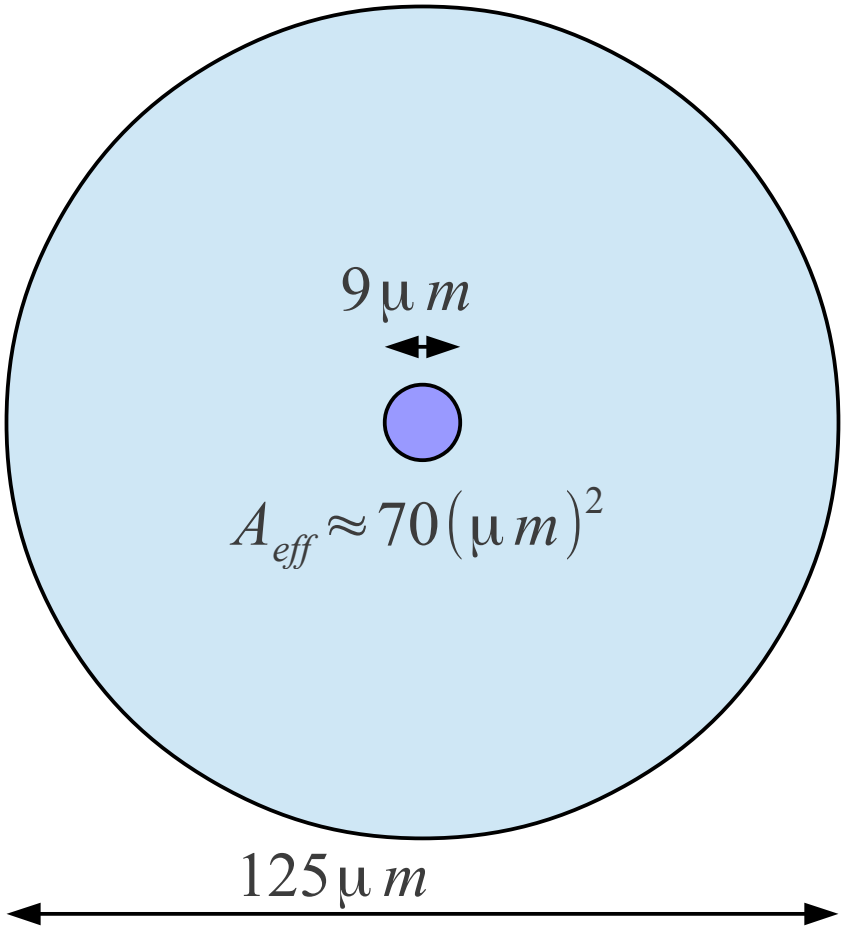
Optične komunikacije

Predavanje 7:

Nelinearne lastnosti svetlobnega vlakna



$$S = \frac{|E|^2}{2Z} = \frac{|E|^2 n_1}{2 Z_0} \qquad n_1 \approx 1.5 \qquad Z_0 \approx 377\,\Omega$$

$$P \approx 100\,mW$$

$$|E| \approx \sqrt{\frac{2 Z_0 S}{n_1}} \approx 860\,kV/m = 8.6\,kV/cm$$

$P \approx 1\,mW \rightarrow$ *nelinearni pojavi !*

$P \approx 10\,mW \rightarrow$ *zažig vtičnic !*

$P \approx 100\,mW \rightarrow$ *max P na vtičnici !*

$P \approx 1\,W \rightarrow$ *max P v vlaknu !*

$P \approx 10\,W \rightarrow$ *taljenje jedra vlakna !*

$SiO_2 + GeO_2$ *G.652*

$P \approx 100\,mW$

$$S = \frac{P}{A_{eff}} \approx \frac{100\,mW}{70\,\mu m^2} \approx 1.4 \cdot 10^9\,W/m^2 = 1.4\,GW/m^2 = 140\,kW/cm^2$$

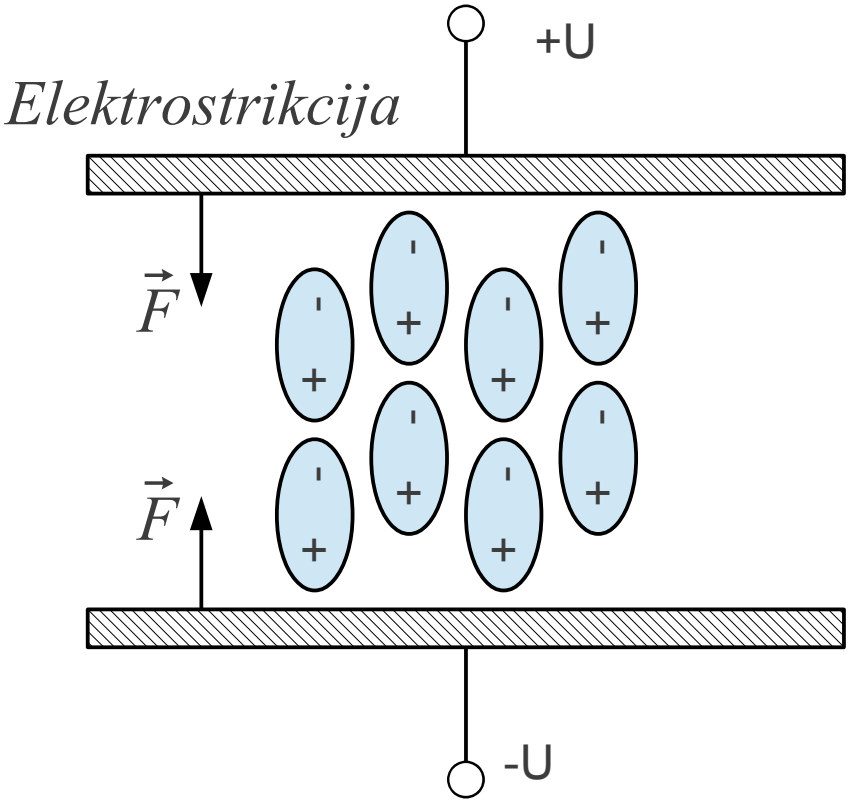
$$n = n_0 + n_1 \cdot E + n_2 \cdot E^2 + n_3 \cdot E^3 + ...$$

$n_1 \equiv Pockelsov\ pojav$

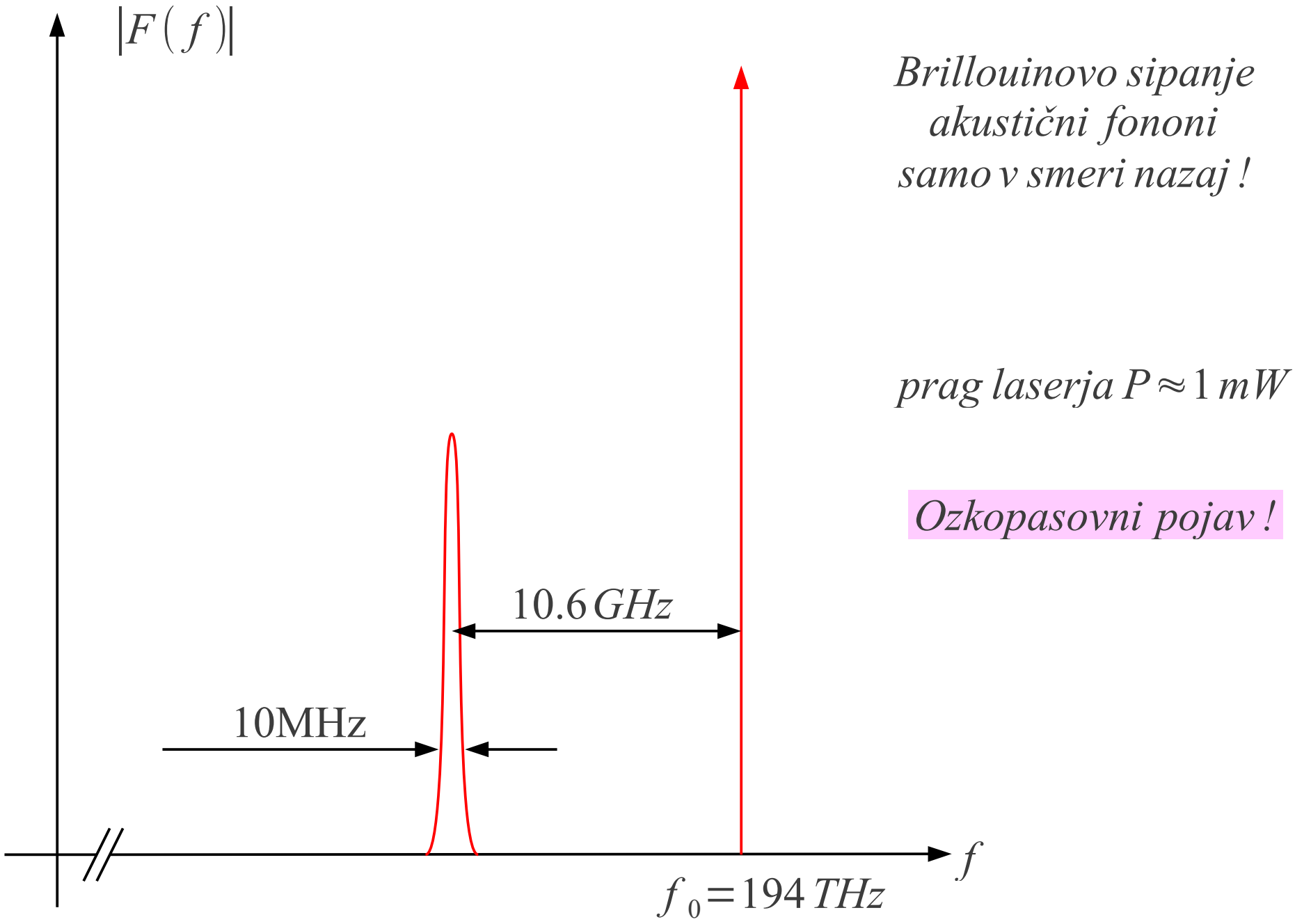
$n_2 \equiv Kerrov\ pojav$

$E^2 \rightarrow S$

$n = n_0 + n_2 \cdot S \qquad n_0 \approx 1.46$



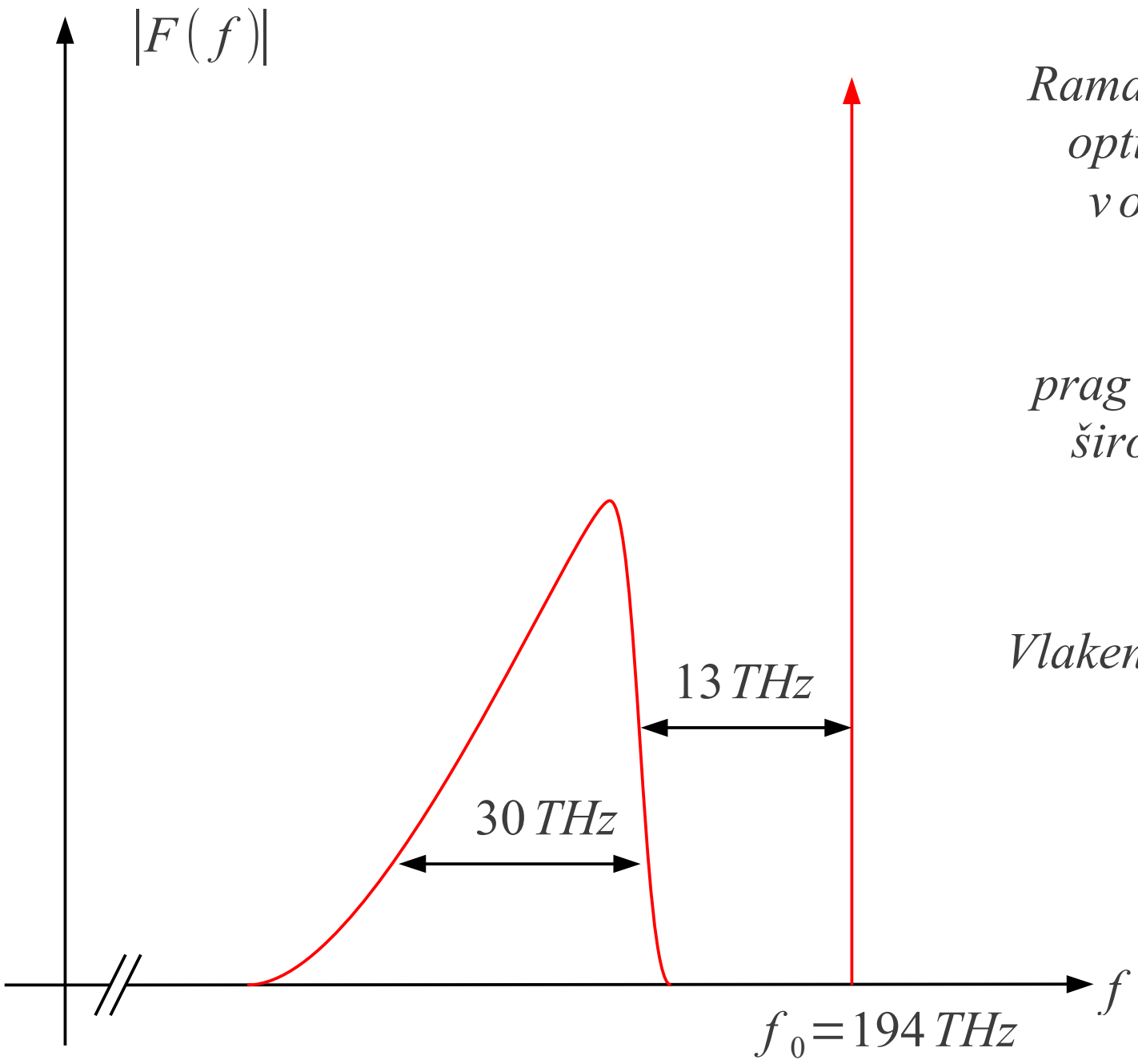
$SiO_2 + GeO_2 \rightarrow n_2 \approx 2.5 \cdot 10^{-20}\, m^2/W \ldots 3.2 \cdot 10^{-20}\, m^2/W$



Brillouinovo sipanje
akustični fononi
samo v smeri nazaj !

prag laserja $P \approx 1\ mW$

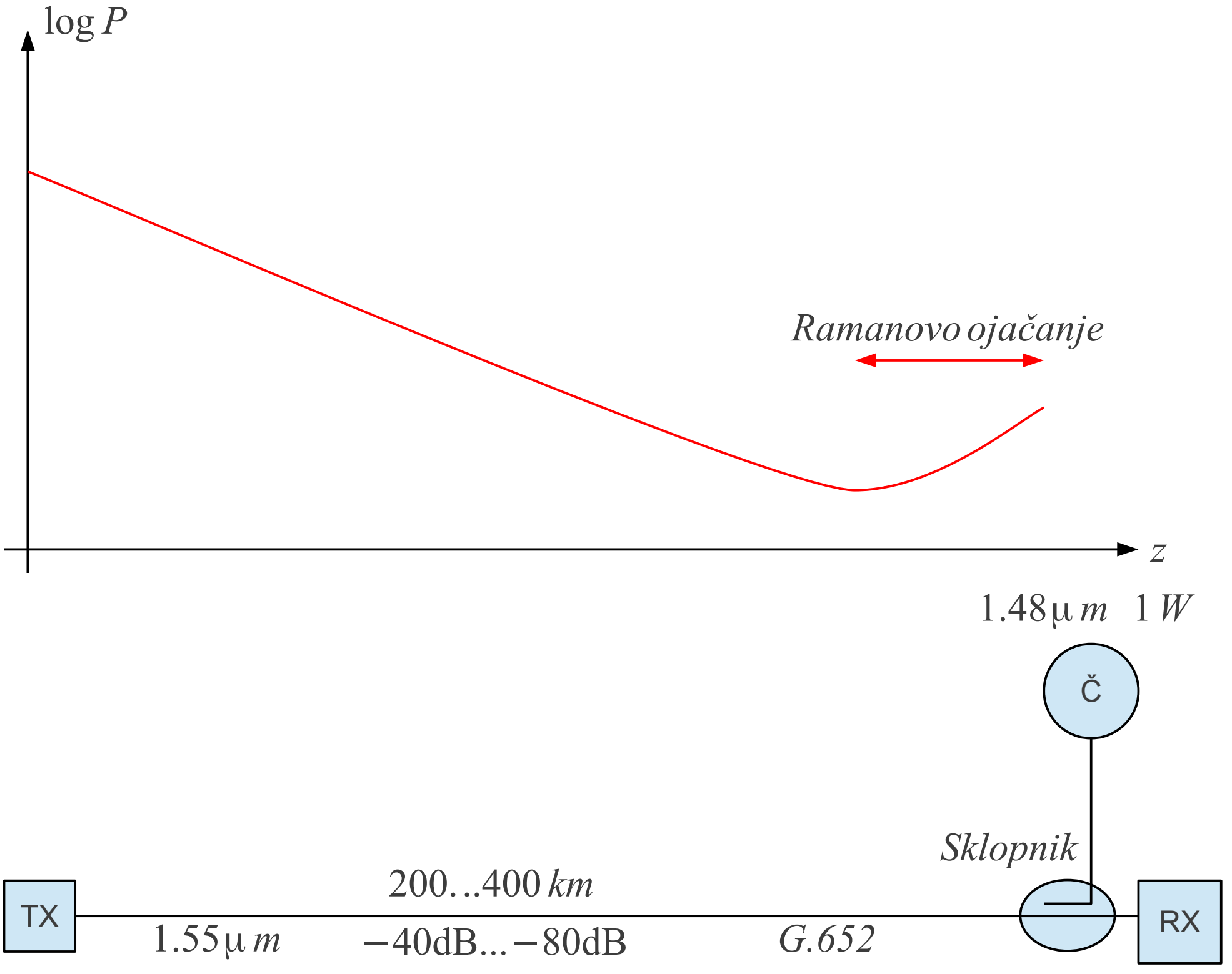
Ozkopasovni pojav !



Ramanovo sipanje
optični fononi
v obe smeri !

prag laserja $P \approx 100\ mW$
širokopasoven pojav

Vlakenski optični ojačevalnik
$P_{črpalke} \approx 1\ W$


log P
Ramanovo ojačanje
z
1.48 μ m 1 W
Č
Sklopnik
TX
200...400 km
1.55 μ m
−40dB...−80dB
G.652
RX

Lastna fazna modulacija

$$n = n_0 + n_2 \cdot S$$

$$\phi = -k \cdot l = -n \cdot k_0 \cdot l = \frac{-n \cdot 2\pi}{\lambda_0} \cdot l$$

$$P \approx 100\, mW$$

$$A_{eff} \approx 70 (\mu m)^2$$

$$\Delta\phi = -\Delta n \cdot \frac{2\pi}{\lambda_0} \cdot l = n_2 \cdot S \cdot \frac{2\pi}{\lambda_0} \cdot l = \frac{2\pi \cdot n_2 \cdot P}{A_{eff} \cdot \lambda_0} \cdot l \approx 0.15\, rd$$

$$n_2 \approx 2.5 \cdot 10^{-20}\, m^2 / W$$

$$l = 1\, km$$

linearni D + nelinerani n → Solitonski prenos ! (1995)

Soliton ≡ skrbno izbrana obilka impulza

Lastna fazna modulacija z upoštevanjem slabljenja vlakna !

$$a \approx 0.2\, dB/km \qquad P(z) = P(0)\cdot 10^{-\frac{a\cdot z}{10}} = P(0)\cdot e^{-\frac{a\ln 10}{10}\cdot z}$$

$$\Delta\phi = \frac{-2\pi\cdot n_2}{A_{eff}\cdot\lambda_0}\cdot\int_0^l P(z)\,dz = \frac{-2\pi\cdot n_2\cdot P(0)}{A_{eff}\cdot\lambda_0}\cdot\int_0^l e^{-\frac{a\ln 10}{10}\cdot z}\,dz$$

$$l_{eff} = \int_0^l e^{-\frac{a\ln 10}{10}\cdot z}\,dz \approx \int_0^\infty e^{-\frac{a\ln 10}{10}\cdot z}\,dz = \frac{10}{a\ln 10} = 21.7\, km$$

$$\Delta\phi = \frac{-2\pi\cdot n_2\cdot P(0)}{A_{eff}\cdot\lambda_0}\cdot l_{eff} \approx -2.83\, rd$$

$$P \approx 100\, mW$$

$$A_{eff} \approx 70\,(\mu m)^2$$

$$n_2 \approx 2.5\cdot 10^{-20}\, m^2/W$$

$$l > 50\, km$$

Dvotonsko krmiljenje

$$E = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t \qquad \ldots (\textit{zanemarim polarizacijo !})$$

$$\Delta \omega = \omega_1 - \omega_2 \ll \omega_1 , \omega_2 \rightarrow \textit{utripanje !}$$

$$p(t) = \alpha |E|^2 = \alpha \left| A_1 \cos \omega_1 t + A_2 \cos \omega_2 t \right|^2$$

$$p(t) = \alpha \left| A_1^2 \cos^2 \omega_1 t + A_2^2 \cos^2 \omega_2 t + 2 A_1 A_2 \cos \omega_1 t \cos \omega_2 t \right|^2$$

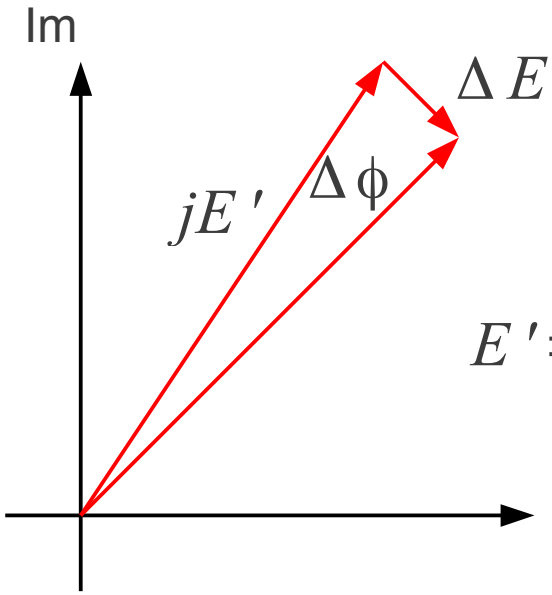
$$\cos x \cos y = \frac{1}{2} [\cos(x+y) + \cos(x-y)]$$

$$P = \langle p(t) \rangle = P_1 + P_2 + 2\sqrt{P_1 P_2} \cos \Delta \omega t \qquad \ldots \textit{samo počasni členi !}$$

Utripanje

$$\Delta \phi = \frac{-2\pi \cdot n_2}{A_{eff} \cdot \lambda_0} \cdot l_{eff} \cdot 2\sqrt{P_1 P_2} \cos \Delta \omega t \qquad \ldots . \textit{samo utripanje}$$

Križna fazna modulacija !



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

$$E' = E_0 \sin \omega t$$

$$\Delta E = E_0 \left(\frac{2\pi n_2 l_{eff}}{A_{eff} \lambda_0} \right) 2\sqrt{P_1 P_2} \cos \Delta\omega t \sin \omega t$$

$$\cos x \sin y = \frac{1}{2}\left(\sin(y+x) + \sin(y-x)\right)$$

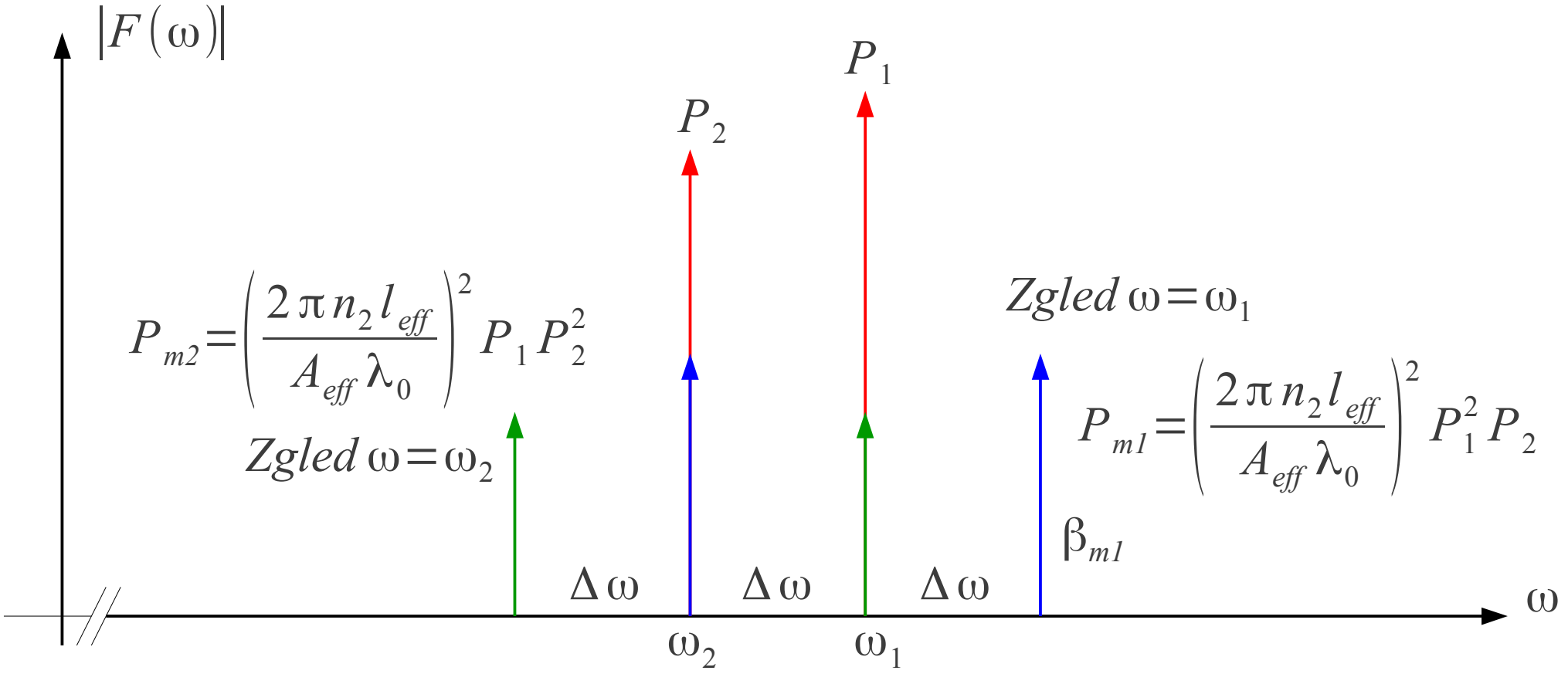
$$\Delta E = E_0 \left(\frac{2\pi n_2 l_{eff}}{A_{eff} \lambda_0} \right) \sqrt{P_1 P_2} \left[\sin(\omega + \Delta\omega) t + \sin(\omega - \Delta\omega) t \right]$$

Dve novi frekvenci ≡ mešanje !

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

Štirivalovno mešanje FWM (Four – Wave Mixing)

Elektroinženirji 50 let pred fiziki ! Intermodulacijsko popačenje IMD

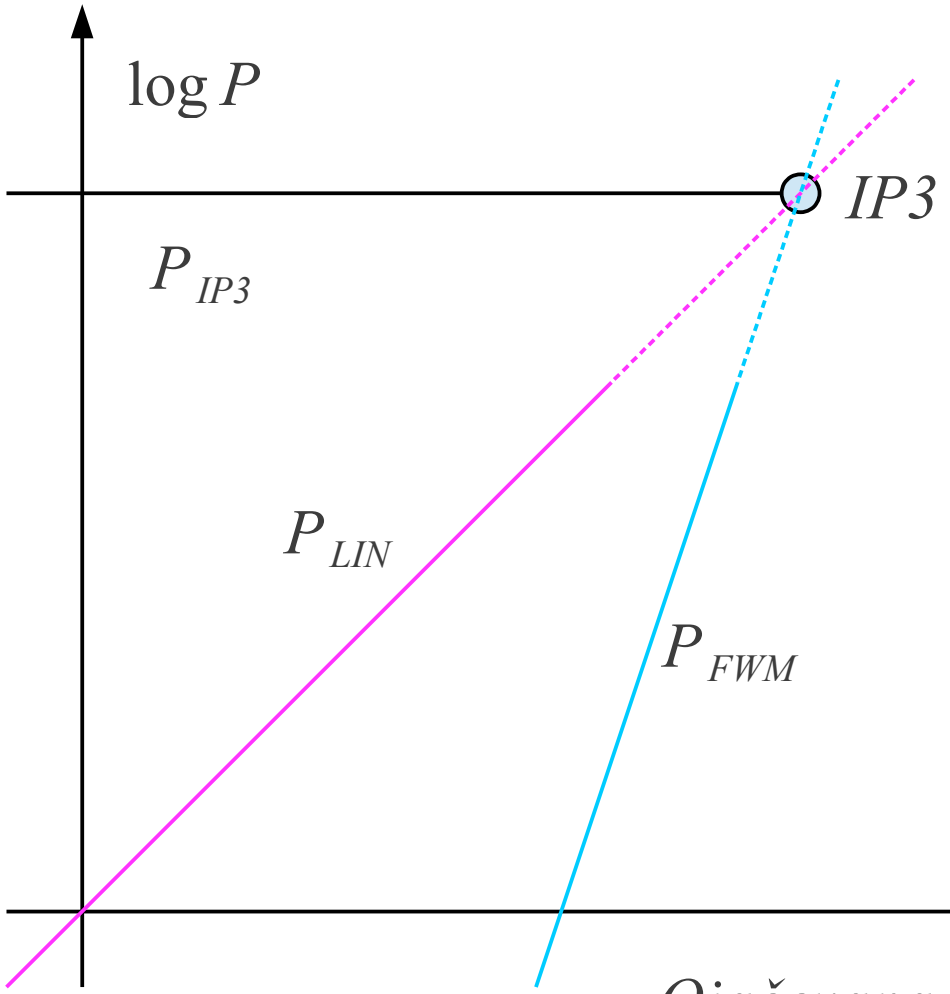


$$P_{m1}=\left(\frac{2\pi n_2 l_{eff}}{A_{eff}\lambda_0}\right)^2 P_1^2 P_2=\frac{P_1^2 P_2}{P_{IP3}^2}$$

$$P_{m2}=\left(\frac{2\pi n_2 l_{eff}}{A_{eff}\lambda_0}\right)^2 P_1 P_2^2=\frac{P_1 P_2^2}{P_{IP3}^2}$$

$$\left(\frac{2\pi n_2 l_{eff}}{A_{eff}\lambda_0}\right)^2 \left[W^{-2}\right]$$

$$P_{IP3}=\left(\frac{A_{eff}\lambda_0}{2\pi n_2 l_{eff}}\right)\left[W\right]$$



$$DSF\ G.653 \quad A_{eff}\approx 30\left(\mu m\right)^2$$

$$n_2\approx 2.5\cdot 10^{-20}\, m^2/W$$

$$l_{eff}=21.7\text{km}$$

$$P_{IP3}=\left(\frac{A_{eff}\lambda_0}{2\pi n_2 l_{eff}}\right)=14\,mW$$

Ojačevana zveza $N\cdot l_{eff}$ *! ! !*

vlakno

porazdeljena nelineranost → porazdeljeno mešanje

$$l_{eff}=\left|\int_0^l e^{-\frac{a\ln 10}{10}\cdot z}\,e^{-j\Delta\beta}\,dz\right|\approx\frac{1}{\sqrt{\left(\frac{a\ln 10}{10}\right)^2+(\Delta\beta)^2}}$$

$$\Delta\omega=2\pi\cdot 100\,GHz$$

$$l_{eff}\approx\frac{1}{\Delta\beta}\approx 0.4\,km$$

$$Fazna\ neusklajenost\equiv\Delta\beta=\beta_2+\beta_{m1}-2\beta_1\approx\frac{d^2\beta}{d\omega^2}\cdot(\Delta\omega)^2\approx-2.51\,rd/km$$

$$t_g=\frac{l}{v_g}=l\frac{d\beta}{d\omega}$$

$$NZDSF\ G.655\quad D\approx 5\ ps/(nm.km)$$

$$\frac{d\,t_g}{d\omega}=l\frac{d^2\beta}{d\omega^2}=\frac{d\,t_g}{d\lambda_0}\cdot\frac{d\lambda_0}{d\omega}=D\cdot l\cdot\frac{-\lambda_0^2}{2\pi c_0}$$

$$\frac{d^2\beta}{d\omega^2}=D\cdot\frac{-\lambda_0^2}{2\pi c_0}$$

$$\Delta\omega = 2\pi \cdot 100\,GHz$$

$$WDM \approx 100\,kanalov\ po\,100\,GHz$$

$$l_{eff} \approx \frac{1}{\Delta\beta} \approx 0.4\,km$$

$$NZDSF\ G.655 \quad D \approx 5\ ps/(nm.km)$$

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

$$P_{IP3} = \left(\frac{A_{eff}\,\lambda_0}{2\pi\, n_2\, l_{eff}}\right) = 2\,W$$

$$P_{m1} = \left(\frac{2\pi\, n_2\, l_{eff}}{A_{eff}\,\lambda_0}\right)^2 P_1^2\, P_2 = \frac{P_1^2\, P_2}{P_{IP3}^2} \approx 2\,nW$$

$$P_1 = P_2 = 2\,mW$$

$$Ojačevana\ zveza\ N \cdot l_{eff} = 40\,km \qquad N = 100$$

$$P_{IP3} \approx 20\text{mW} \rightarrow P_{m1} \approx 0.02\,mW$$

vlakno LEAF
Large Effective Aera Fiber