!

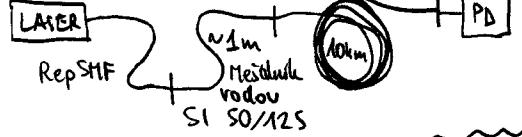


Posebni primer:

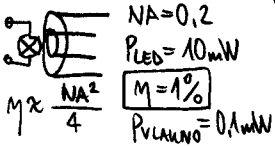
G.652 \rightarrow G.651 \rightarrow G.652

V G.651 vzbudimo samo nižje r. rodove \rightarrow UPORABNO!

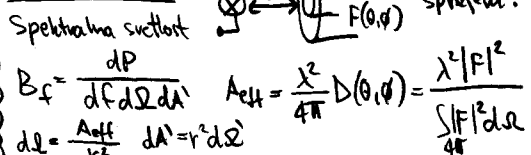
Meritve MMF:



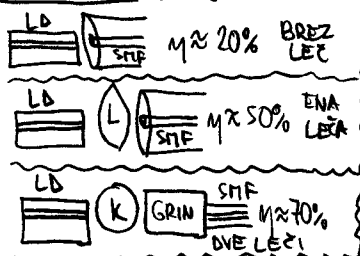
LED \rightarrow MMF:



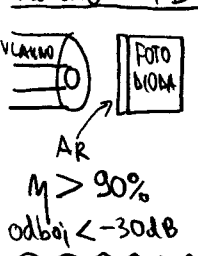
LED \rightarrow SMF:



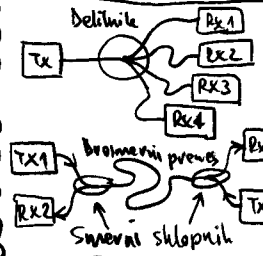
LD \rightarrow SMF: prilagoditev rodov?



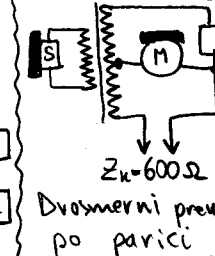
Vlakno \rightarrow PD:



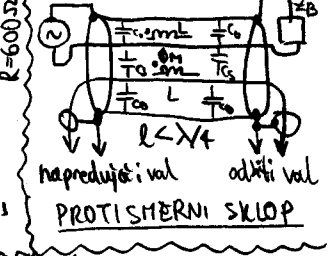
Delitniki in sklopniki:



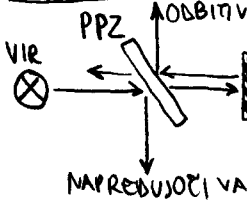
Telefonike vilnice:



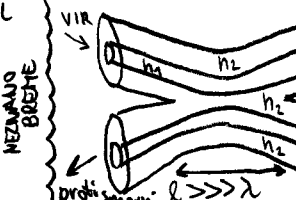
Radialni (kvadratni) sklopnik:



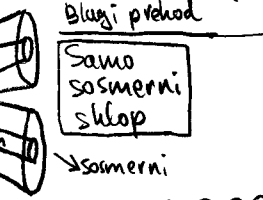
Polprepusno zrcalo:



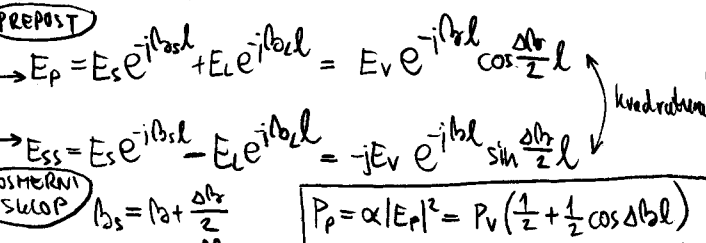
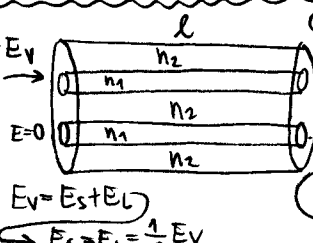
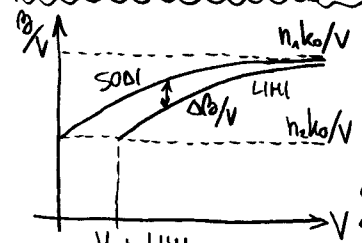
Vlakenski sklopniki:



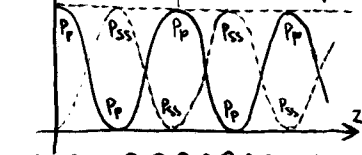
SODI (SOFARNI) ROD:



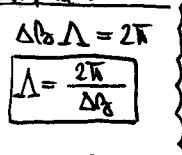
LIHNI (PROTIFARNA) ROD:



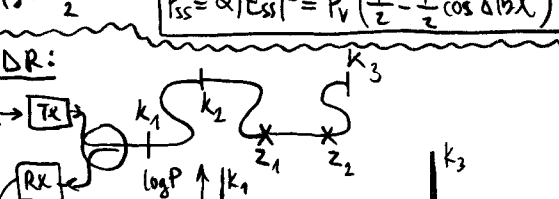
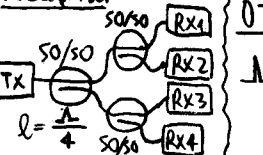
Utripna dolžina:



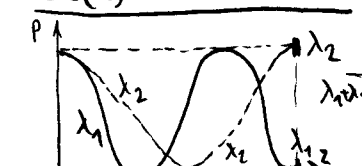
Razcepniki:



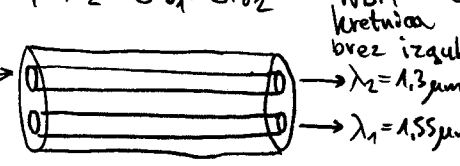
OTDR:



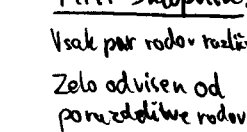
Delta beta (lambda) -> kretnica WDM:



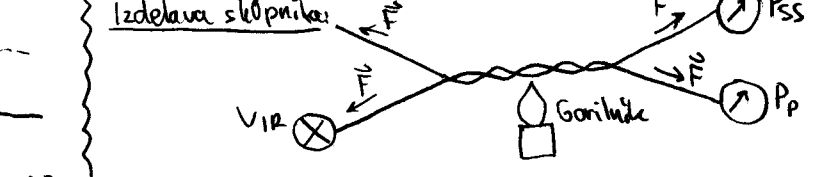
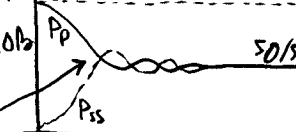
WDM kretnica brez izgub!



MMF sklopnik:



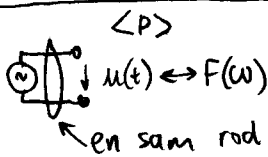
Izdelava sklopnika:



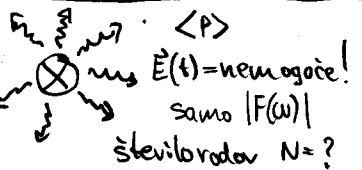
Optične komunikacije # 9

17/4/2014

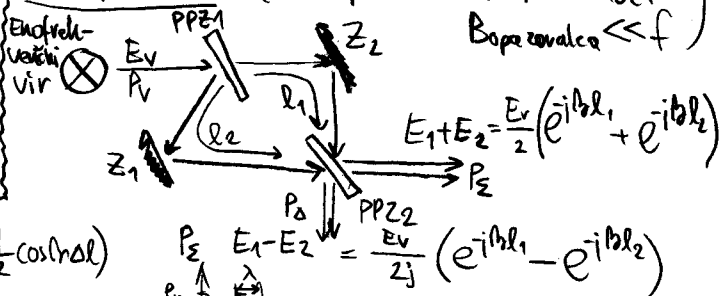
Električni vir $< 1 \text{ THz}$



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

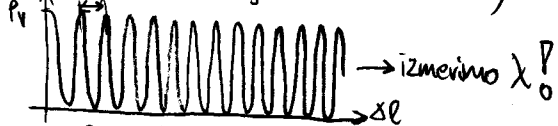


Interferometer: (samo počasna meritev moči)
 Boprezovalca $\ll f$

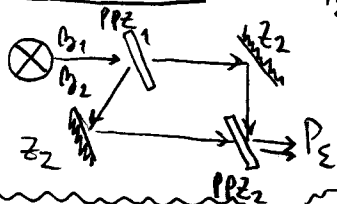


$$E_1 + E_2 = E_V e^{-j\beta l_1 t} \cos \frac{\beta \Delta l}{2} \rightarrow P_Z = P_V \left(\frac{1}{2} + \frac{1}{2} \cos \beta \Delta l \right)$$

$$E_1 - E_2 = E_V e^{-j\beta l_1 t} \sin \frac{\beta \Delta l}{2} \rightarrow P_D = P_V \left(\frac{1}{2} - \frac{1}{2} \cos \beta \Delta l \right)$$



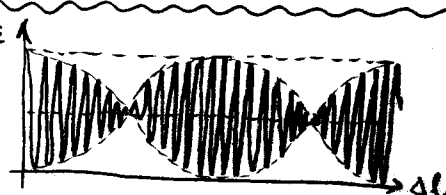
Dvofrekvenčni vir:



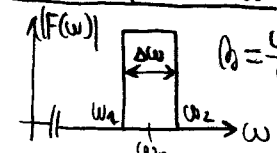
$$P_Z = P_1 \left(\frac{1}{2} + \frac{1}{2} \cos \beta_1 \Delta l \right) + P_2 \left(\frac{1}{2} + \frac{1}{2} \cos \beta_2 \Delta l \right)$$

Zgled: $P_1 = P_2 = P_V/2$ (HeNe laser na črtnah)

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

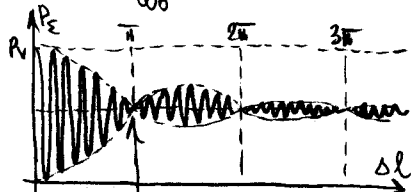


Zvezni spekter $\Delta \omega$:



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

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



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

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

vzdolžna koherenčna dolžina d

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

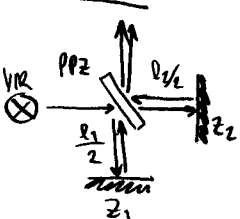
Valovna dolžinska širina:

$$\lambda = \frac{c_0}{f} \rightarrow \left| \Delta \lambda \right| = \frac{c_0}{f^2} \left| \Delta f \right| = \frac{\lambda^2}{c_0} \left| \Delta f \right|$$

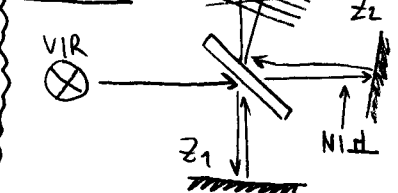
$$\frac{d\lambda}{df} = -\frac{c_0}{f^2}$$

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

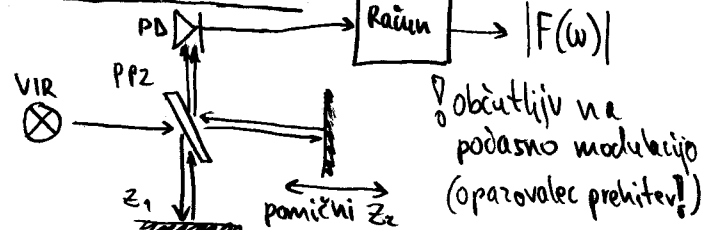
Michelson:



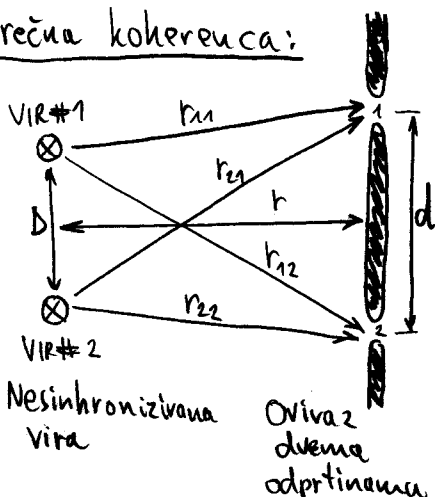
Neporavnan Michelson:



Interferometrijski SA:



Prečna koherenca:



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

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

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

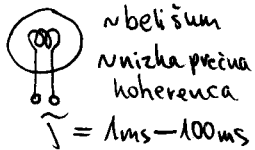
$$\frac{\lambda}{2} = r + \frac{(d+D)^2}{8r} - r - \frac{(d-D)^2}{8r} = \frac{2dD + 2dD + 2dD + 2dD}{8r} = \frac{dD}{r}$$

$$d = \frac{\lambda r}{2D} \text{ prečna koherenčna dolžina } d$$

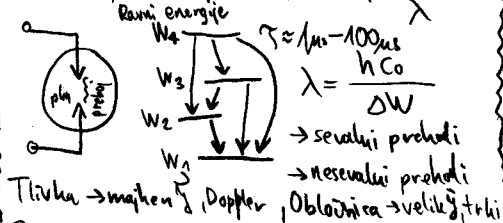
Enofrekvenčni vir: $d_{\text{prečna}} \rightarrow \infty$

Žarnica z nitko:

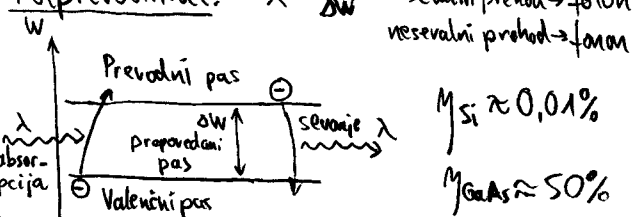
→ TOPLOTNI VIR



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



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



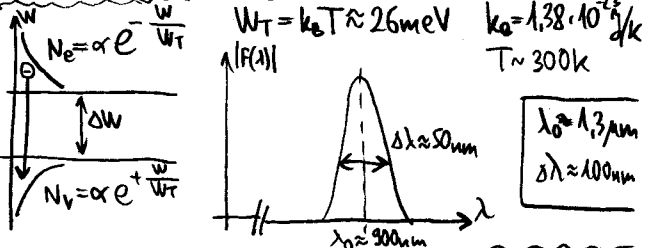
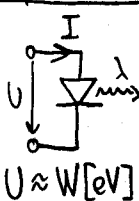
Merska enota eV:

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

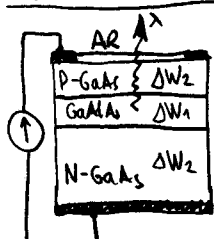
$W = hf = \frac{hc}{\lambda} = |Q_e| U$ $Q_e = -1.6 \cdot 10^{-19} \text{ As}$

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

Spekter LED:

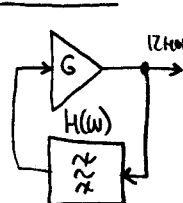


Heterostruktural ED:

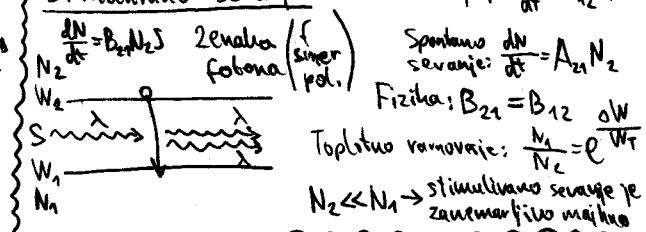


Nehoteren vir:
 G6S1
 M_{NHF} ≈ 1%
 G6S2
 M_{SHF} < 0,1%
 slab stolpni izkoristek
 τ = 10ns - 1μs
 ΔW₁ < ΔW₂
 Ni absorpcije v oblagah!

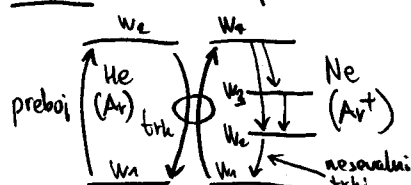
Oscilator:



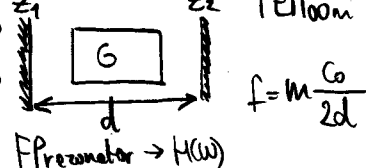
Stimulirano sevanje:



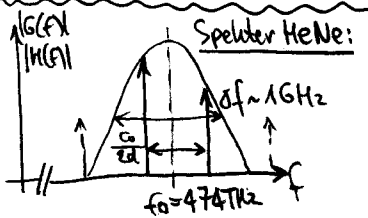
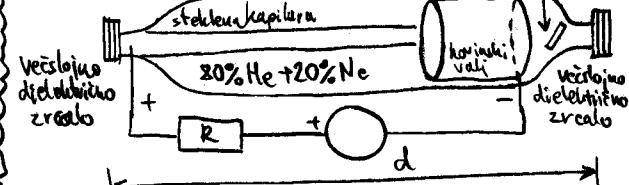
Laser: obratna naseljenost N2 > N1



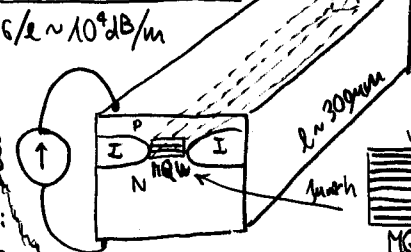
Oscilator:



HeNe laser: G/L ≈ 1dB/m

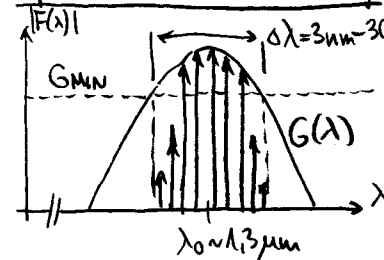


Polprevodniški laser:

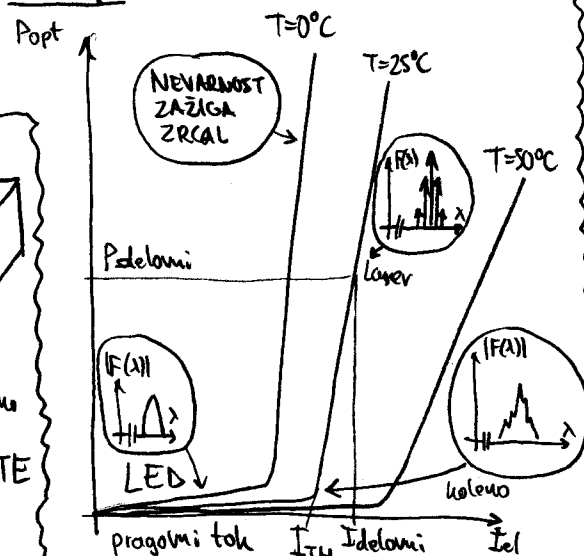


$W > 10\mu\text{m}$ → prečni rodovi, močnejši laser
 $W < 10\mu\text{m}$ → samo vzdolžni rodovi, TK laser < 100mW

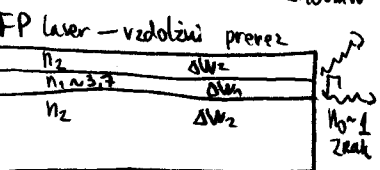
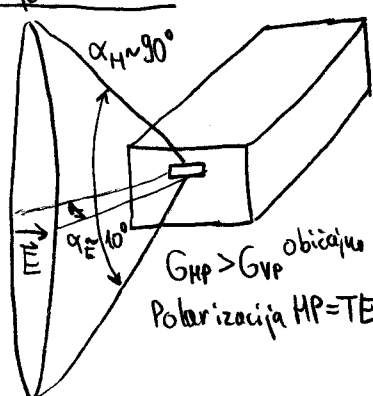
Spekter InGaAsP-FP laserja:



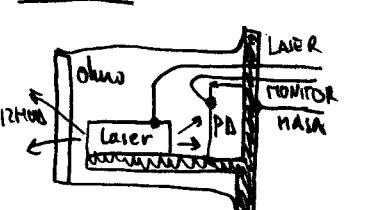
Modulacijska krivulja:



Sevanje FP laserja:



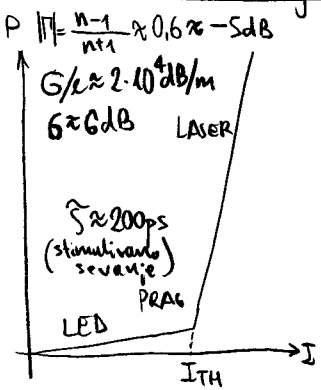
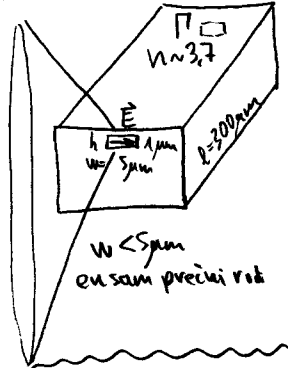
Opisje laserja:



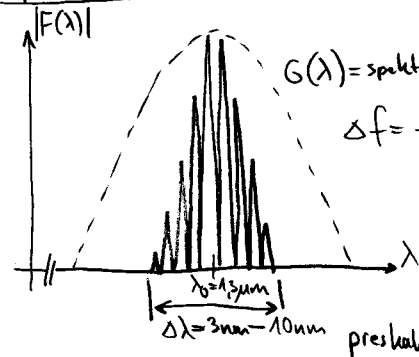
Snop nazaj uporabimo za monitorsko fotodiodo!

	ITH	Idelovni
1980	20mA	100mA
1995	15mA	25mA
danes	1mA	10mA

Ponovitev: FP laser



Spekter FP laserja:



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

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

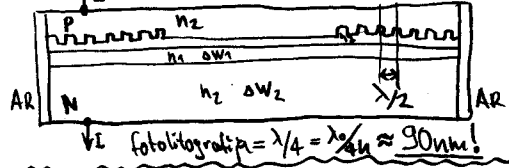
$\Delta f = \frac{c_0}{2Ln} = 135\text{GHz}$ $L = 300\mu\text{m}$

$\Delta f' = \frac{\Delta\lambda c_0}{\lambda_0^2} = 1,8\text{THz}$ $n = 3,7$ $\Delta\lambda = 10\text{nm}$

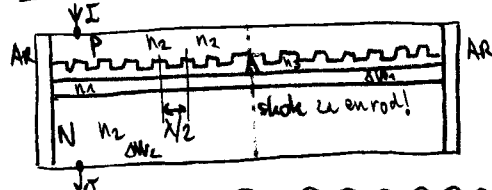
$N_{\text{rodov}} = \frac{\Delta f'}{\Delta f} = 13\text{rodov}$

preskakanje med rodovi → šum!

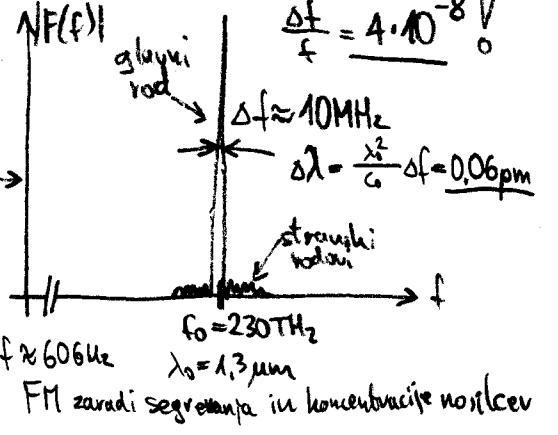
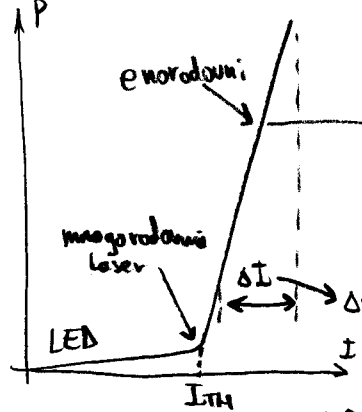
Distributed Bragg Reflector = DBR



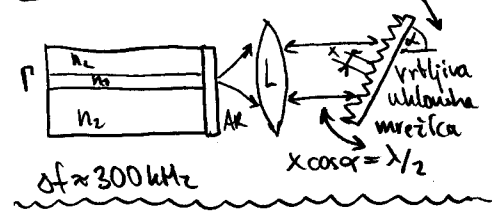
Distributed Feed-Back = DFB



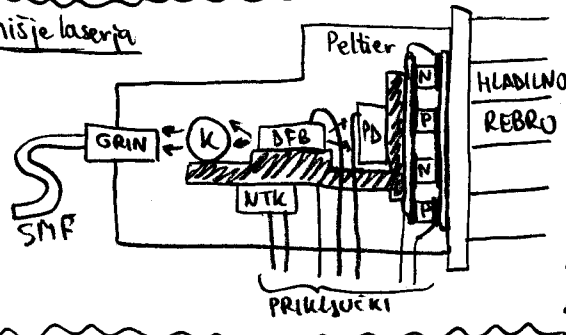
Modulacija DFB1



External Cavity = EC Mehanka=#



Ohišje laserja



Koherenčna dolžina

vdolžina $d = \frac{c_0}{\Delta f}$

FP $\Delta f = 1,8\text{THz} \rightarrow d = 170\mu\text{m}$

DFB $\Delta f = 10\text{MHz} \rightarrow d = 30\text{m}$

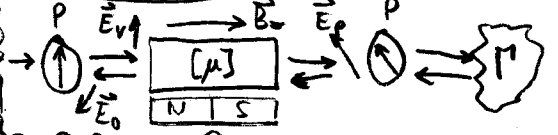
EC $\Delta f = 300\text{kHz} \rightarrow d = 1\text{km}$

Ločitev oscilatorji:

- n recipročni optični valnik
- n recipročni pasivni gradnik = IZOLATOR



Enopolarizacijski izolator:

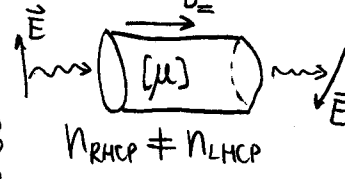


YIG ferit v B_z:

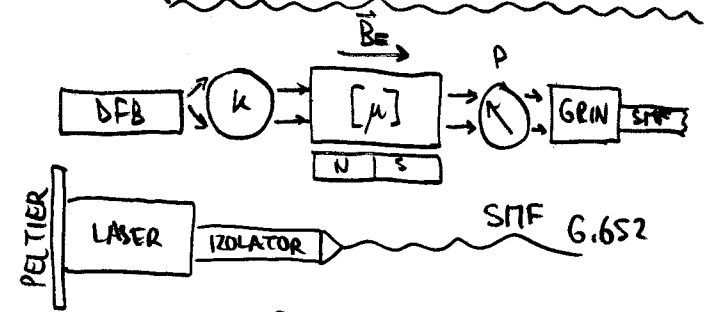
$$[\mu] = \begin{bmatrix} \mu_1 & j\mu_2 & 0 \\ -j\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix}$$

n recipročni tenzor!

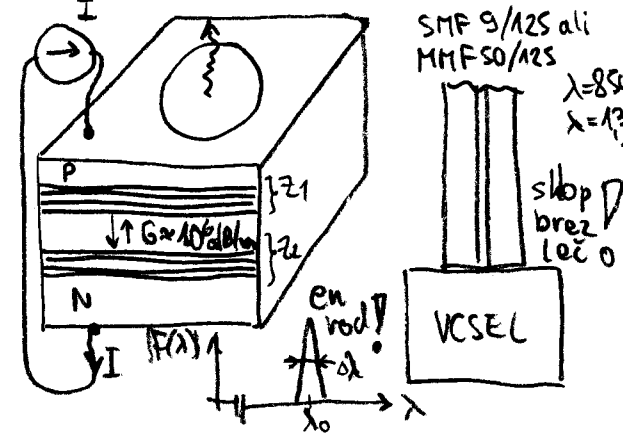
Faraday: B_z



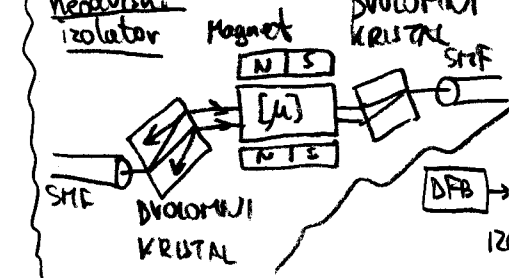
Vgradnja DFB1



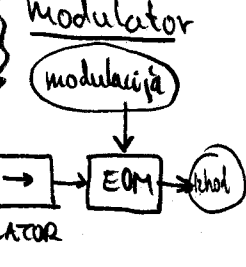
Vertical Cavity Surface Emitting Laser = VCSEL



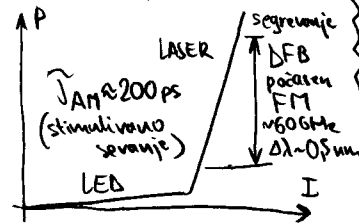
Polarizacijsko neodvisni izolator



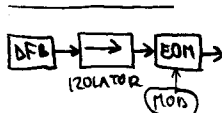
Zunanji modulator



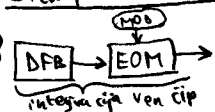
Ponovitev: neporedna modulacija FP/DFB



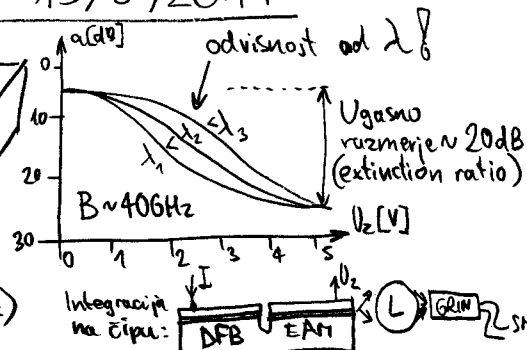
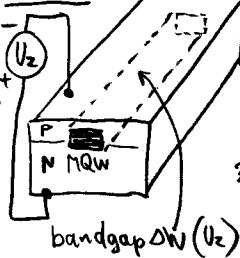
Vrhunski Tx:



Srednje kakovosten Tx:



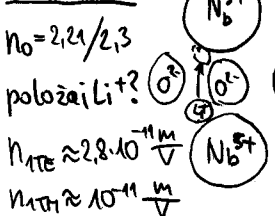
EAM:



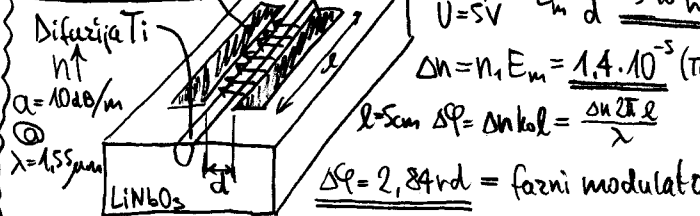
Kerr in Pockels:

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

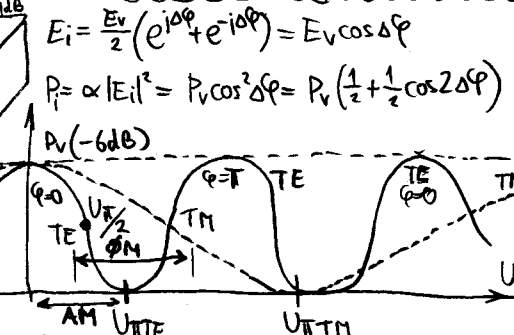
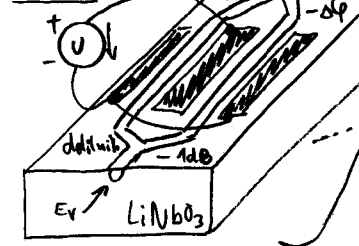
LiNbO₃:



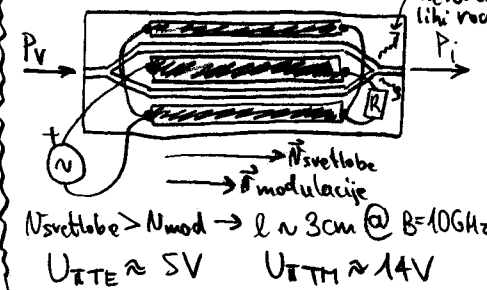
Valovod LiNbO₃:



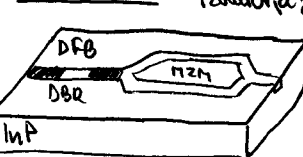
MZM:



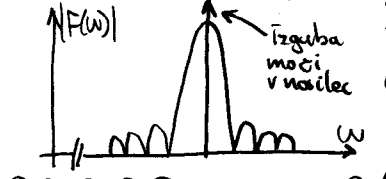
Elektrode na potujoči val:



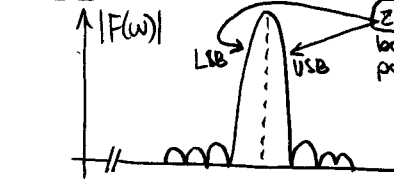
DFB + MZM:



AM: U_{BIAS} = U_{π/2} (ASK)

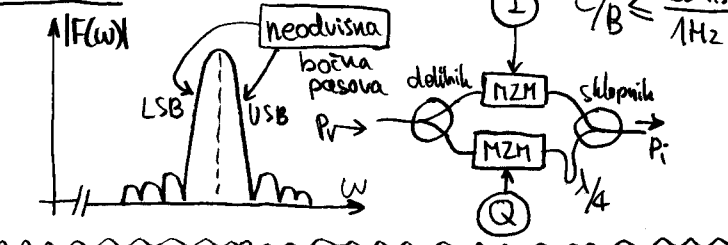


QPM: U_{BIAS} = U_π → BPSK

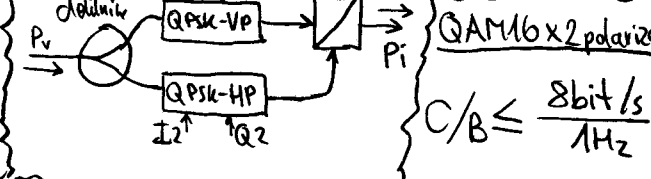


Spektralna učinkovitost:
 $C/B \leq \frac{1 \text{ bit/s}}{1 \text{ Hz}}$

QPSK:



QPSK x 2 polarizaciji: Polarization Beam Splitter PBS

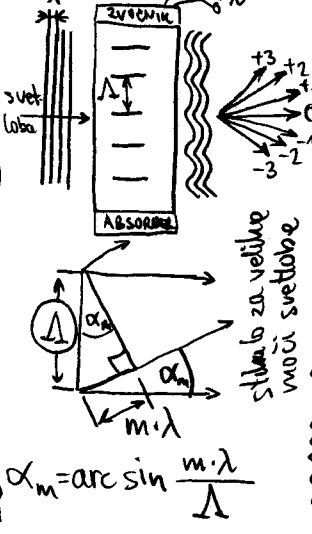


Zvok: (ultrazvok)

- 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

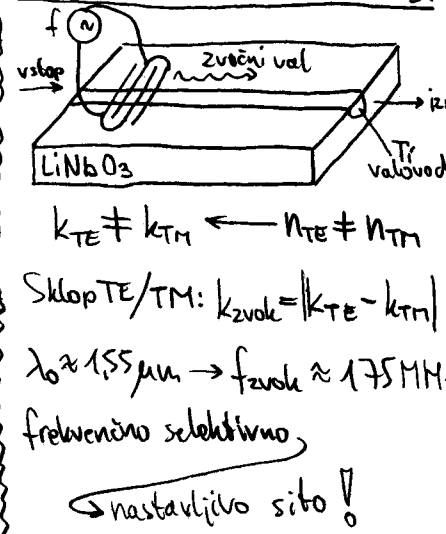
Raman-Nath: (uklon)



Bragg: (odboj)



Vzdolžna akustoptika v LiNbO₃:



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

Toplotni sprejemnik:
 $P = \alpha |E|^2$
 $P_{min} = 7 \text{ dBm}$
 $\tau \sim 1 \text{ ms}$
črna telo
termični

Fotopor: Se (1873)
 $N_f \gg N_e$
 $W_f \geq \Delta W_{se}$
 $T \sim 1 \mu s$ (rekombinacija)

Fotodioda: FOTOVOLTAČNI REŽIM
 $P = \text{max}$
 $M = \frac{N_e}{N_f}$
 $W_f \geq \Delta W$

FOTOPOROVM REŽIM ($M = \text{max}$)
 $M = 0,2 @ 500 \text{ nm}$
 $M = 10^{-6} @ 1,55 \mu m$
 $M = 0,5 - 0,7$
 $\tau < 50 \text{ ps}$

Ponovitev: $W [\text{eV}]$
 $W [\text{eV}] = \frac{W [\text{J}]}{|Q_e|} = \frac{hc_0}{|Q_e| \lambda}$
 $h = 6,626 \cdot 10^{-34} \text{ Js}$
 $Q_e = -1,6 \cdot 10^{-19} \text{ As}$
 $W [\text{eV}] = \frac{1,24 \text{ eV} \cdot \mu m}{\lambda [\mu m]}$

Bandgap:
 $\Delta W_{Si} = 1,1 \text{ MeV}$
 $\Delta W_{Ge} = 0,67 \text{ eV}$
 $\Delta W_{InGaAs} = 0,35 \text{ eV}$
 $In_{x-1}Ga_xAs$

Hetero struktura:
 $P = InP \quad E \Delta W_2$
 $I = InGaAs \quad \Delta W_1$
 $N = InP \quad \Delta W_2$

Odzivnost: $I/p = \frac{dq/dt}{dW/dt} = \frac{N_e |Q_e| \lambda}{N_f h c_0} = \eta \frac{|Q_e| \lambda}{h c_0}$
 $I/p = \frac{\eta \lambda [\mu m]}{1,24 \text{ eV} \cdot \mu m} [\text{A/W}]$
 $\Delta W_2 \quad \Delta W_1$
 $TK \ 1,3 - 1,55 \mu m$
 $I/p = 0,5 - 1 \text{ A/W}$

Občutljivost RX: $\Sigma C = C_d + C_0 \approx 0,5 \text{ pF}$
 $U_s = \frac{N_e |Q_e|}{\Sigma C}$
 $N_e = 1 \rightarrow U_s = 0,32 \mu V$

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

Toplotni šumi: $T = 300 \text{ K}$
 $P_n = B k_B T \quad k_B = 1,38 \cdot 10^{-23} \text{ J/K}$
 $B = \frac{1}{2 \pi R \Sigma C} \quad U_{neff} = \sqrt{P_n R}$
 $U_{neff} = \sqrt{\frac{k_B T}{2 \pi \Sigma C}} \approx 36 \mu V_{eff}$
Znati $U_{neff} = \frac{|Q_e|}{\Sigma C} \sqrt{N_e} \ll U_{neff \text{ toplotni}}$

Razmerje $S/N = Q = \frac{\langle U_n \rangle - \langle U_0 \rangle}{\sigma_1 + \sigma_0}$
 $BER = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right)$
 $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du$
Uporaba $Q = 6-7$
 $U_s \approx 450 \mu V$
 $N_e \approx 1400$
 $M = 0,7$
 $N_f \approx 2000$

Zaled: zveza $C = 16 \text{ Gbit/s}$
 $50\% \text{ enic} \rightarrow \langle N_f \rangle = \frac{N_f}{2} = 1000$
 $\frac{d\langle N_e \rangle}{dt} = \langle N_f \rangle \cdot C = 10^{12} \text{ fotonov/s}$
 $P = W_f \frac{d\langle N_e \rangle}{dt} = \frac{hc_0}{\lambda} \frac{d\langle N_e \rangle}{dt} = \frac{W_s}{6,5 \cdot 10^{18}} \frac{d\langle N_e \rangle}{dt}$
 $\lambda = 1,3 \mu m$
 $P = 1,53 \cdot 10^{-7} \text{ W} = -38,2 \text{ dBm}$

Dometa: $P_{rx} = 10 \text{ mW} = +10 \text{ dBm}$
točka-točka
 $P_{rx}/P_{tx} = 48,2 \text{ dB}$
 $\alpha/k = 0,35 \text{ dB/km}$
 $l = 137 \text{ km}$
(16 Gbps)

PON 100 Mbps
Centrala
Recep -3dB \rightarrow -3,5dB
64 uporabnikov
6 razge pov \rightarrow -24dB
64 uporab. x 100 Mbps = 6,4 Gbps (-8dB)

dometa = 48dB - 8dB - 21dB = 19dB !!! MAJO REZERVE!

Fotopomoževalka:
Prevodni tok
 $I_A = I_n M^N$
 $N = 3 \quad (8-14)$
 $M = 3-5 \quad (@ 100V)$
 $I_A = I_n M^N$
 $T \sim 1 \mu s$
 $M = ? @ \lambda = 1,55 \mu m$
konektinski tok

Plazovne fotodiode:
plinska
 $I_A = M \cdot I_{FK}$
APD

Izvedba APD: Ge 1,3 μm $M = 10$ $U_B = 30V$
Si 0,85 μm $M = 100$ $U_B = 150V$
InGaAs 1,55 μm $M = 20$ $U_B = 70V$

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

Ponovitev: šum

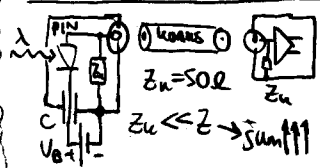


PIN-FET ~ 1000 fotonov/bit

APD-FET ~ 200 fotonov/bit

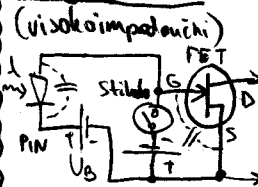
hlajen APD ~ 60 fotonov/bit (samo Si vidna svetloba)

Nizkoimpedančni RX:



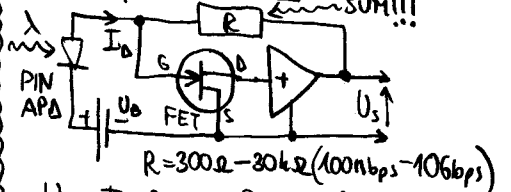
širokopasovna merilna tehnika → šum!!!
10⁴ - 10⁶ fotonov/bit

Integracijski RX:



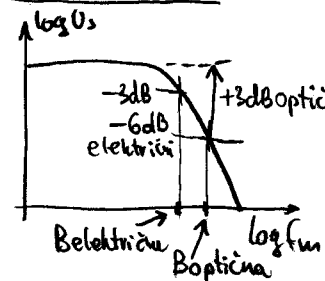
(visokoimpedančni)
teoretska občutljivost!
težavo kamiljenje stikala (reset)?

Transimpedančni RX:



šum!!!
R = 300Ω - 30kΩ (100Mbps - 10Gbps)
U_s = I_D · R_T R_T ~ R, R_T < R
Moduli: PIN-FET ali APD-FET → optična optika!

Pasovna širina:



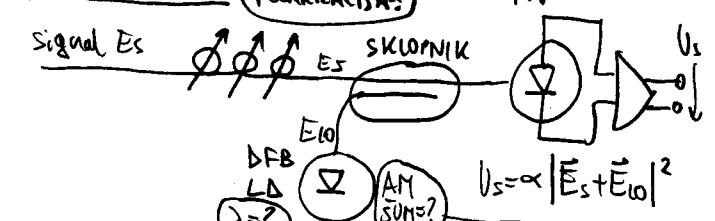
U_s = I_D R_T = R_T (I/P) P = R_T (I/P) A $\frac{|E|^2}{2\epsilon_0}$

U_s = α |E_{opt}|²

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

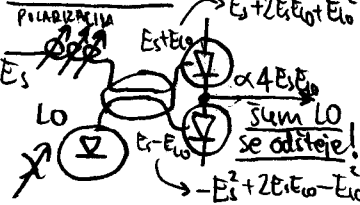
Kvadraten odziv detektorja moči!

Koharentni RX:

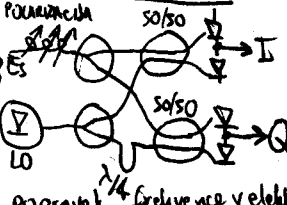


U_s = α (E_s + E_{LO}) (E_s + E_{LO})^{*} = γ (|E_s|² + E_sE_{LO}^{*} + E_s^{*}E_{LO} + |E_{LO}|²)
običajno |E_s| << |E_{LO}|
dobitek ≈ 2|E_{LO}|/|E_s|
MEJANJE FREKVENCA=?
POLARIZACIJA=?

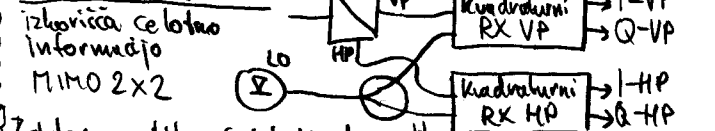
Balanci RX:



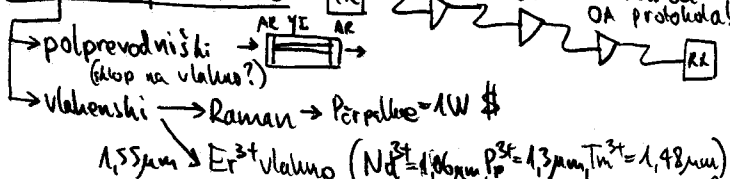
Kvadraturni RX:



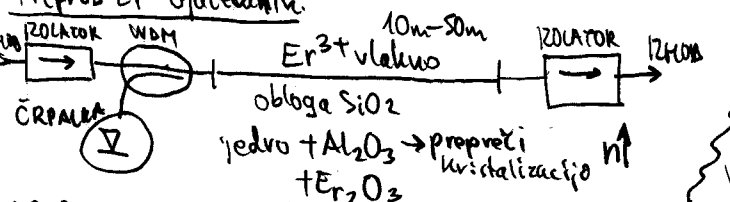
Dvopolizacijski RX:



Optični ojačevalnik:



Preprost Er³⁺ ojačevalnik:



ASE šum ojačevalnika: (za vsakod valovanja)

P_{ASE} = μ(G-1) h f Δf μ = $\frac{N_2}{N_2 - N_1}$

Zgled: λ_c = 980nm → μ ≈ 1

G = 40dB = 10⁴ = 10000

h = 6.626 · 10⁻³⁴ J s

f = 194 THz (λ = 1.55 μm)

Δf = 4 THz (širina Er³⁺ v SiO₂)

P_{ASE} = 5.1 mW!!! za en rod VP+HP, napretnazuj → 4P_{ASE} = 20.6 mW

P₀ = P_{ASE} $\frac{\lambda_{ASE}}{\lambda_c} = 33 mW!!!$

Definicija šumnega stevila:

F [dB] = 10 log₁₀ $\frac{(S/N)_{VHOD}}{(S/N)_{IZHOD}} = 10 log_{10} \frac{P_s}{G P_s} = 10 log_{10} 2\mu$

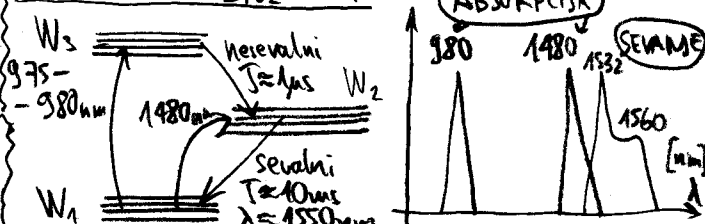
Zgledi F:

Er³⁺ vlakno + 980nm → F = 3dB - 3.5dB

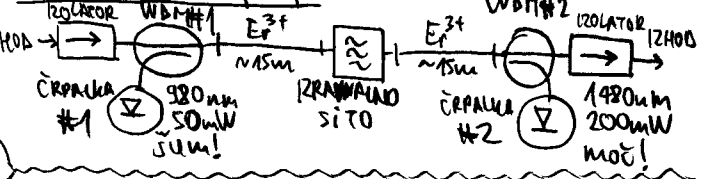
Er³⁺ vlakno + 1480nm → F = 4dB - 5dB

Polprevodniški → F = 6dB - 9dB (izgube siloape čip-vlakno)

Lastnosti Er³⁺ v SiO₂ stekla:



Dvosmerno čipanje:

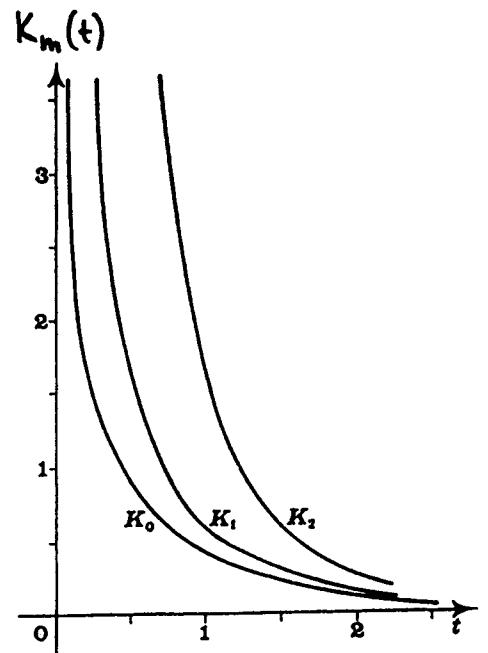
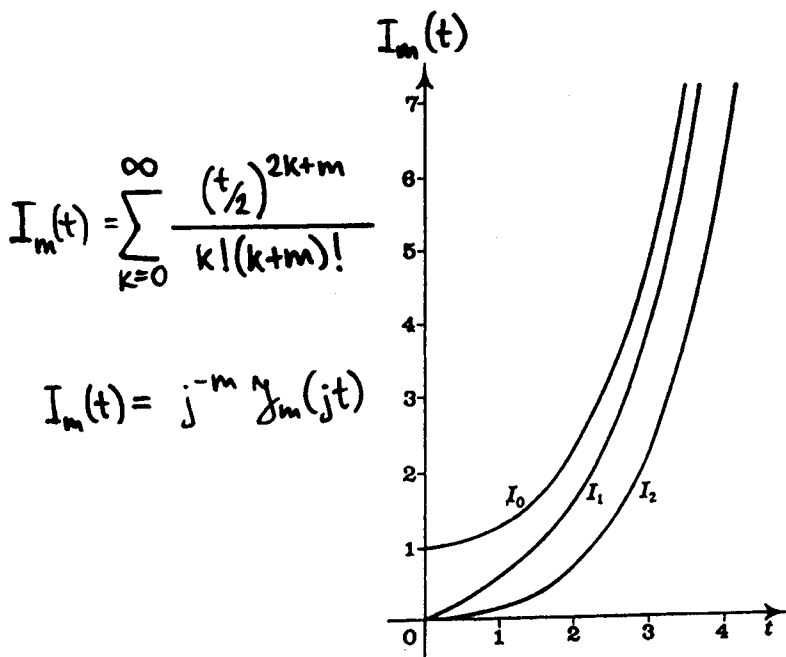
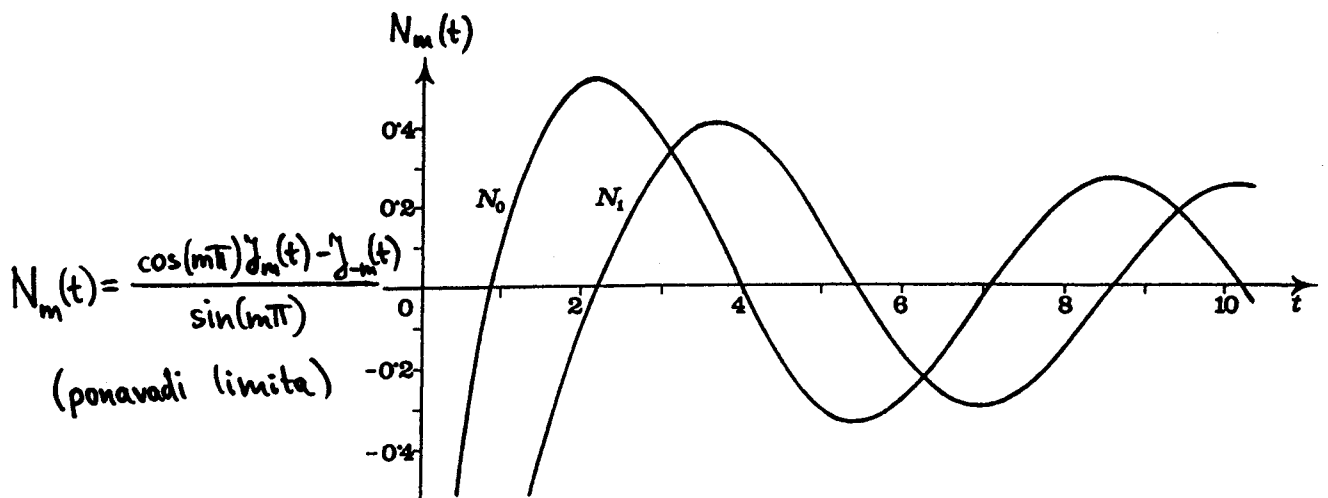
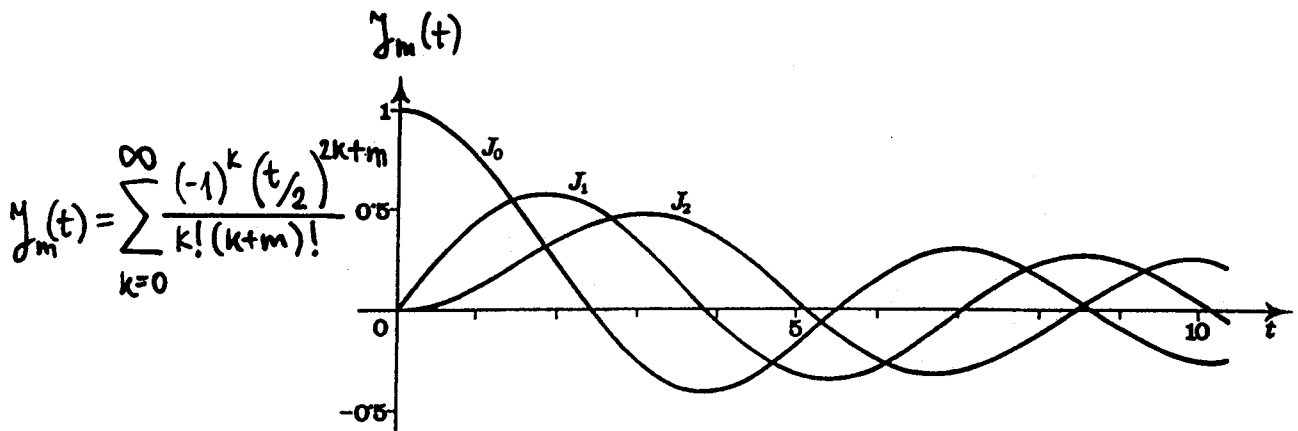


Zračni šum P₂ = $\frac{1}{2} h f \Delta f$

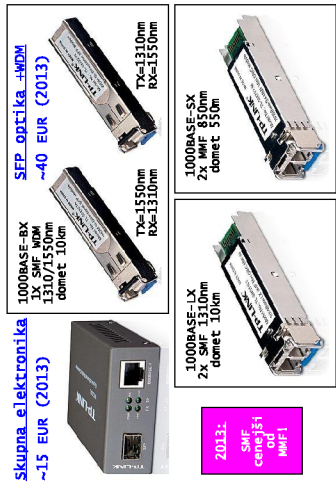
Optične komunikacije #15 - 5/6/2014

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:



$$K_m(t) = \frac{\pi [I_{-m}(t) - I_m(t)]}{2 \sin(m\pi)} \quad (\text{ponavadi limita})$$



Skupna elektronika
~15 EUR (2013)

SEP optika ~40 EUR (2013)

100BASE-BX
1310nm
RX=1550nm
domet 10km

100BASE-LX
2x SMF 1310nm
domet 10km

100BASE-SX
2x SMF 850nm
domet 550m

2013: SMF, Cenzurji, MMF!

29 - Različice 1Gbps Media Converter-jev

Inačica	Opis
40BASE-KR4	Vzporedno vodilo na tiskanem vezju domet 5m
40BASE-CR4	Vzporedni kabel 4x twinax domet 5m
40BASE-SR4	Vzporedni trak (ribbon) 4x MMF 850nm domet 125m
40BASE-LR4	4x 10Gbps WDM v pasu 1310nm SMF domet 10km
40BASE-IR4	40Gbps 1550nm SMF domet 2km
100BASE-CR10	Vzporedni kabel 10x twinax domet 5m
100BASE-SR10	Vzporedni trak (ribbon) 10x MMF 850nm domet 125m
100BASE-LR4	4x 25Gbps WDM v pasu 1310nm SMF domet 10km
100BASE-ER4	4x 25Gbps WDM v pasu 1550nm SMF domet 40km
10x10M8A	10x 10Gbps WDM 1522-1595nm SMF domet 2km

Več standardov kot delujočih izdelkov na tržišču. Izredno draga, nezanesljiva optoelektronika >100bps

30 - Ethernet standardi 40Gbps in 100Gbps

Pastvno žično omrežje HALF-DUPLEX in CSMA/CD, torej začetna zasnova Ethernet, so se izkazali neuporabni. HALF-DUPLEX se uporablja samo na 10Mbps, čeprav ga standardi dopuščajo tudi na 100Mbps in 1Gbps. Beseda "Ether" je izgubila pomen.

Primer: uporaba "Jumbo" okvirjev >>>1536byte?

Ethernet je bil vedno načrtovan od spodaj navzgor! Ethernet pomeni 33 let popolne združljivosti od 1980 do danes (2013) kljub razmerju prenosne zmogljivosti 1Mbps:100Gbps ali 1:100000!

Ethernet je združljiv in nadgradljiv v vse smeri! Ethernet oprema ima vgrajen (built-in) self-test!

Radijski podajilek Etherneta WLAN (WiFi) 802.11 je edini res svetovni dostopni standard!

Zaprti, nezdržljivi in neučinkoviti protokoli se nezdružujejo v požabo. Danes komaj opazimo take anahronične otočke v oceanu Etherneta...

33 - Kaj je to Ethernet danes (2013)?

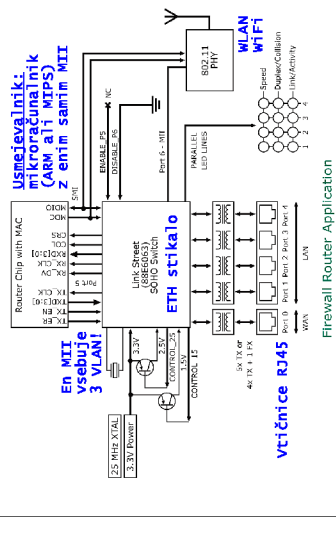
31 - Neuspehi Etherneta

90% Ethernet standardov ni nikoli zaživel!

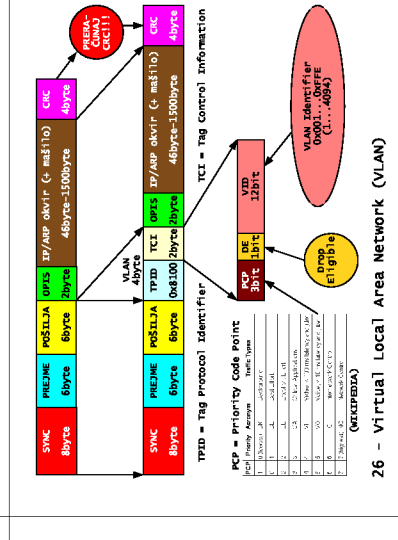
99% Ethernet standardov se ne uporablja več...

Nekatera določila Ethernet standardov so se kršila oziroma se še vedno zavestno in namerno kršijo...

Primer: uporaba "Jumbo" okvirjev >>>1536byte?



25 - Uporaba stikala v domačem usmerjevalniku



26 - Virtual Local Area Network (VLAN)

1987 - FOIRL (Fiber-Optic Inter-Repeater Link) 10Mbps, 850nm, domet 1km, par vlakn 62.5/125 za povezavo med zgradbami in galvansko ločitev, izbojšan 1993 tudi na 100Mbps in 1Gbps.

1995 - 100BASE-TX dvijakna standard za 100Mbps, po MMF/SMF na 850/1310/1550nm z velikim dometom 100m do 40km, istočasno z žičnim 100BASE-TX dometom 100m.

1998 - 100BASE-X izvorna izvedba 1Gbps Ethernet, po MMF/SMF na 850/1310/1550nm z velikim dometom 200m do 70km, UTP inačica pride šele leto kasneje (1999).

2003 - 100BASE-SR16/ER164/SW/LW/EW 40Gbps Ethernet po MMF/SMF na 850/1310/1550nm z velikim dometom 200m do 80km, WAN inačice SW/LW/EW delajo z 9.953Gbps za neposredno združljivost s STM-64 opto brez ATM!

2004 - "Ethernet in the first mile" in 1Gbps EPON

2009 - 10Gbps EPON

2010 - prvi standard za 40Gbps in 100Gbps Ethernet kot nadomestek za SDH STM-256, ki se umika iz uporabe

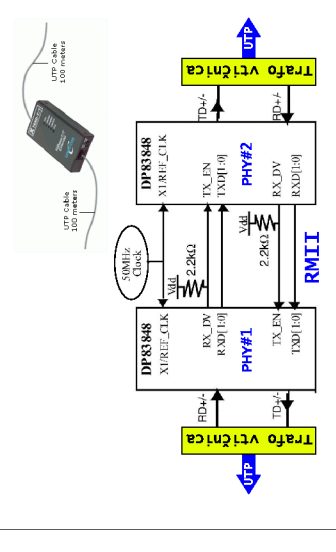
27 - Zgodovina optičnega Etherneta

Izvedba	Hkratna prenos	Linjska kodirajba	Linjska hitrost	Polnilno
FOIRL 100BASE-FL	10Mbps	Manchester	20Mbps	Pravokotnik 1MHz
Družina 100BASE-TX	100Mbps	4B/5B NRZ(L)	125Mbps	62.5MHz (GDMZ)
Družina 100BASE-X	1Gbps	8B/10B NRZ(L)	1.25Gbps	8B/10B TDLE
Družina 10GBASE-SR/LW/ER	10Gbps	64B/66B NRZ(L)	10.3125Gbps	64B/66B TDLE

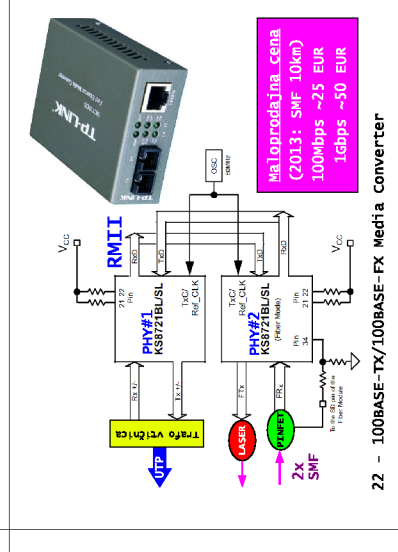
Linjsko kodiranje, jantci enosmerno komponento signala (CRP) in eno smerno ščitilo (ENC in INČ) sta no regeneracijo karka in usmerjajoče (dabe), začetek in konec okvirja.

Modulacija oddajnika (laserja) je vedno dvigoviska amplitudna on/off (ASK). Sprejemnik je občutljiv pri-FET. Auto nosp v optiki ni možen (samopisna nava R/TX vlakno). Auto Negotiation občutljivo ni vgrajen v optični Ethernet.

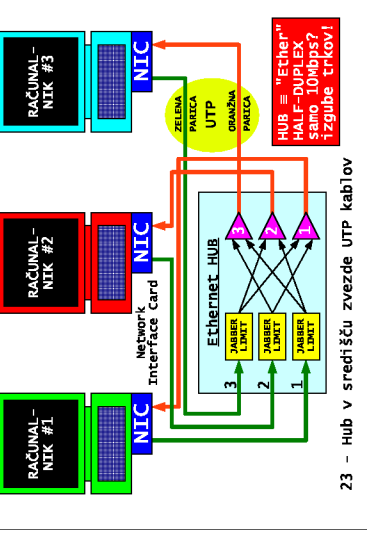
28 - Linjsko kodiranje v optičnem Ethernetu



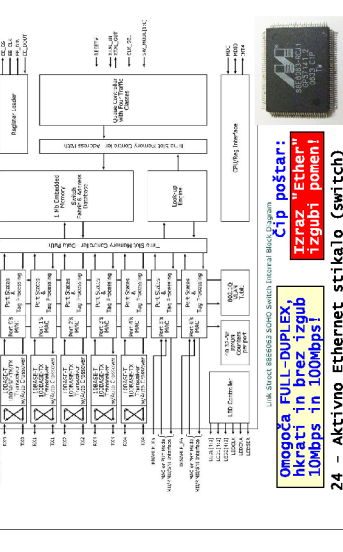
21 - 100BASE-TX 3R regenerators (Extender)



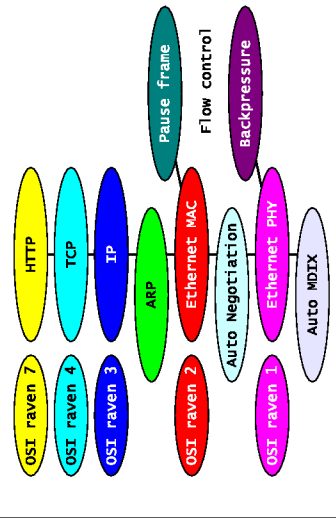
22 - 100BASE-TX/100BASE-FX Media Converter



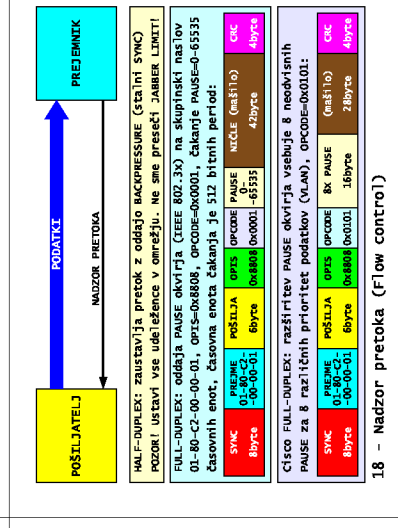
23 - Hub v središču zvezde UTP kablov



24 - Aktivno Ethernet stikalo (switch)



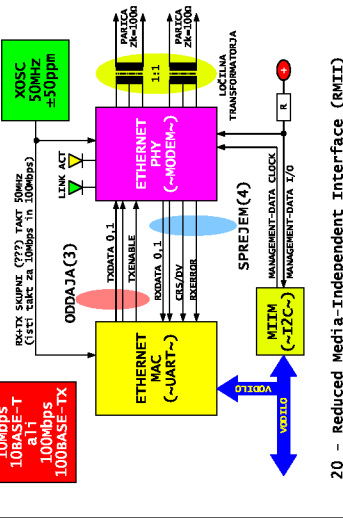
17 - TCP/IP/Ethernet/UTP sklad protokolov



18 - Nadzor pretoka (Flow control)

Ime	Vmesnik	Hitrost	Vodilo	Prikllop
AUI	Attachment Unit Interface	10Mbps	2x 1bit	3parce
MI	Media-Independent Interface	10/100Mbps	2x 4bit	17pin
RMII	Reduced Media-Independent Interface	10/100Mbps	2x 2bit	10pin
SII	Serial Network Interface	10Mbps	2x 1bit	9(7)pin
GMII	Gigabit Media-Independent Interface	10/100/1000Mbps	2x 8bit	27pin
RGMI	Reduced Gigabit Media-Independent Interface	10/100/1000Mbps	2x 4bit	14pin
SGMI	Serial Gigabit Media-Independent Interface	10/100/1000Mbps	2x 1bit	8parce+takt
XGMII	10 Gigabit Media-Independent Interface	10Gbps	2x 32bit	74pin
XAUI	10 (Gbps) Attachment Unit Interface	10Gbps	2x 4bit	8parce+8B/10B

19 - Različice Media-Independent Interface (MII)



20 - Reduced Media-Independent Interface (RMII)