22. Seminar Optične Komunikacije

Laboratorij za Sevanje in Optiko

Fakulteta za Elektrotehniko

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Nelinearnosti in intermodulacija v optičnih komunikacijah

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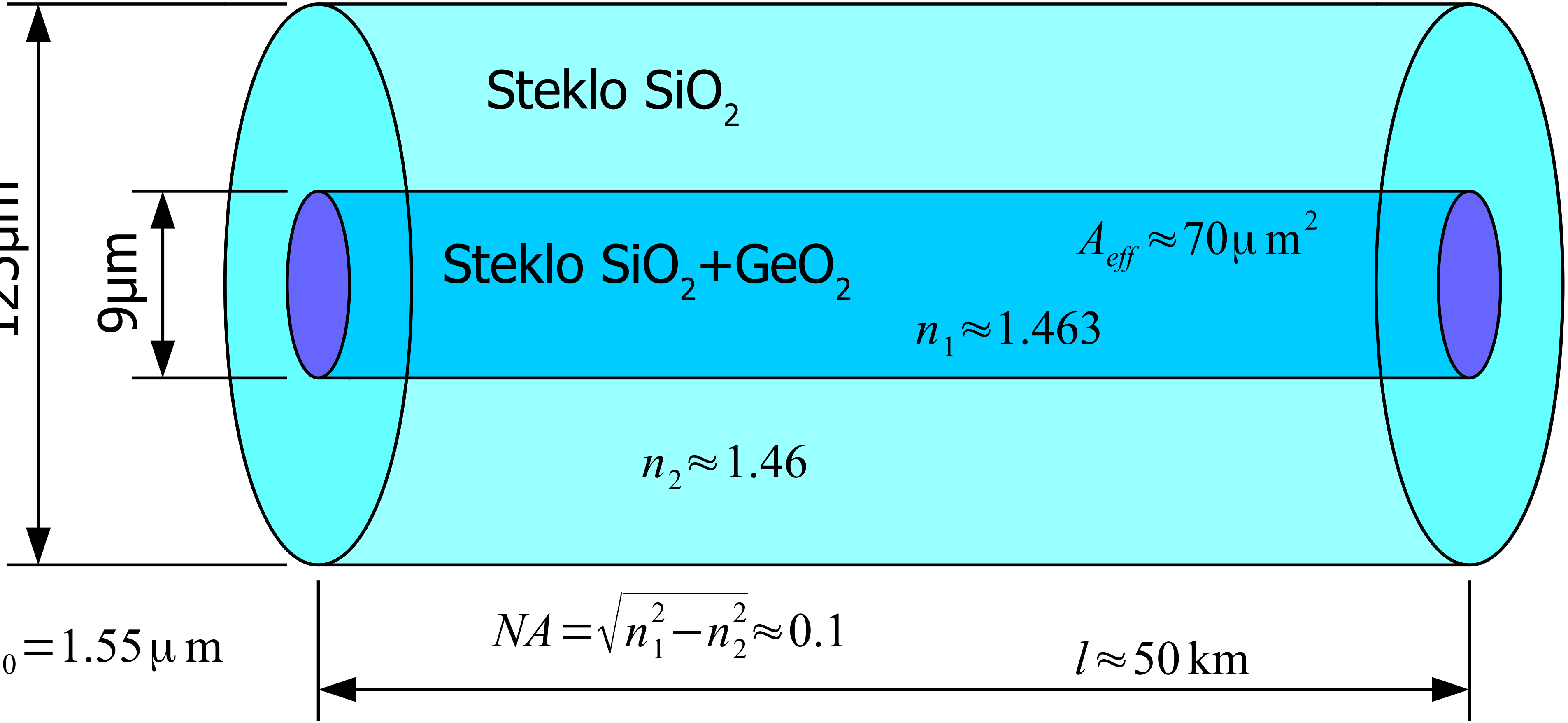
.... Seznam prosojnic: ....



$$\lambda_0 = 1.55\,\mu\mathrm{m}$$

$$a \approx 0.2\,\mathrm{dB/km} = 0.0002\,\mathrm{dB/m}$$

$$\Delta t_g = D \cdot l \cdot \Delta\lambda_0$$

$$D(\lambda_0) \approx 17\,\frac{\mathrm{ps}}{\mathrm{nm}\cdot\mathrm{km}} = 17\cdot 10^{-6}\,\frac{\mathrm{s}}{\mathrm{m}^2}$$

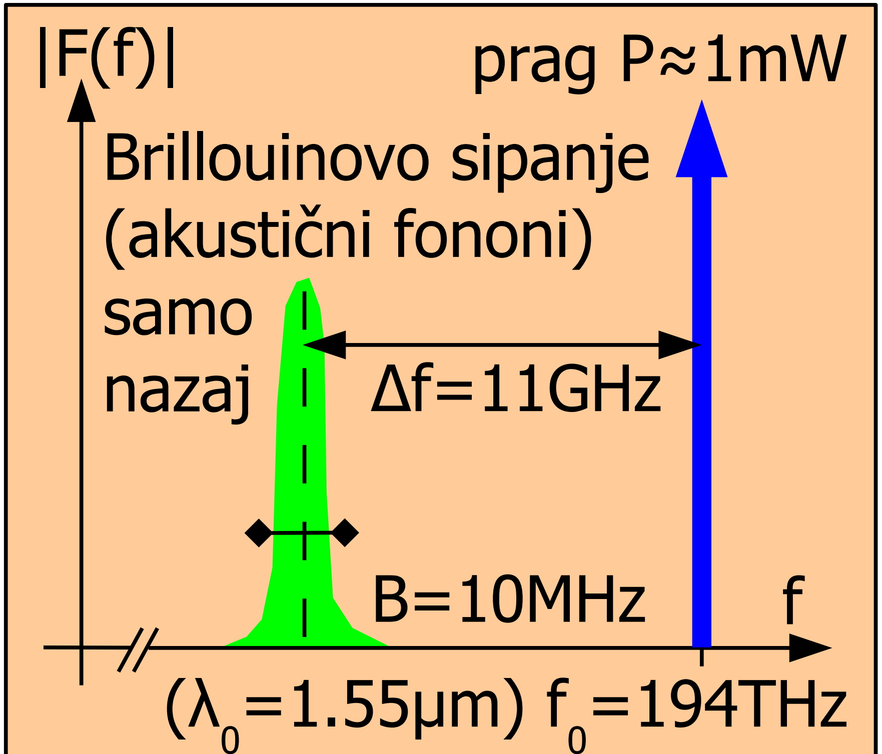
Zgled moči:

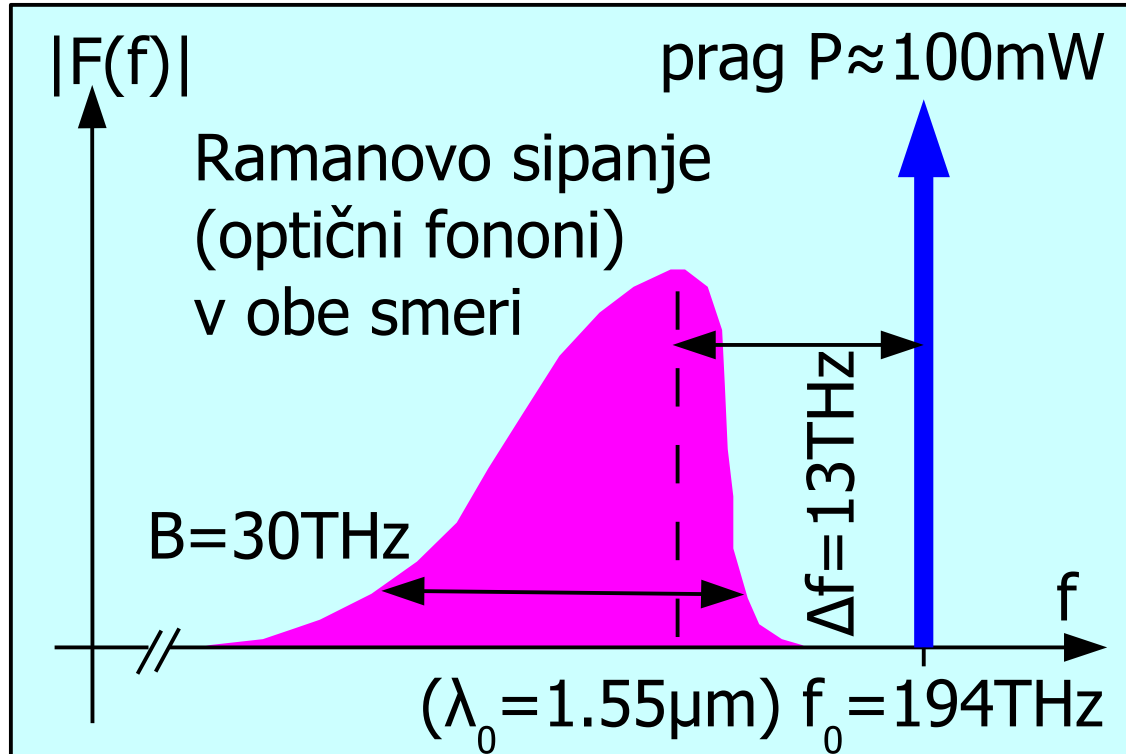
$$P = 100\,\mathrm{mW}$$

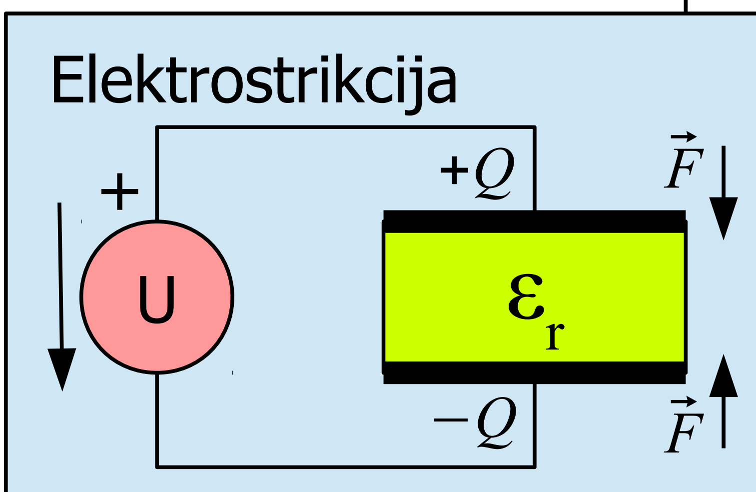
$$S = \frac{P}{A_{eff}} = 1.43\cdot 10^9\,\mathrm{W/m^2} = 143\,\mathrm{kW/cm^2}$$

$$E = \sqrt{S\cdot 2Z_0/n_1} = 8.58\cdot 10^5\,\mathrm{V/m} = 8.58\,\mathrm{kV/cm}$$

1 – Enorodovno svetlobno vlakno







Nelinearni lomni količnik
(Kerrov pojav)

$$n(S) = n_0 + n_2 \cdot S \qquad S = \frac{dP}{dA}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

Kremenovo steklo SiO_2

$$n_0 \approx 1.46 \qquad n_2 \approx 2.5 \cdot 10^{-20}\ \mathrm{m}^2/\mathrm{W}$$

2 – Nelinearni pojavi elektrostrikcije

$l = 1\,\mathrm{km}$ Kratko vlakno, približno konstantna moč

$P = 100\,\mathrm{mW}$ $A_{eff} = 70\,\mu\mathrm{m}^2$ $S = 1.43\,\mathrm{GW/m}^2$ $\lambda_0 = 1.55\,\mu\mathrm{m}$

$$\Delta n = n_2 \cdot S = 3.58 \cdot 10^{-11} \qquad \Delta\varphi = -\Delta n \cdot k_0 \cdot l = -\Delta n \cdot \frac{2\pi}{\lambda_0} \cdot l = -0.145\,\mathrm{rd}$$

$l = 50\,\mathrm{km}$ Dolgo vlakno, moč upada zaradi slabljenja vlakna

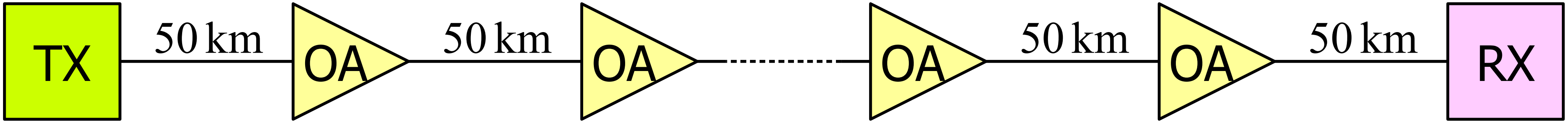
$$\lambda_0 = 1.55\,\mu\mathrm{m} \qquad P(0) = 100\,\mathrm{mW} \qquad S(z) = \frac{P(z)}{A_{eff}} \qquad \Delta n(z) = n_2 \cdot \frac{P(z)}{A_{eff}}$$

$$a = 0.2\,\mathrm{dB/km} = 0.0002\,\mathrm{dB/m} \qquad P(z) = P(0) \cdot 10^{-\frac{a \cdot z}{10}} = P(0) \cdot e^{-\frac{\ln 10}{10} \cdot a \cdot z}$$

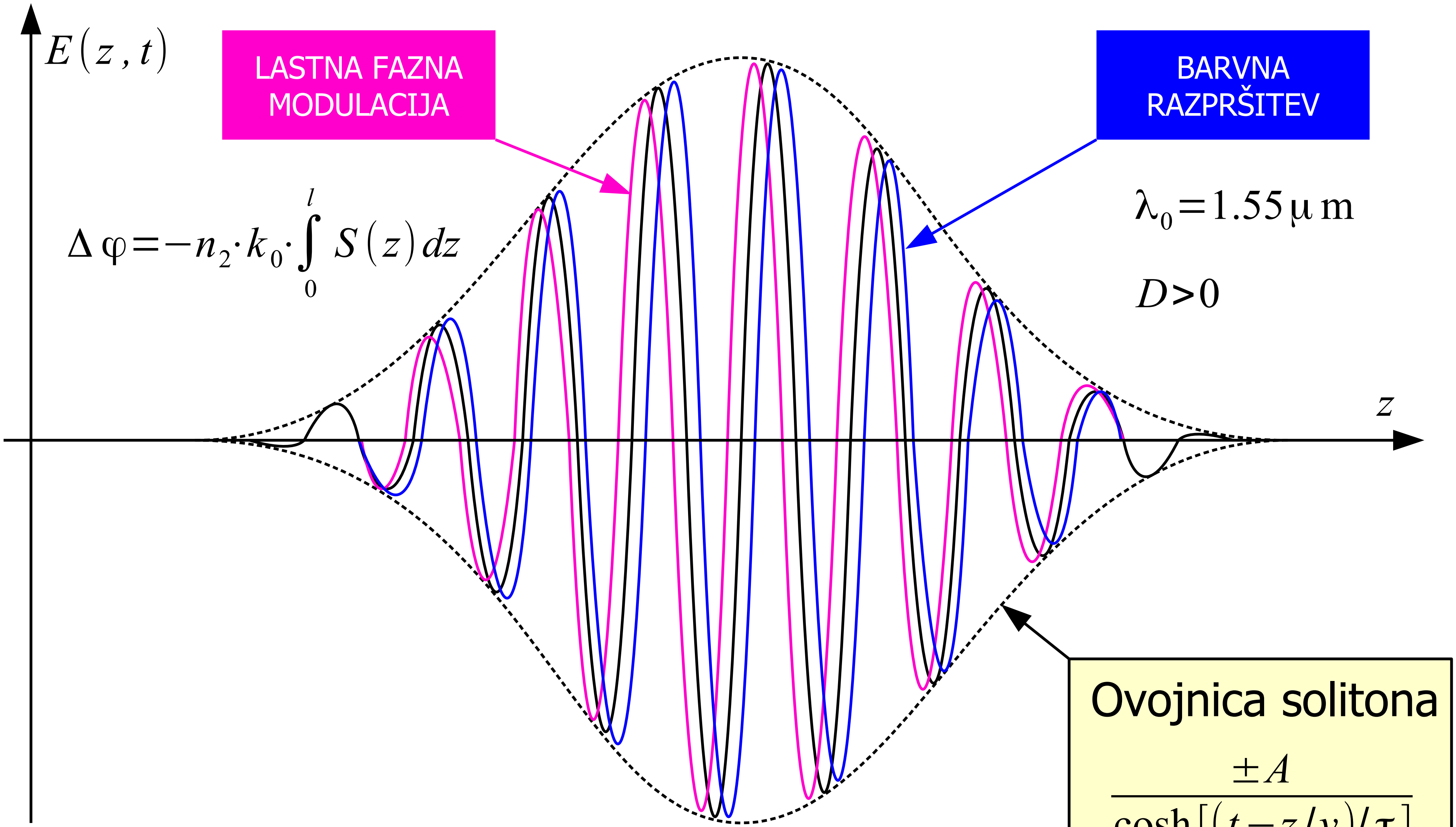
$$\Delta\varphi = -\int_0^l \Delta n(z) \cdot k_0\, dz = -\int_0^l \frac{n_2 \cdot P(0)}{A_{eff}} \cdot \left(e^{-\frac{\ln 10}{10} \cdot a \cdot z} \right) \cdot \frac{2\pi}{\lambda_0}\, dz = -\frac{2\pi \cdot n_2 \cdot P(0)}{A_{eff} \cdot \lambda_0} \cdot \int_0^l e^{-\frac{\ln 10}{10} \cdot a \cdot z}\, dz$$

$$\Delta\varphi = -\frac{20\pi \cdot n_2 \cdot P(0)}{A_{eff} \cdot \lambda_0 \cdot a \cdot \ln 10} \cdot \left(1 - e^{-\frac{\ln 10}{10} \cdot a \cdot l} \right) = -2.83\,\mathrm{rd}$$

3 – Lastna fazna modulacija



Ojačevana prekooceanska zveza brez regeneratorjev



4 – Solitonski prenos

$$E(t)=E_1(t)+E_2(t)=A_1\cdot\cos\omega_1 t+A_2\cdot\cos\omega_2 t$$

Ista polarizacija!

$$p(t)=\alpha\cdot E^2(t)=\alpha\cdot\left[A_1^2\cdot\cos^2\omega_1 t+2A_1A_2\cdot\cos\omega_1 t\cdot\cos\omega_2 t+A_2^2\cdot\cos^2\omega_2 t\right]$$

$$P_1=\alpha\cdot\frac{A_1^2}{2}\qquad P_2=\alpha\cdot\frac{A_2^2}{2}\qquad 2\sqrt{P_1P_2}=\alpha\cdot A_1A_2$$

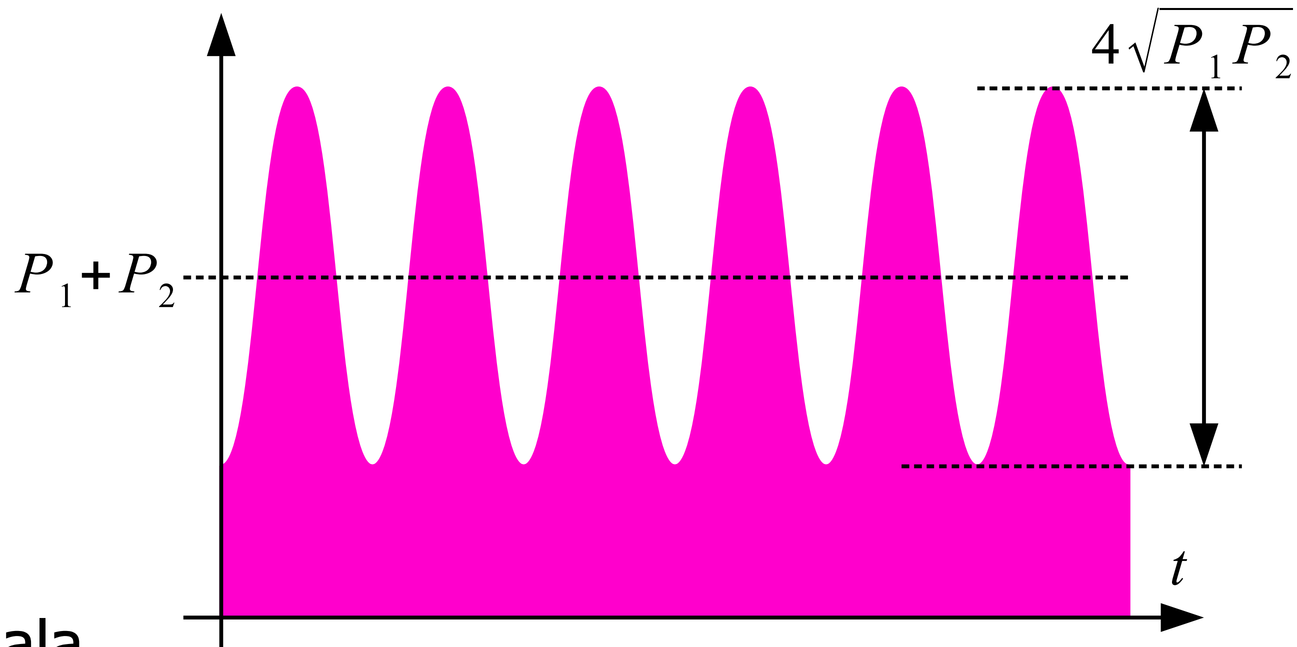
Hitri členi

$$p(t)=P_1\cdot\left(1+\cos 2\omega_1 t\right)+2\sqrt{P_1P_2}\cdot\left[\cos(\omega_1-\omega_2)t+\cos(\omega_1+\omega_2)t\right]+P_2\cdot\left(1+\cos 2\omega_2 t\right)$$

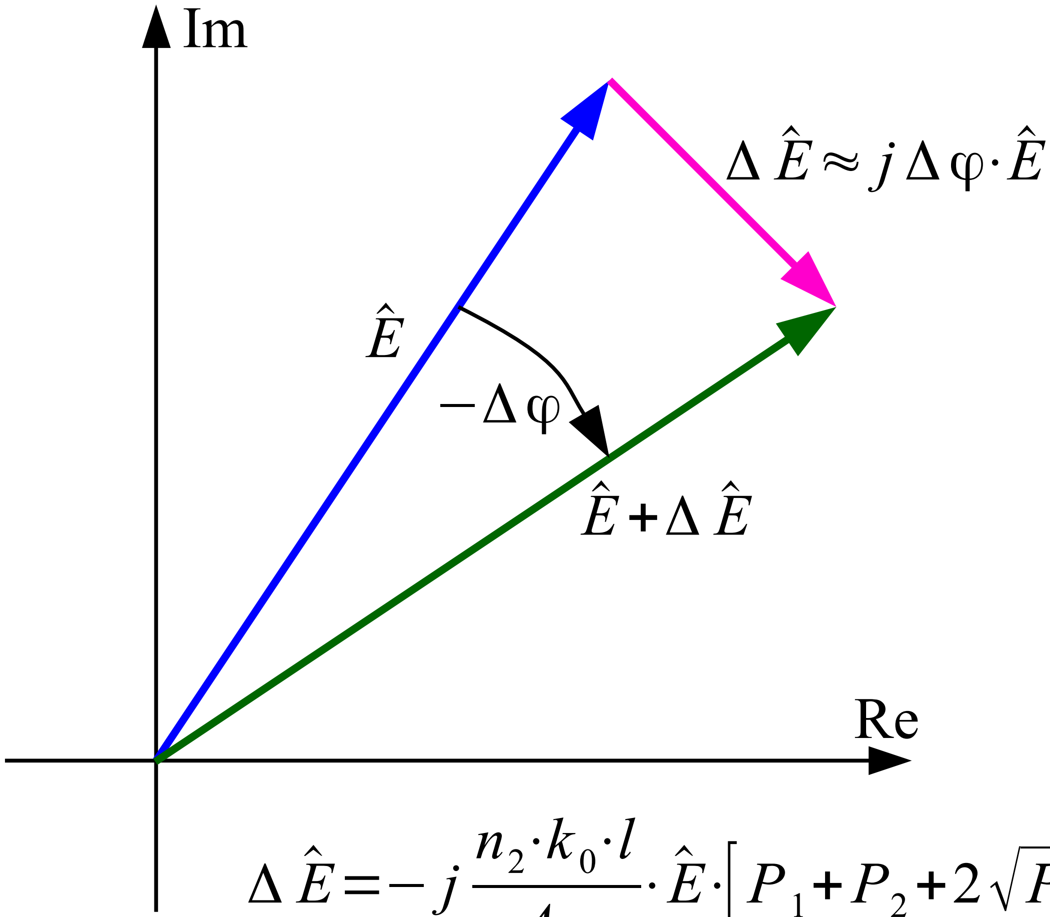
Utripanje moči

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

$$P(t)=P_1+2\sqrt{P_1P_2}\cdot\cos\Delta\omega t+P_2$$



5 – Moč dvotonskega signala



$$\Delta\varphi = -\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot P(t)$$

$$\Delta\hat{E} = -j\,\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot\hat{E}\cdot P(t)$$

$$\Delta\hat{E} = -j\,\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot\hat{E}\cdot\left[P_1+P_2+2\sqrt{P_1 P_2}\cos\Delta\omega t\right]$$

$$E(t) = A\cdot\cos\omega t$$

$$\Delta E(t) = \frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A\cdot\cos(\omega t-\pi/2)\cdot\left[P_1+P_2+2\sqrt{P_1 P_2}\cos\Delta\omega t\right]$$

$$-j = e^{-j\pi/2}$$

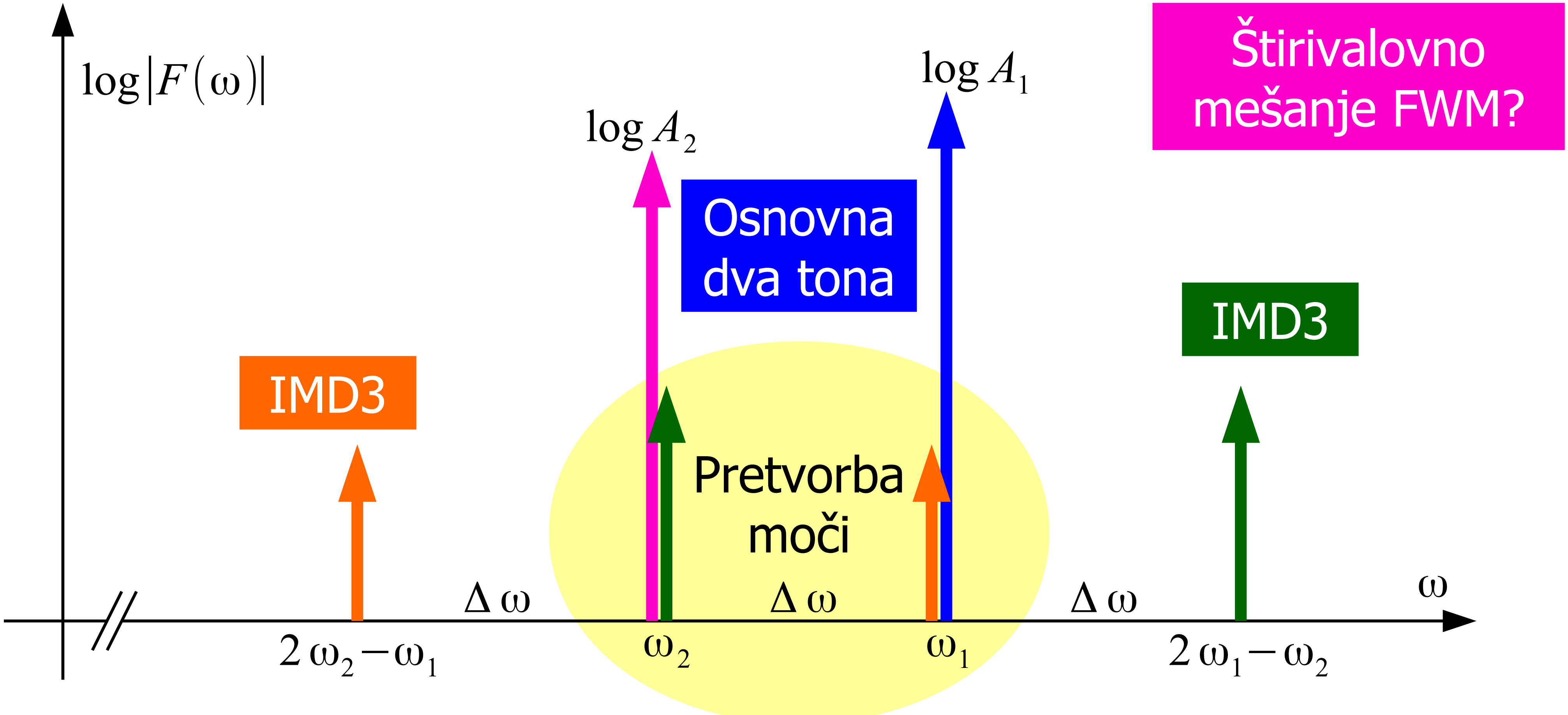
$$\Delta E(t) = \frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A\cdot\left[(P_1+P_2)\cdot\sin\omega t+\sqrt{P_1 P_2}\left(\sin(\omega+\Delta\omega)t+\sin(\omega-\Delta\omega)t\right)\right]$$

Dve novi frekvenci!

6 – Križna fazna modulacija

$$\omega=\omega_1 \qquad \Delta E_1(t)=\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A_1\cdot\left[(P_1+P_2)\cdot\sin\omega_1 t+\sqrt{P_1 P_2}\left(\sin(2\omega_1-\omega_2)t+\sin\omega_2 t\right)\right]$$

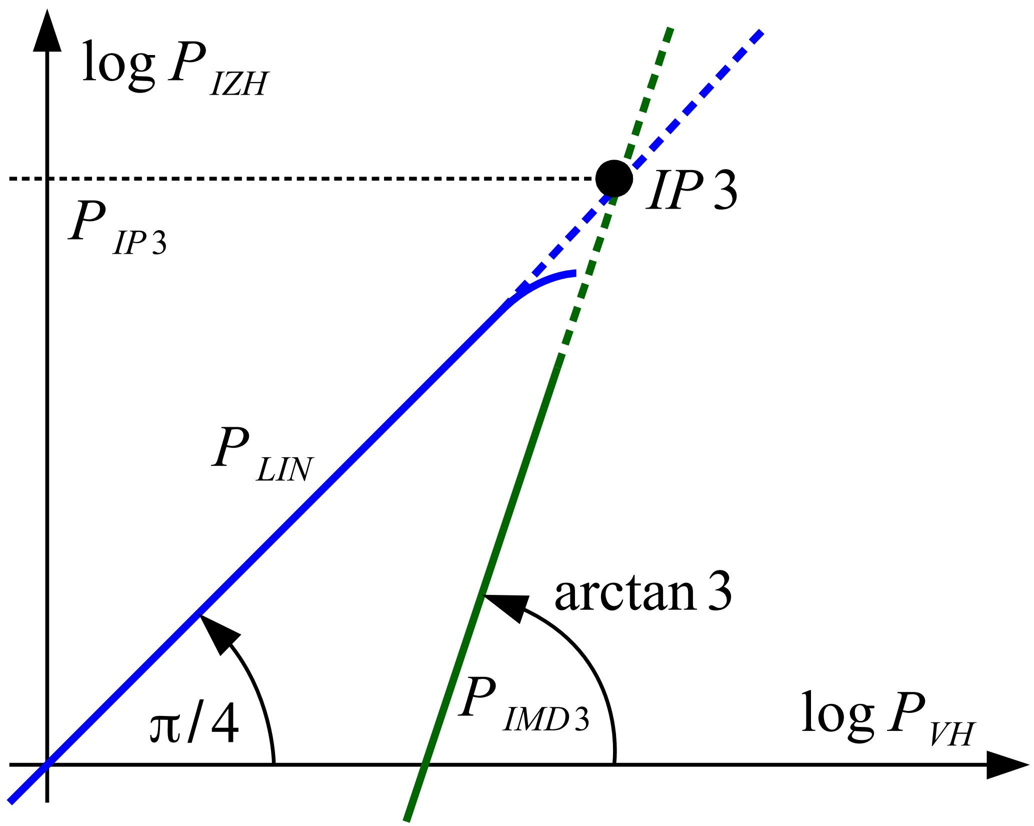
$$\omega=\omega_2 \qquad \Delta E_2(t)=\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A_2\cdot\left[(P_1+P_2)\cdot\sin\omega_2 t+\sqrt{P_1 P_2}\left(\sin\omega_1 t+\sin(2\omega_2-\omega_1)t\right)\right]$$



7 – Intermodulacijsko popačenje tretjega reda

$$E_{2\omega 1-\omega 2}(t)=\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A_1\cdot\sqrt{P_1 P_2}\cdot\sin(2\omega_1-\omega_2)t \qquad P_1=\alpha\cdot\frac{A_1^2}{2}$$

$$P_{2\omega 1-\omega 2}=\alpha\cdot\frac{A_{2\omega 1-\omega 2}^2}{2}=\frac{\alpha}{2}\cdot\left(\frac{n_2\cdot k_0\cdot l}{A_{eff}}\cdot A_1\cdot\sqrt{P_1 P_2}\right)^2=\left(\frac{n_2\cdot k_0\cdot l}{A_{eff}}\right)^2\cdot P_1^2 P_2=\frac{P_1^2 P_2}{P_{IP3}^2}$$



$$P_{2\omega 2-\omega 1}=\left(\frac{n_2\cdot k_0\cdot l}{A_{eff}}\right)^2\cdot P_1 P_2^2=\frac{P_1 P_2^2}{P_{IP3}^2}$$

$$P_{IP3}=\frac{A_{eff}}{n_2\cdot k_0\cdot l}=\frac{A_{eff}\cdot\lambda_0}{2\pi\cdot n_2\cdot l}$$

$$P_{IMD3}=\frac{P_{LIN}^3}{P_{IP3}^2}$$

$$\log P_{IMD3}=3\cdot\log P_{LIN}-2\cdot\log P_{IP3}$$

8 – Moč intermodulacijskih produktov

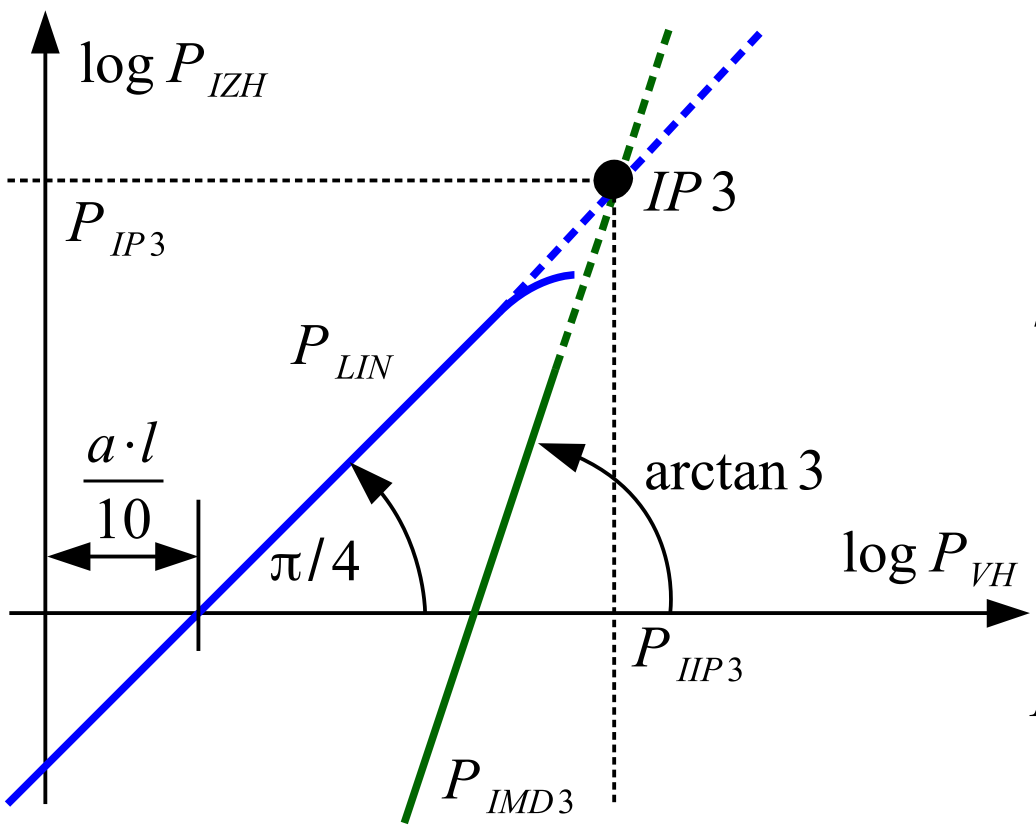
$$\Delta\varphi = -n_2 \cdot k_0 \cdot S(0) \cdot \int_0^l e^{-\frac{\ln 10}{10} \cdot a \cdot z} dz = -\frac{10 \cdot n_2 \cdot k_0 \cdot S(0)}{a \cdot \ln 10} \cdot \left(1 - e^{-\frac{\ln 10}{10} \cdot a \cdot l}\right) = -n_2 \cdot k_0 \cdot S(0) \cdot l_{eff}$$

$$\lambda_0 = 1.55\,\mu\mathrm{m} \qquad a \approx 0.2\,\mathrm{dB/km}$$

Efektivna dolžina

$$l_{eff} = \frac{10}{a \cdot \ln 10} \cdot \left(1 - e^{-\frac{\ln 10}{10} \cdot a \cdot l}\right)$$

$$l \gg l_{eff} \approx \frac{10}{a \cdot \ln 10} = 21.7\,\mathrm{km}$$



$$P_{IIP3} = \frac{A_{eff}}{n_2 \cdot k_0 \cdot l_{eff}} = \frac{A_{eff} \cdot \lambda_0}{2\pi \cdot n_2 \cdot l_{eff}}$$

$$n_2 \approx 2.5 \cdot 10^{-20}\,\mathrm{m^2/W} \qquad A_{eff} \approx 30\,\mu\mathrm{m}^2$$

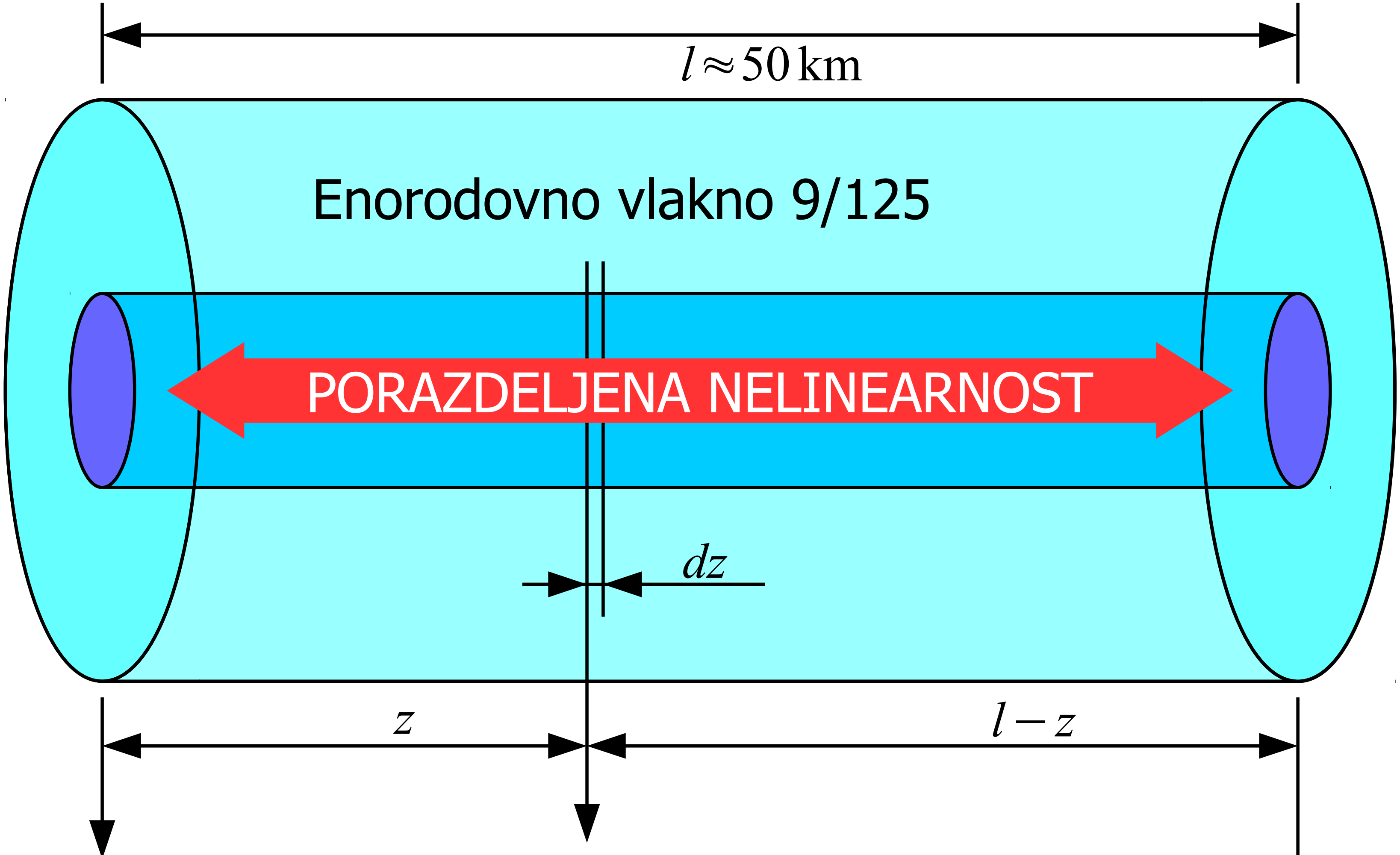
$P_{IIP3} \approx 13.6$mW$\approx +11.4$dBm

WDM ni izvedljiv z DSF!

$$P_{LIN} = P_{VH} \cdot 10^{-\frac{a \cdot l}{10}} \qquad P_{IP3} = P_{IIP3} \cdot 10^{-\frac{a \cdot l}{10}}$$

$$P_{IMD3} = \frac{P_{LIN}^3}{P_{IP3}^2} = \frac{P_{VH}^3}{P_{IIP3}^2} \cdot 10^{-\frac{a \cdot l}{10}}$$

9 – Intermodulacija v vlaknu s slabljenjem



$\hat{E}_1(0) \rightarrow \hat{E}_1(z)=\hat{E}_1(0)\cdot 10^{-\frac{a\cdot z}{20}}\cdot e^{-j\beta_1 z}$

$\hat{E}_2(0) \rightarrow \hat{E}_2(z)=\hat{E}_2(0)\cdot 10^{-\frac{a\cdot z}{20}}\cdot e^{-j\beta_2 z}$

$d\,\hat{E}_m(z) \rightarrow d\,\hat{E}_m(l)=d\,\hat{E}_m(z)\cdot 10^{-\frac{a\cdot(l-z)}{20}}\cdot e^{-j\beta_m(l-z)}$

10 – Fazni zamik do/od porazdeljene nelinearnosti

$$\omega_m = 2\omega_1 - \omega_2 \qquad D \neq 0 \longrightarrow \beta_m \neq \beta_1 \neq \beta_2 \neq \beta_m$$

$$dE_m(z,t) = \frac{n_2 \cdot k_0 \cdot dz}{A_{eff}} \cdot A_1(z) \cdot \sqrt{P_1(z) \cdot P_2(z)} \cdot \sin\left[(2\omega_1 - \omega_2)t - 2\beta_1 z + \beta_2 z\right]$$

$$A_1(z) = \sqrt{P_1(z) \cdot 2/\alpha} \qquad P_1(z) = P_1(0) \cdot 10^{-\frac{a \cdot z}{10}} \qquad P_2(z) = P_2(0) \cdot 10^{-\frac{a \cdot z}{10}}$$

$$d\,\hat{E}_m(z) = \frac{n_2 \cdot k_0 \cdot dz}{A_{eff}} \cdot \sqrt{P_1^2(z) \cdot P_2(z) \cdot 2/\alpha} \cdot (-j)\, e^{-j(2\beta_1 z - \beta_2 z)}$$

Fazna neusklajenost

$$\Delta\beta = \beta_m + \beta_2 - 2\beta_1$$

$$\hat{E}_m(l) = \int_0^l 10^{-\frac{a\cdot(l-z)}{20}} \cdot e^{-j\beta_m(l-z)}\, d\,\hat{E}_m(z)$$

Kazalčna vsota!

$$\hat{E}_m(l) = \frac{n_2 \cdot k_0}{A_{eff}} \cdot \sqrt{P_1^2(0) \cdot P_2(0) \cdot 2/\alpha} \cdot 10^{-\frac{a \cdot l}{20}} \cdot (-j)\, e^{-j\beta_m l} \int_0^l 10^{-\frac{a \cdot z}{10}} \cdot e^{j\Delta\beta z}\, dz$$

$$P_m(l) = \alpha \cdot \frac{\left|\hat{E}_m(l)\right|^2}{2} = \left(\frac{n_2 \cdot k_0}{A_{eff}}\right)^2 \cdot P_1^2(0) \cdot P_2(0) \cdot 10^{-\frac{a \cdot l}{10}} \cdot \left|\int_0^l 10^{-\frac{a \cdot z}{10}} \cdot e^{j\Delta\beta z}\, dz\right|^2$$

$$\int_0^l 10^{-\frac{a\cdot z}{10}}\cdot e^{j\,\Delta\beta\, z}\,dz=\int_0^l e^{\left(-\frac{a\cdot \ln 10}{10}+j\,\Delta\beta\right)z}\,dz=\frac{1}{\frac{a\cdot\ln 10}{10}-j\,\Delta\beta}\cdot\left[1-e^{\left(-\frac{a\cdot \ln 10}{10}+j\,\Delta\beta\right)l}\right]$$

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

$$l_{eff}\approx\frac{1}{\sqrt{\left(\frac{a\cdot\ln 10}{10}\right)^2+\Delta\beta^2}}$$

$$P_m(l)=\left(\frac{n_2\cdot k_0\cdot l_{eff}}{A_{eff}}\right)^2\cdot P_1^2(0)\cdot P_2(0)\cdot 10^{-\frac{a\cdot l}{10}}$$

→

$$P_{IIP3}=\frac{A_{eff}}{n_2\cdot k_0\cdot l_{eff}}=\frac{A_{eff}\cdot\lambda_0}{2\pi\cdot n_2\cdot l_{eff}}$$

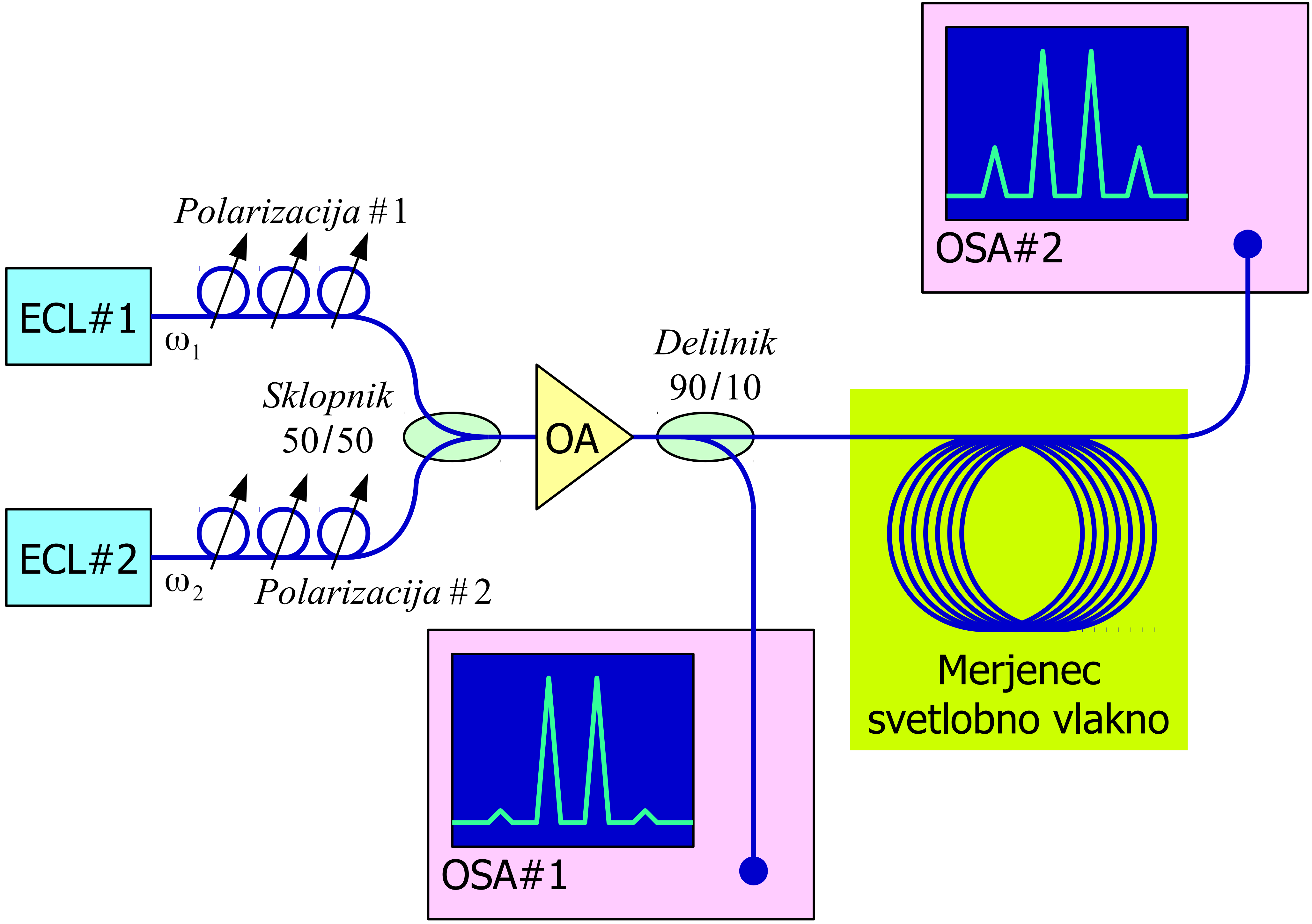
$$D\cdot l=\frac{d\,t_g}{d\,\lambda_0}=-\frac{2\pi\cdot c_0}{\lambda_0^2}\cdot\frac{d\,t_g}{d\,\omega}=-\frac{2\pi\cdot c_0}{\lambda_0^2}\cdot\frac{d}{d\,\omega}\left(\frac{l}{v_g}\right)=-\frac{2\pi\cdot c_0}{\lambda_0^2}\cdot l\cdot\frac{d}{d\,\omega}\left(\frac{d\,\beta}{d\,\omega}\right)=-\frac{2\pi\cdot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

$$\Delta\beta=\beta(\omega+\Delta\omega)+\beta(\omega-\Delta\omega)-2\beta(\omega)\approx\Delta\omega^2\cdot\frac{d^2\beta}{d\,\omega^2}=-\frac{\lambda_0^2}{2\pi\cdot c_0}\cdot D\cdot\Delta\omega^2=-\frac{2\pi\cdot\lambda_0^2}{c_0}\cdot D\cdot\Delta f^2$$

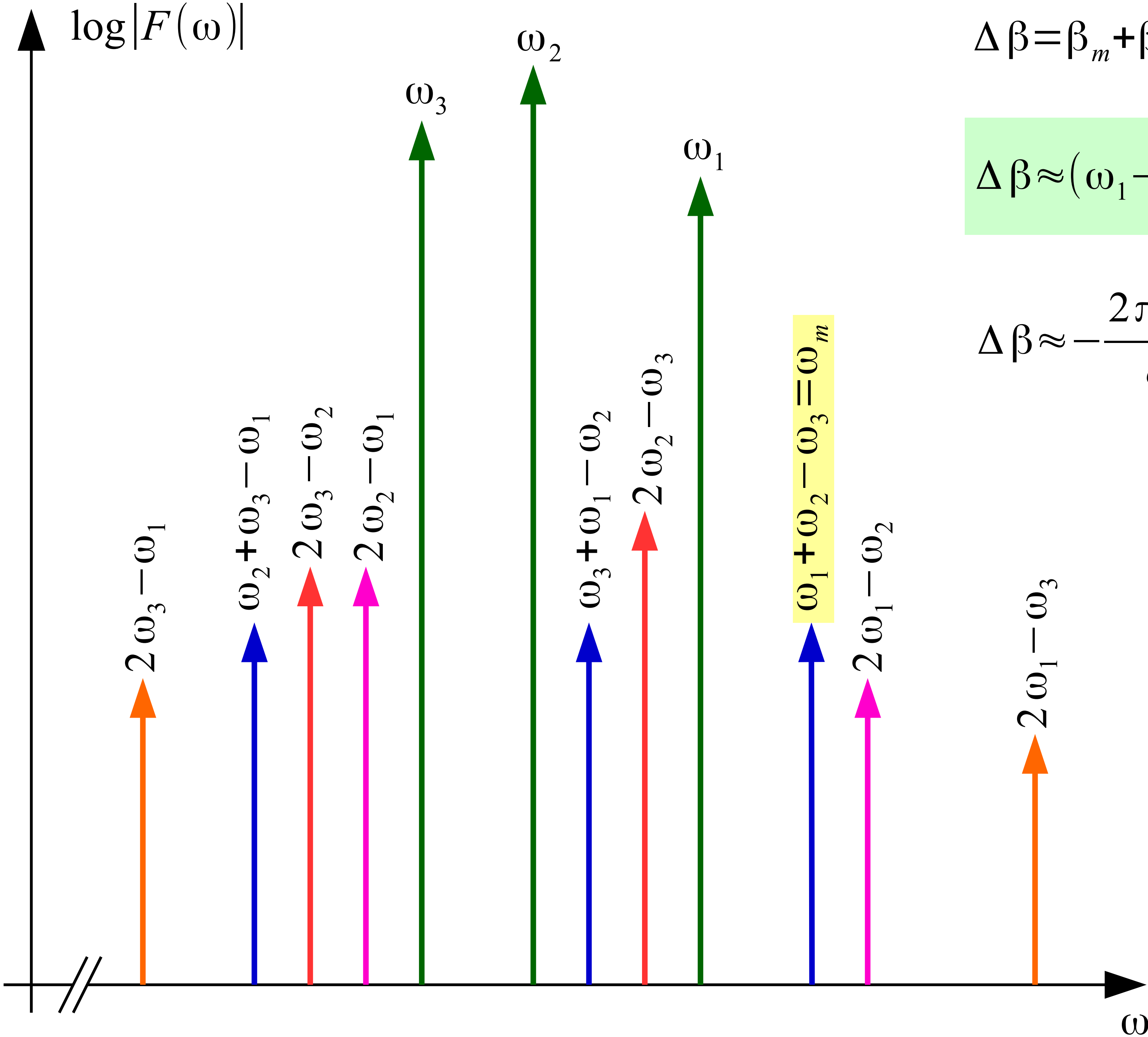
12 – Intermodulacija v vlaknu z barvno razpršitvijo (2)

	Vlakno SMF a=0.2dB/km $A_{eff}=70\mu m^2$ D=17ps/nm.km			Vlakno NZDSF a=0.2dB/km $A_{eff}=80\mu m^2$ D=5ps/nm.km		
Δf	$\Delta\beta$	l_{eff}	P_{IIP3}	$\Delta\beta$	l_{eff}	P_{IIP3}
1GHz	-0.00086rd/km	21.7km	15.0dBm	-0.00025rd/km	21.7km	15.6dBm
3GHz	-0.0077rd/km	21.4km	15.1dBm	-0.0023rd/km	21.7km	15.6dBm
10GHz	-0.0855rd/km	10.3km	18.3dBm	-0.0252rd/km	19.1km	16.2dBm
25GHz	-0.535rd/km	1.86km	25.7dBm	-0.157rd/km	6.1km	21.1dBm
50GHz	-2.14rd/km	468m	31.7dBm	-0.63rd/km	1.59km	27.0dBm
100GHz	-8.55rd/km	117m	37.7dBm	-2.52rd/km	397m	33.0dBm
200GHz	-34.2rd/km	29.2m	43.7dBm	-10.1rd/km	99m	39.0dBm
400GHz	-137rd/km	7.3m	49.8dBm	-40.3rd/km	25m	45.0dBm
1THz	-855rd/km	1.2m	57.7dBm	-252rd/km	4m	53.0dBm

13 – Fazna neusklajenost, efektivna dolžina in Piip3



14 – Meritev intermodulacije v svetlobnem vlaknu

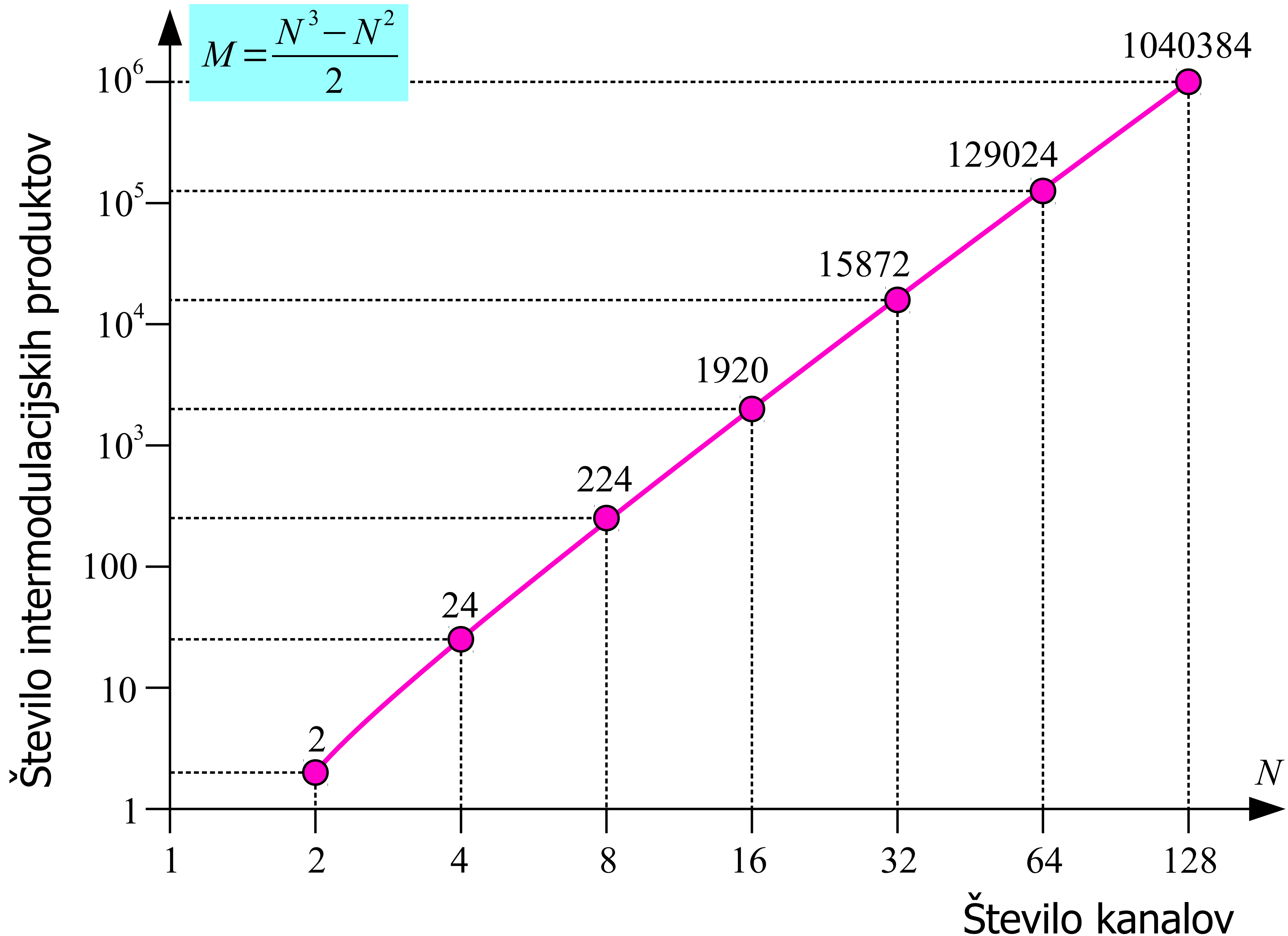


$$\Delta\beta = \beta_m + \beta_3 - \beta_1 - \beta_2$$

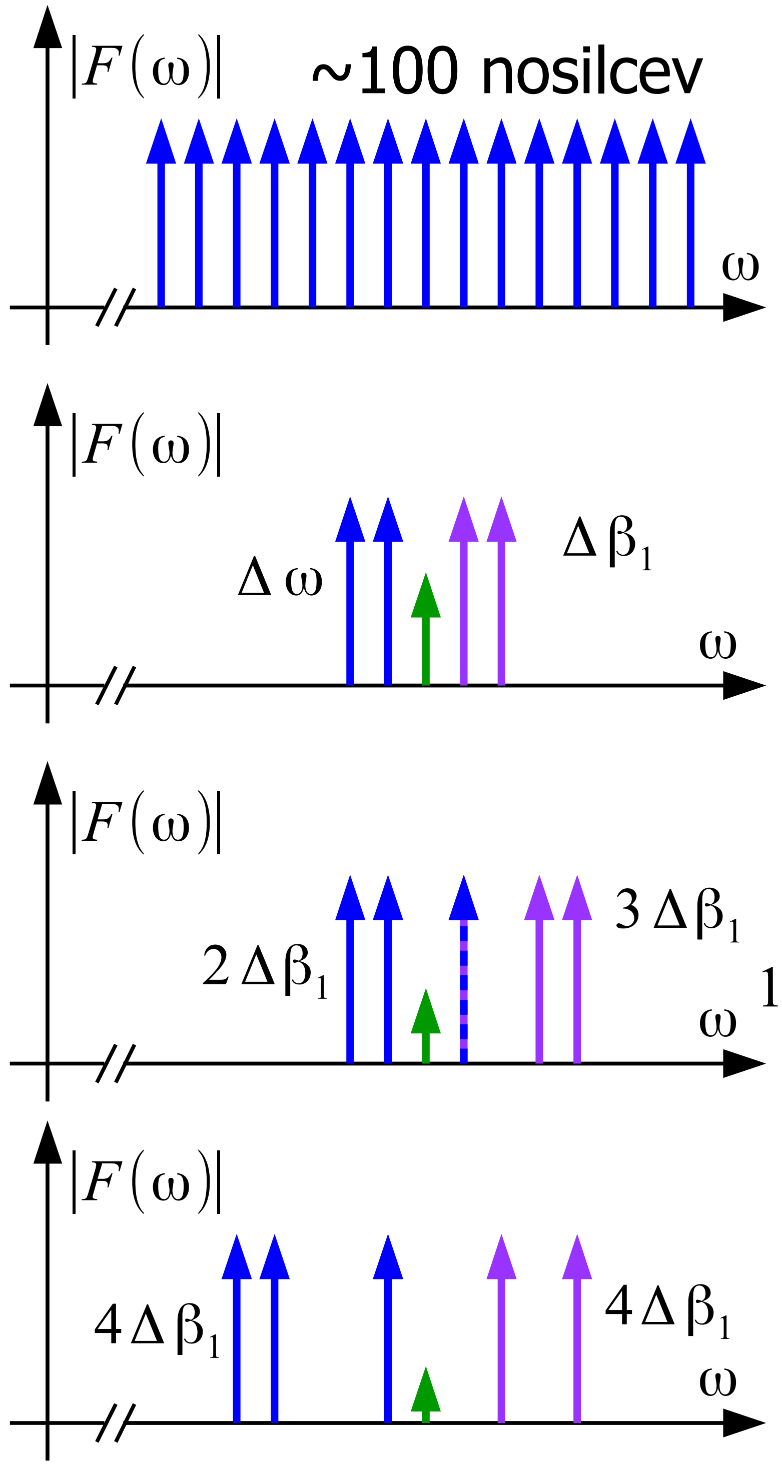
$$\Delta\beta \approx (\omega_1 - \omega_3)\cdot(\omega_2 - \omega_3)\cdot\frac{d^2\beta}{d\omega^2}$$

$$\Delta\beta \approx -\frac{2\pi\cdot\lambda_0^2}{c_0}\cdot D\cdot\Delta f_{13}\cdot\Delta f_{23}$$

15 – Tri-tonsko intermodulacijsko popačenje



16 – Število intermodulacijskih produktov WDM



$$\Delta f = 50\,GHz \rightarrow l_{eff} \approx \frac{1}{\Delta\beta}$$

Ista polarizacija?

$$P_{IIMD3} = \frac{P_{VH}^3}{P_{IIP3}^2} \cdot 2 \cdot \sum \left(\frac{\Delta\beta_1}{\Delta\beta}\right)^2$$

$$\Delta\beta \approx -\frac{2\pi \cdot \lambda_0^2}{c_0} \cdot D \cdot (n \cdot \Delta f) \cdot (m \cdot \Delta f)$$

$$P_{IIMD3} \approx \frac{P_{VH}^3}{P_{IIP3}^2} \cdot 2 \cdot \left(\sum_{n=1}^{\infty} \frac{1}{n^2}\right) \cdot \left(\sum_{m=1}^{\infty} \frac{1}{m^2}\right) = \frac{P_{VH}^3}{P_{IIP3}^2} \cdot 5.4$$

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \zeta(2) = \frac{\pi^2}{6} \approx 1.6449$$

$$10\log P_{IIMD3} \approx 3 \cdot (10\log P_{VH}^3) - 2 \cdot (10\log P_{IIP3}^2) + 7.3\,dB$$

$$\text{NZDSF} \quad \Delta f = 50\,GHz \rightarrow P_{IIP3} \approx +27\,\text{dBm}$$

$$P_{VH} = 1\,\text{mW} = +0\,\text{dBm} \rightarrow P_{IIMD3} = -46.7\,\text{dBm}$$

Prekooceanski $100\,odsekov \times 50\,\text{km} = 5000\,\text{km}$

$$S/N = P_{VH} / (100 \cdot P_{IIMD3}) = 26.7\,\text{dB}$$

17 – Presluh v gostem WDM