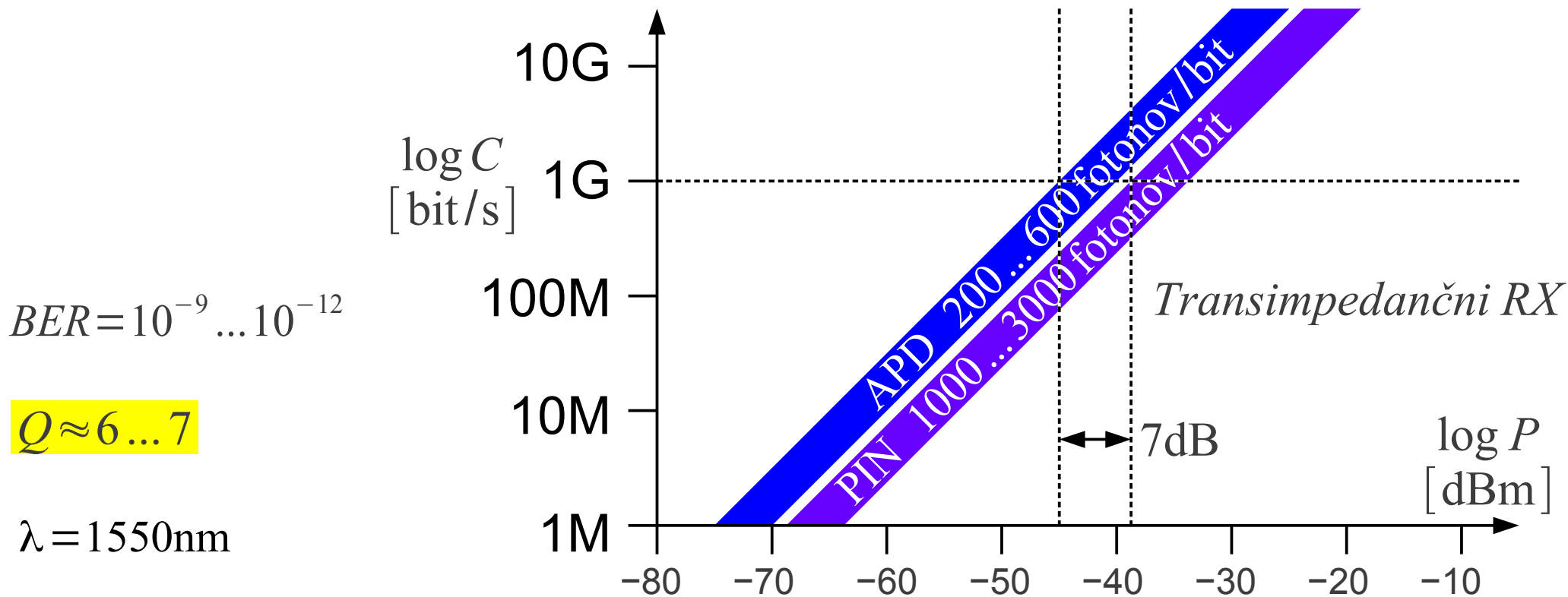
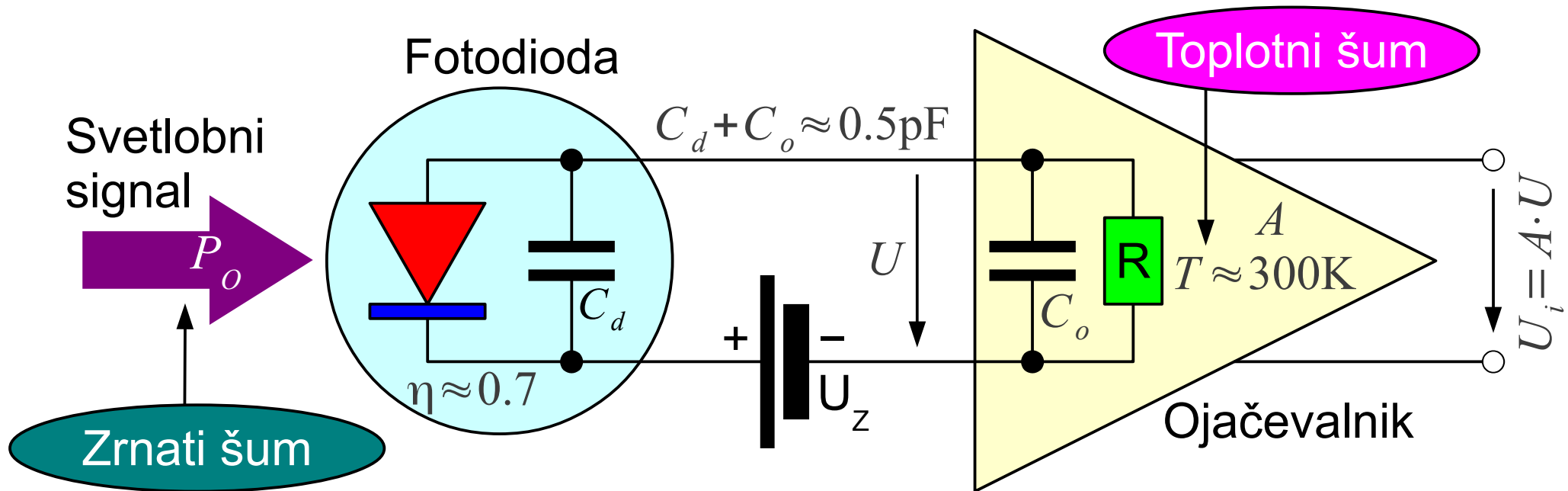


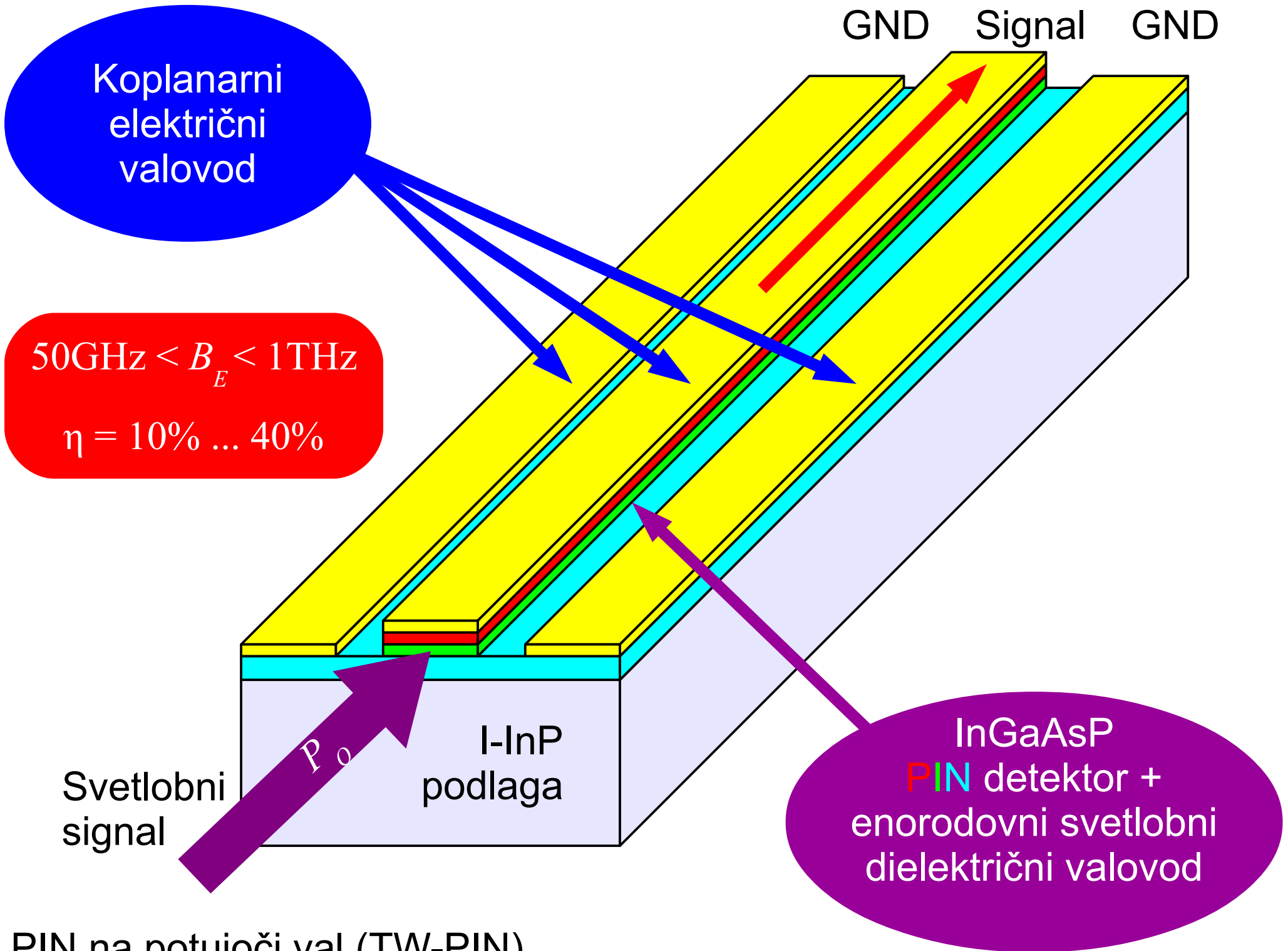
# Optične komunikacije

## Predavanje 14:

### Zveze po svetlobnih vlaknih



Občutljivost PIN / APD sprejemnika



Koplanarni električni valovod

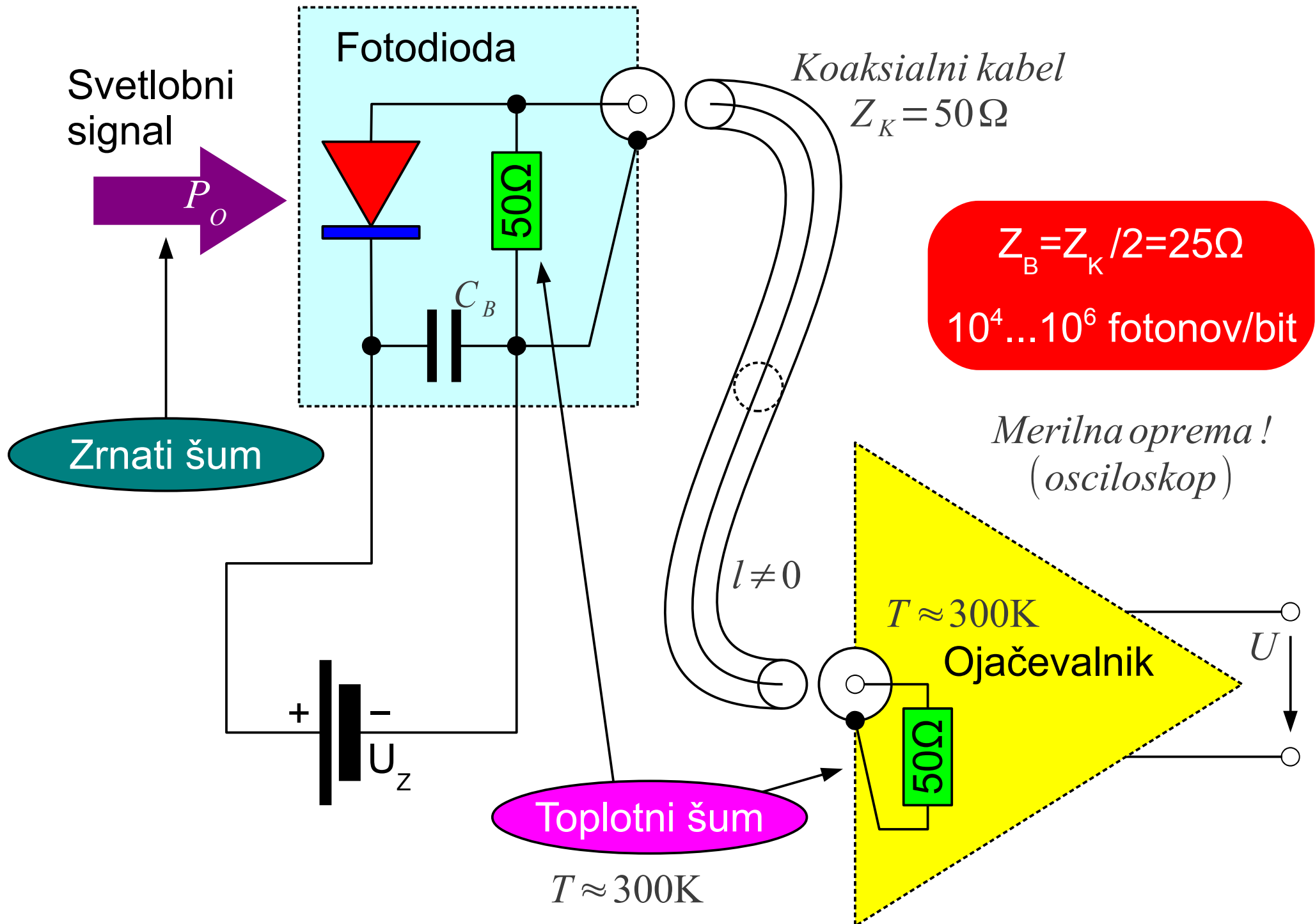
$50\text{GHz} < B_E < 1\text{THz}$   
 $\eta = 10\% \dots 40\%$

GND Signal GND

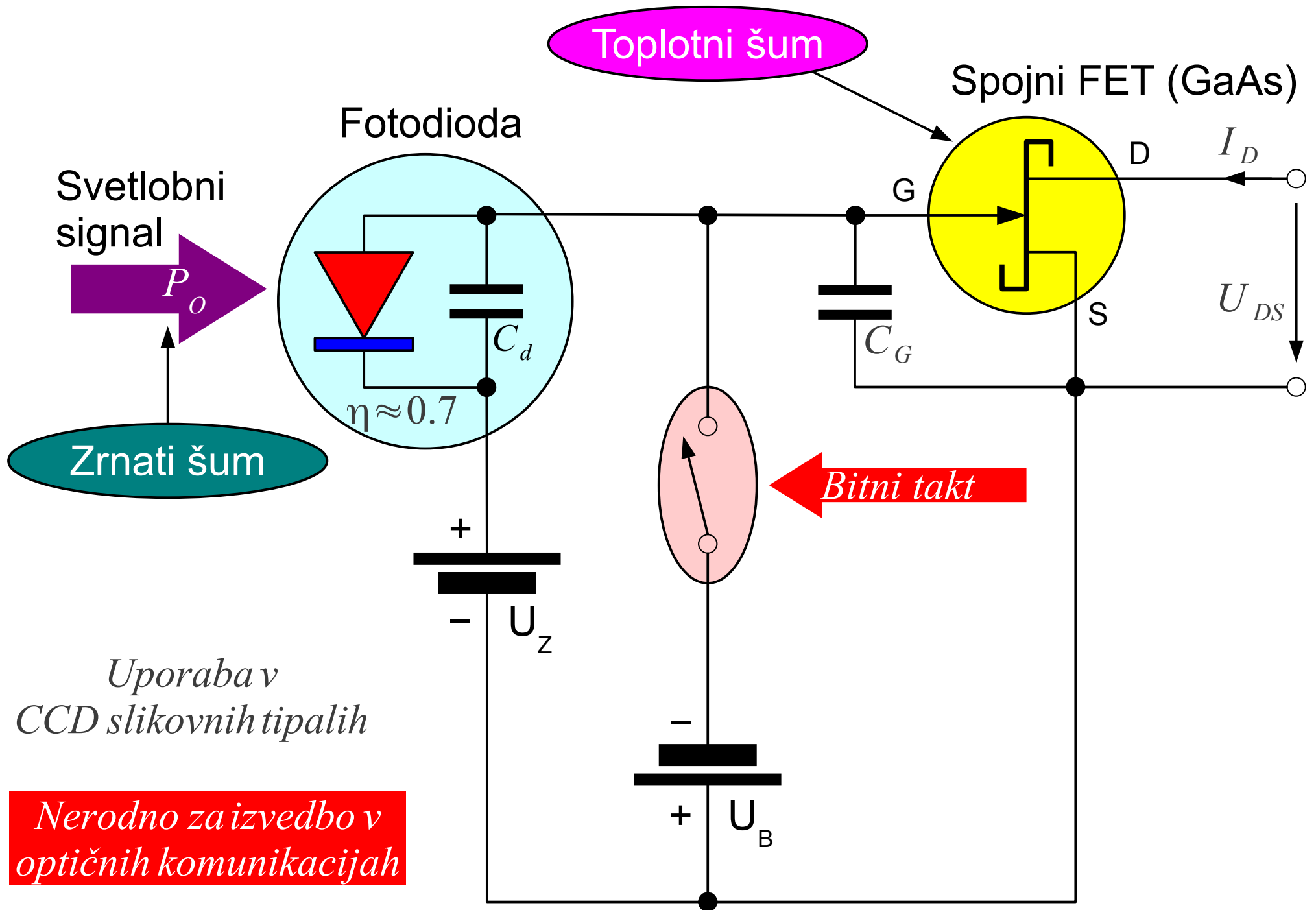
Svetlobni signal  $P_0$   
 I-InP podlaga

InGaAsP  
 PIN detektor +  
 enorodovni svetlobni  
 dielektrični valovod

PIN na potujoči val (TW-PIN)



Nizokoimpedančni sprejemnik

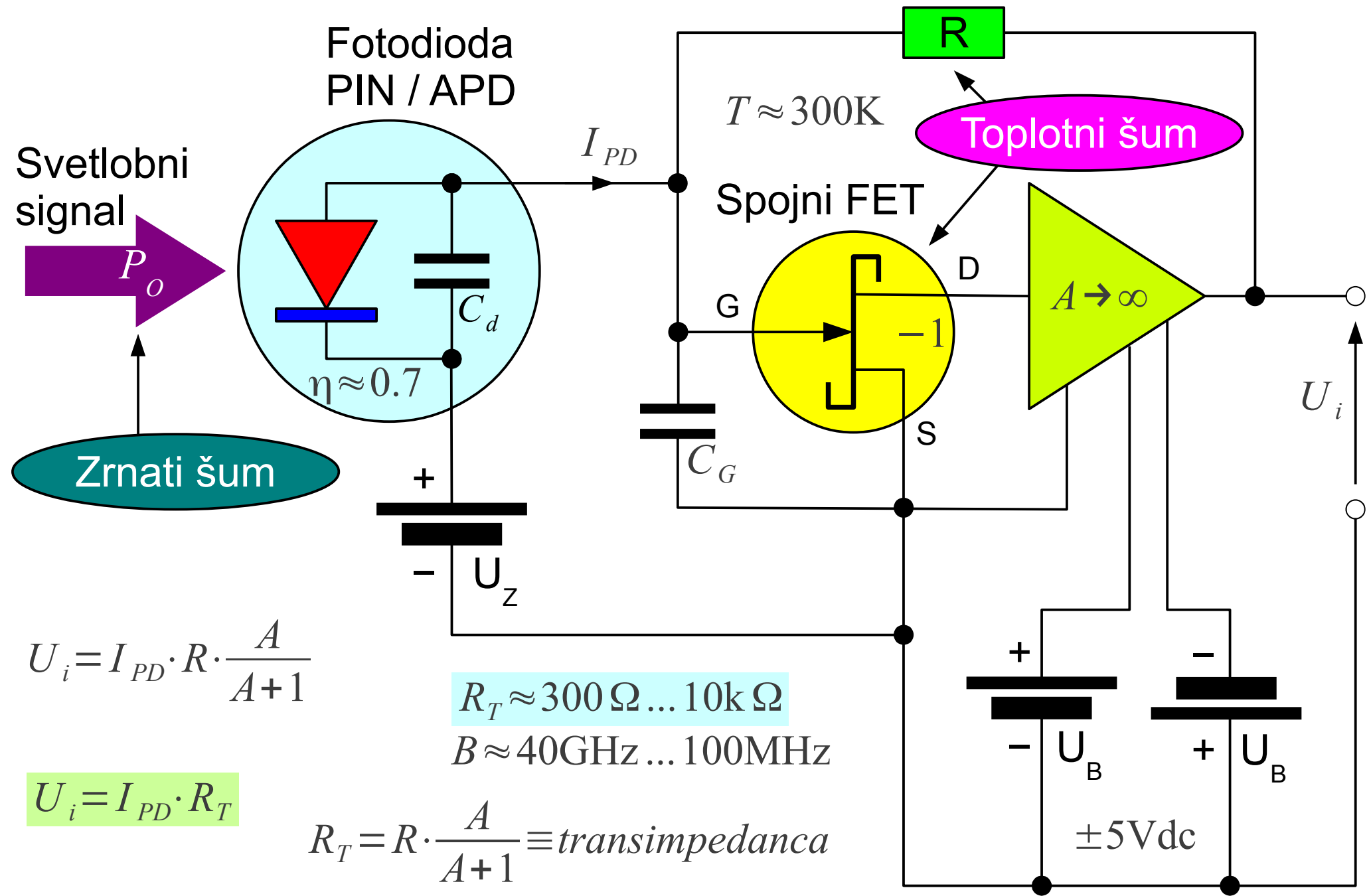


*Uporaba v  
CCD slikovnih tipalih*

*Nerodno za izvedbo v  
optičnih komunikacijah*

Visokoimpedančni (integracijski) sprejemnik

Negativna povratna vezava



$$U_i = I_{PD} \cdot R \cdot \frac{A}{A+1}$$

$$R_T \approx 300 \Omega \dots 10k \Omega$$

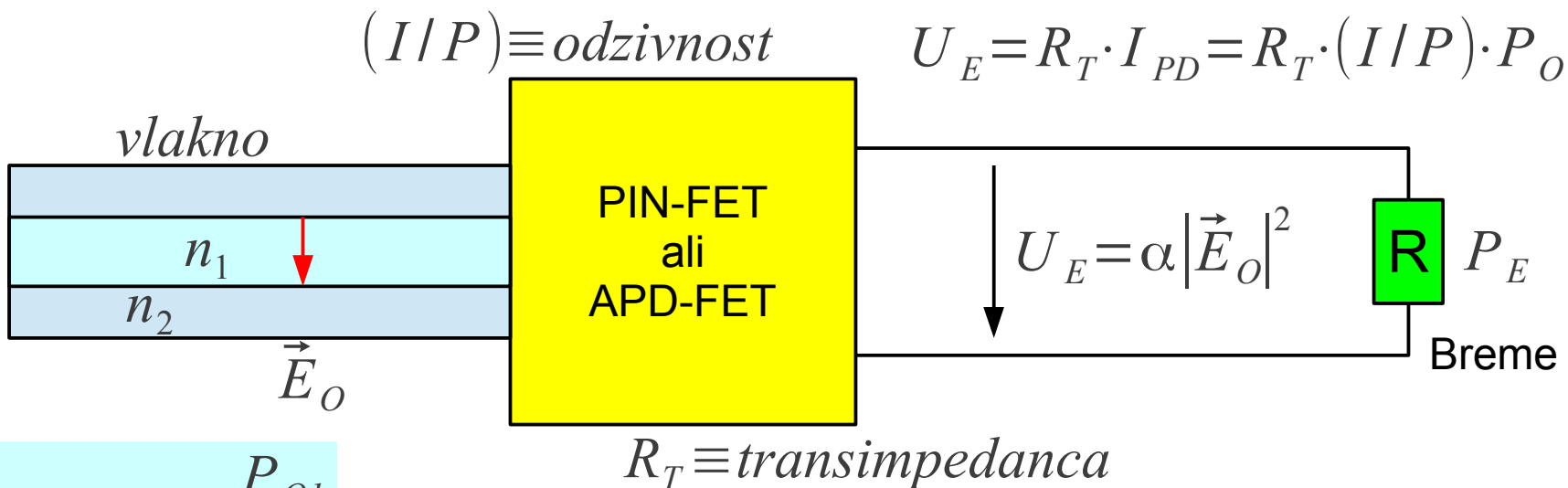
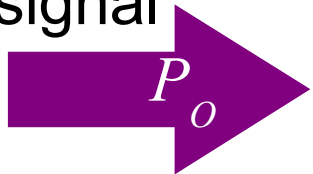
$$B \approx 40GHz \dots 100MHz$$

$$U_i = I_{PD} \cdot R_T$$

$$R_T = R \cdot \frac{A}{A+1} \equiv transimpedanca$$

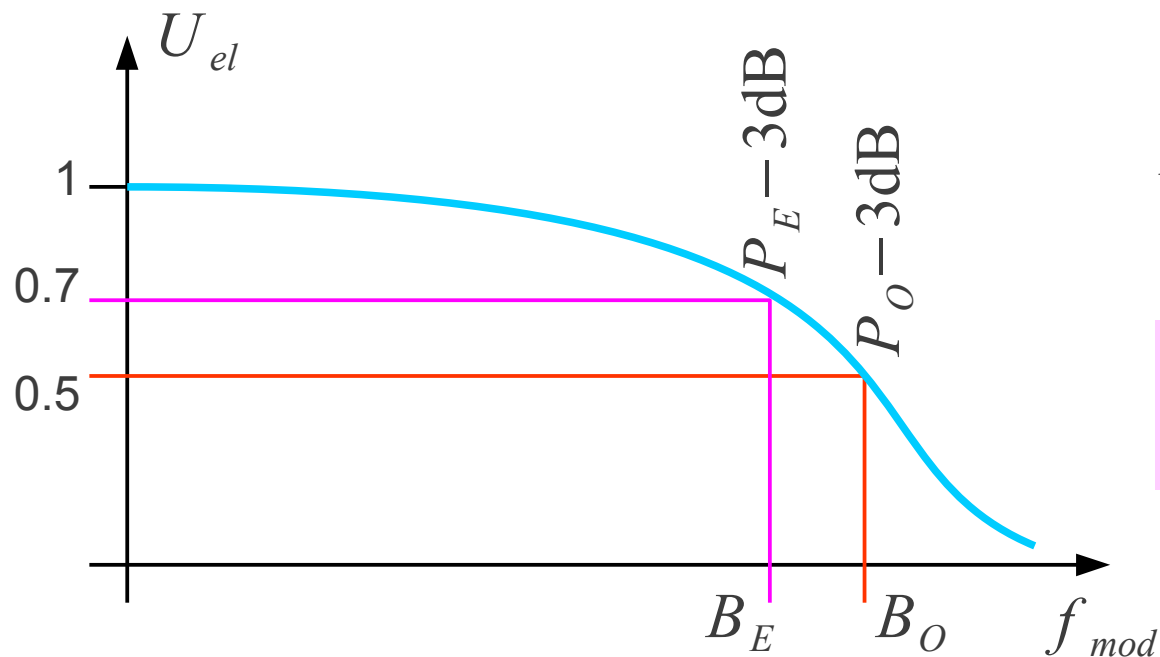
Transimpedančni sprejemnik

Svetlobni signal



$$a_O[\text{dB}] = 10 \log_{10} \frac{P_{O1}}{P_{O2}}$$

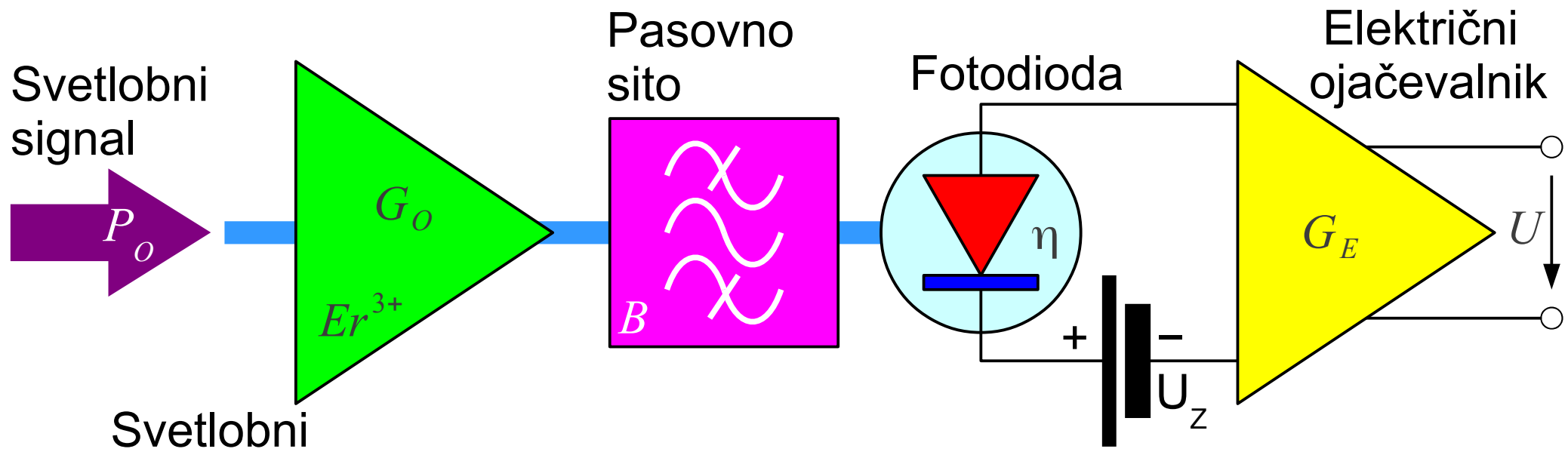
$$a_E[\text{dB}] = 10 \log_{10} \frac{P_{E1}}{P_{E2}}$$



$$P_E = \frac{U_E^2}{R} = \frac{R_T^2 \cdot (I/P)^2 \cdot P_O^2}{R} = \alpha' \cdot P_O^2$$

$$a_E[\text{dB}] = 2 \cdot a_O[\text{dB}] = 20 \log_{10} \frac{P_{O1}}{P_{O2}}$$

Optični in električni decibeli ter pasovne širine



$$U = \alpha \left| \vec{E}_{\text{šum}} + \vec{E}_{\text{signal}} \right|^2 = \alpha \left( \left| \vec{E}_{\text{šum}} \right|^2 + 2 \operatorname{Re} \left[ \vec{E}_{\text{šum}} \cdot \vec{E}_{\text{signal}}^* \right] + \left| \vec{E}_{\text{signal}} \right|^2 \right)$$

*ASE šum ojačevalnika enrod, ena polarizacija*

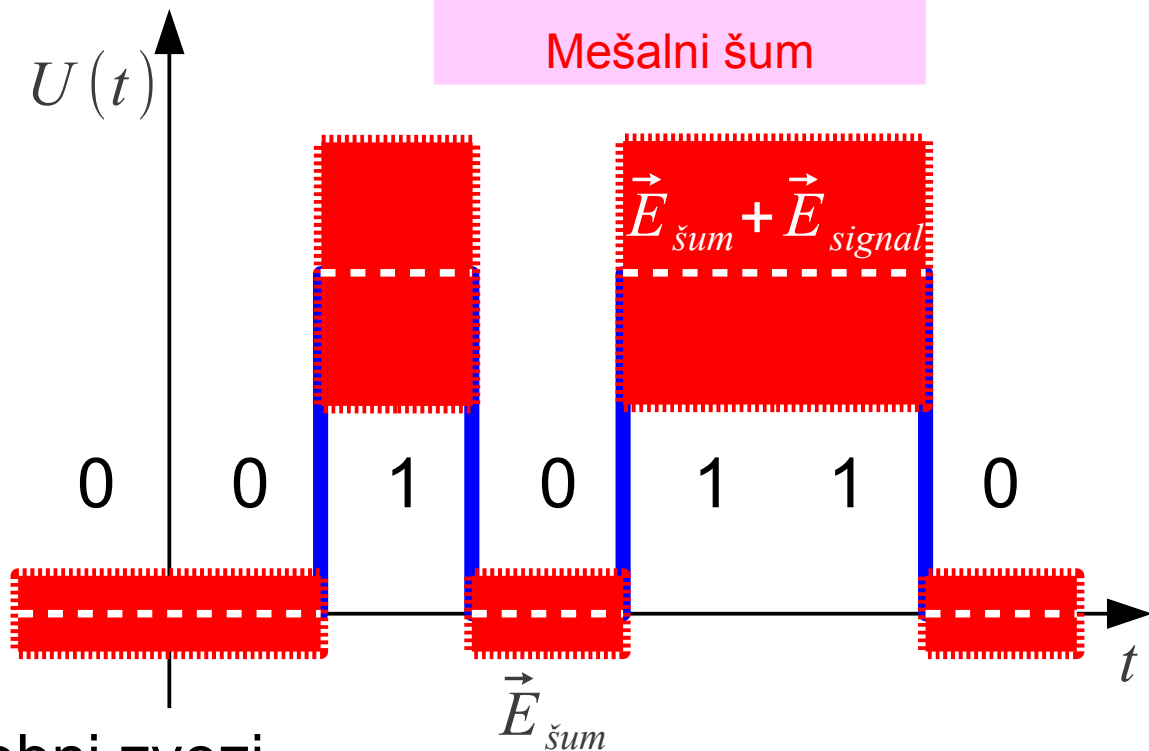
$$P_{ASE} = \mu \cdot (G_o - 1) \cdot h \cdot f \cdot B$$

*Faktor inverzne naseljenosti*

$$\mu = \frac{N_2}{N_2 - N_1} \geq 1$$

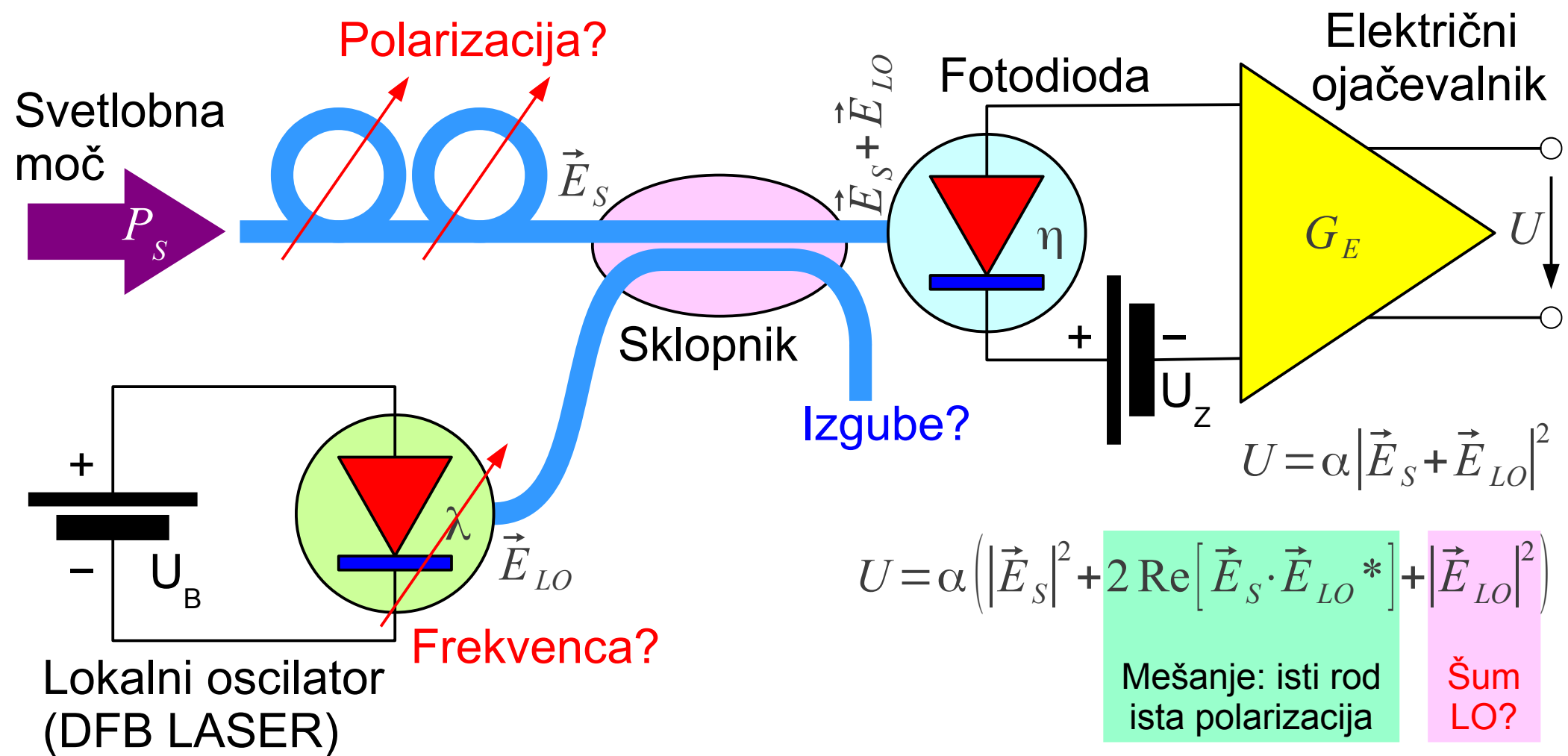
**<100 fotonov/bit**

Mešalni šum



Signal in šum v ojačevani svetlobni zvezi



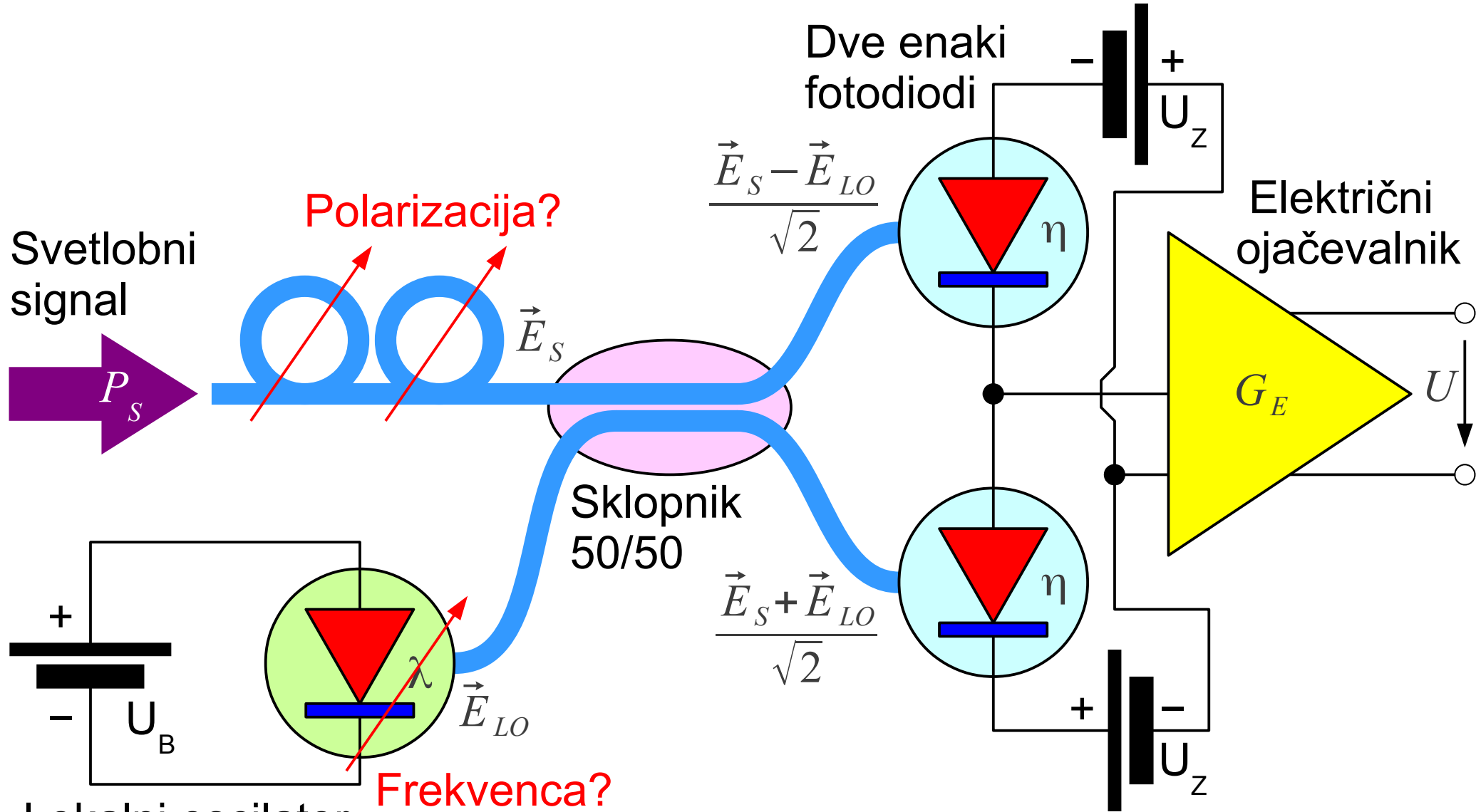


*Dobitek mešanja*  $\frac{U_{koherentni}}{U_{nekoherentni}} \leq \frac{2 |\vec{E}_{LO}|}{|\vec{E}_S|} = 2 \sqrt{\frac{P_{LO}}{P_S}}$

- (1) Občutljivost!
- (2) Selektivnost!
- (3) Modulacije!

Amplitudni šum LO?  
 Točna frekvenca LO?  
 Skladnost polarizacije?

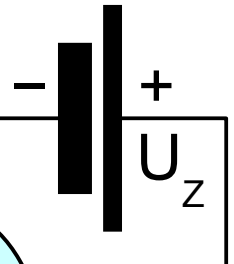
Koherentni svetlobni sprejemnik



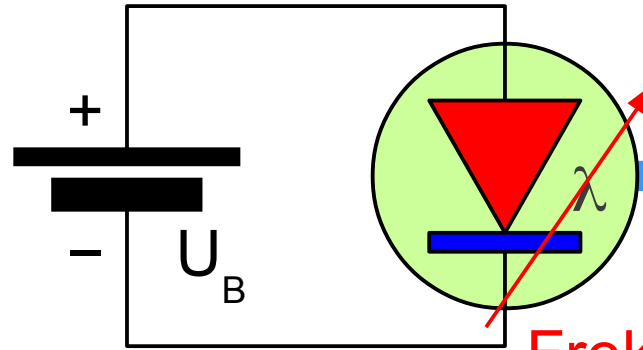
Svetlobni signal

Polarizacija?

Dve enaki fotodiodi



Električni ojačevalnik



Lokalni oscilator (DFB LASER)

Frekvenca?

$$U = \frac{\alpha}{2} \left[ \left| \vec{E}_S + \vec{E}_{LO} \right|^2 - \left| \vec{E}_S - \vec{E}_{LO} \right|^2 \right]$$

BPSK < 30 fotonov/bit

Balančni svetlobni sprejemnik

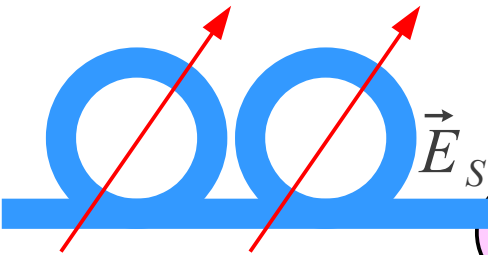
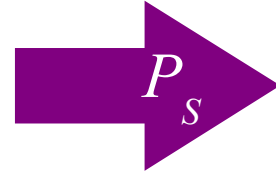
$$U = \alpha \cdot 2 \operatorname{Re} \left[ \vec{E}_S \cdot \vec{E}_{LO}^* \right]$$

Odštevanje šuma LO!

Štiri enake fotodiode

Svetlobni signal

Polarizacija?



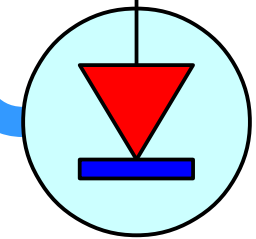
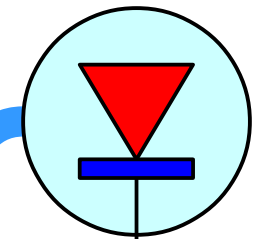
$\vec{E}_s$

Delilnik 50/50

Sklopnik 50/50

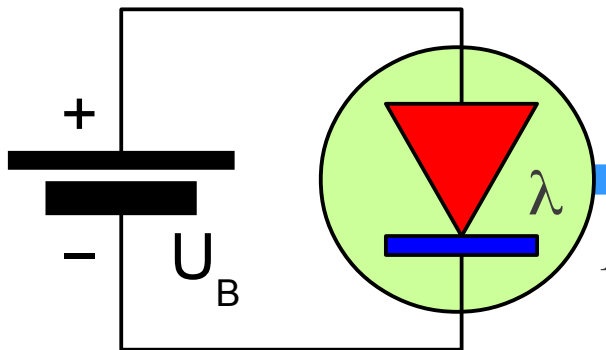
$l_s$

$l_{LO}$



$I$

Ničelna medfrekvenca



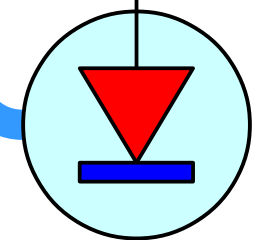
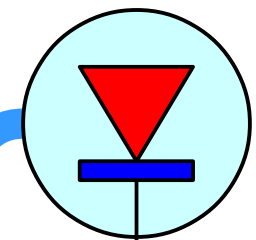
Lokalni oscilator (DFB LASER)

Delilnik 50/50

Sklopnik 50/50

$l_s + \lambda/4$

$l_{LO}$

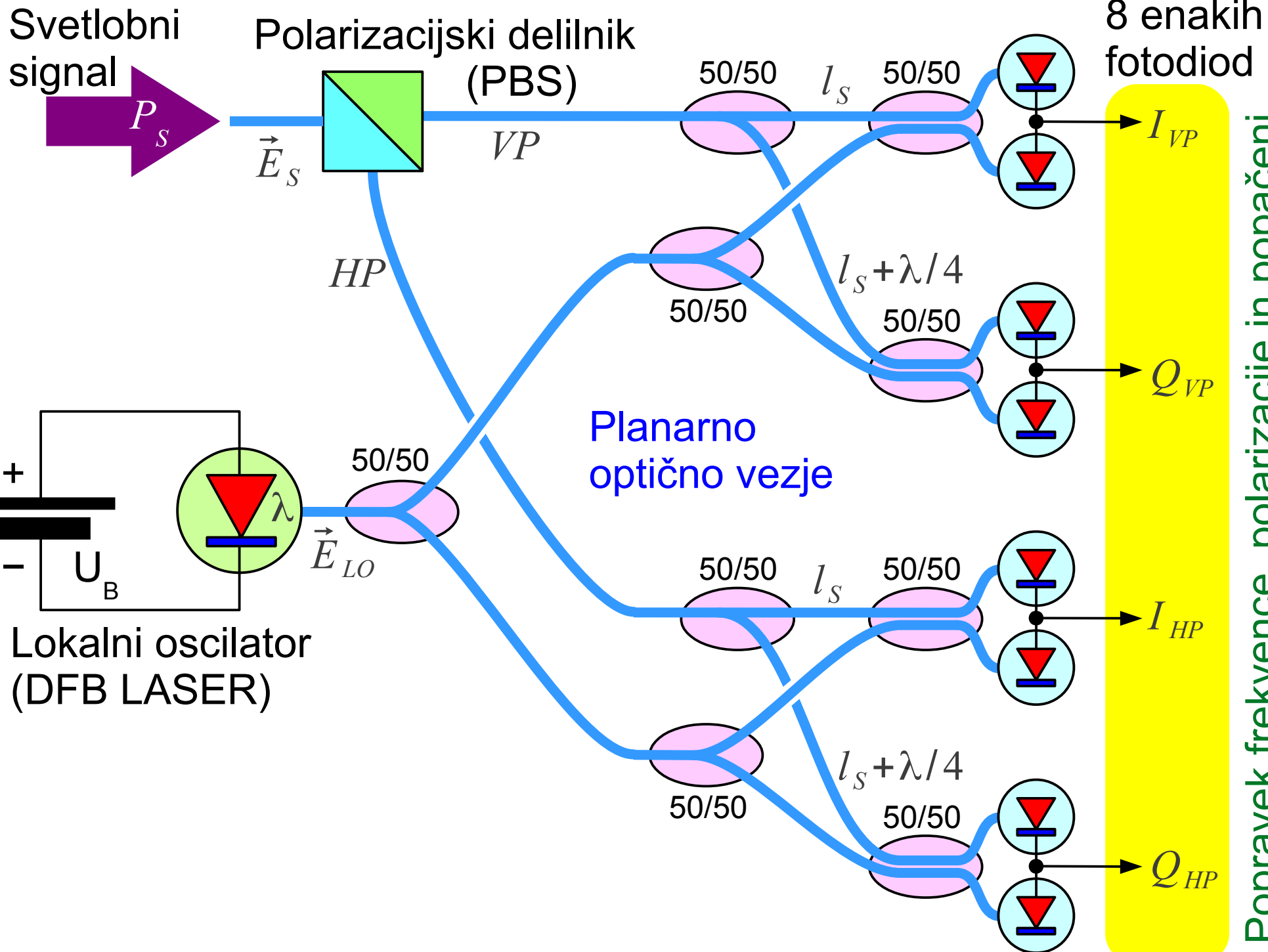


$Q$

Planarno optično vezje

Popravek frekvence v ceneni elektroniki ničelne medfrekvence!

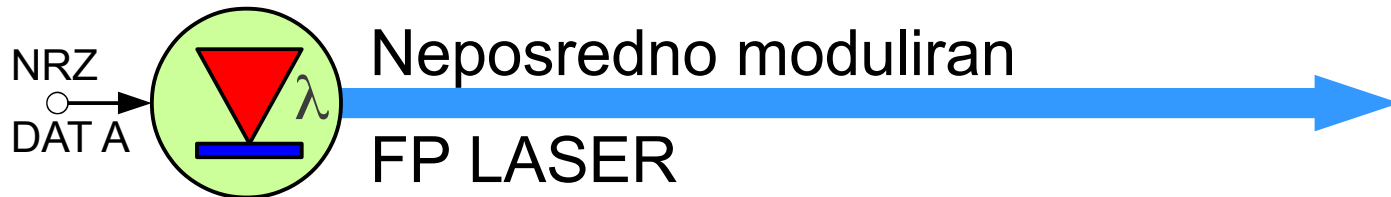
Kvadrturni (QPSK/QAM) svetlobni sprejemnik



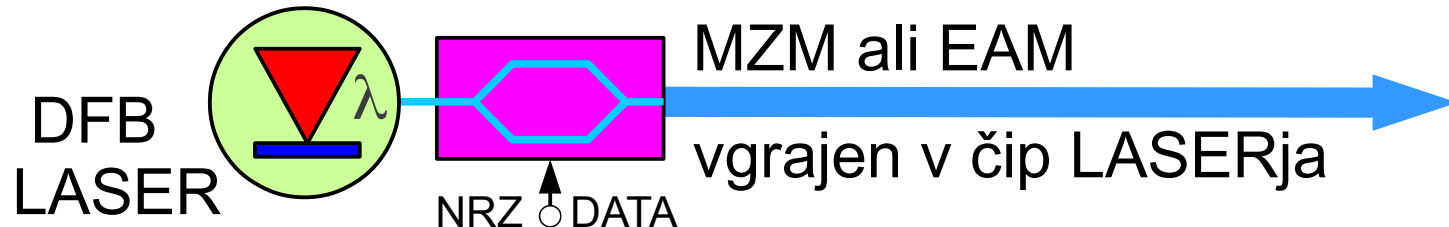
Popravek frekvence, polarizacije in popačenj v ceneni elektronični ničelni medfrekvenca!

Dvopolarizacijski (MIMO) svetlobni sprejemnik **Celotna informacija v vlaknu**

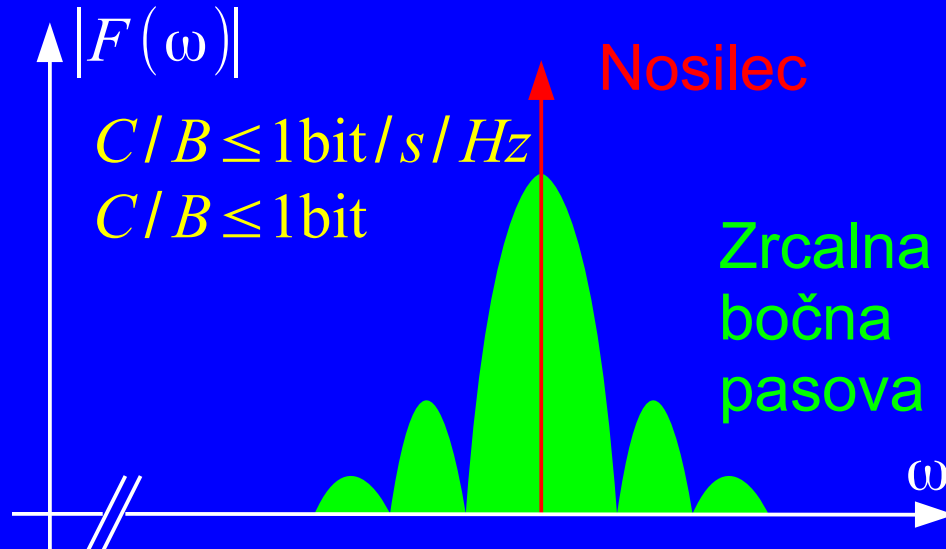
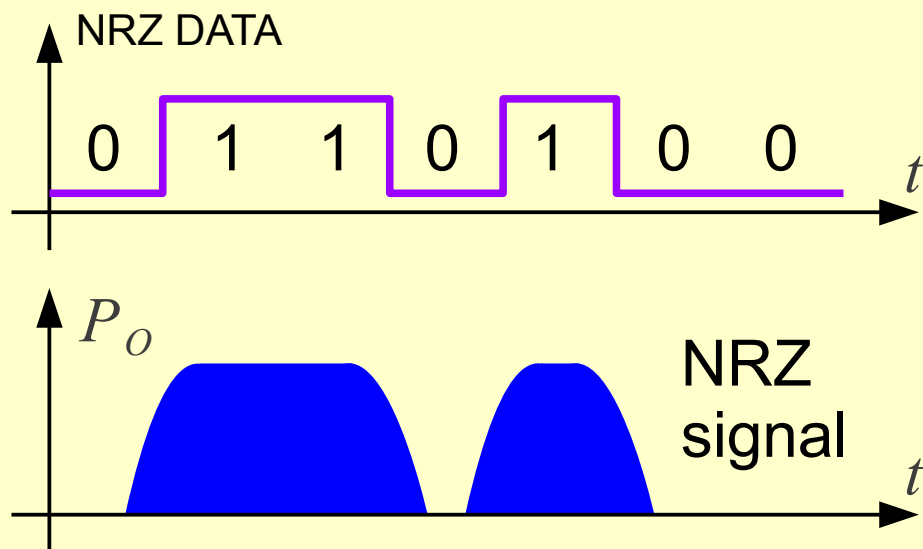
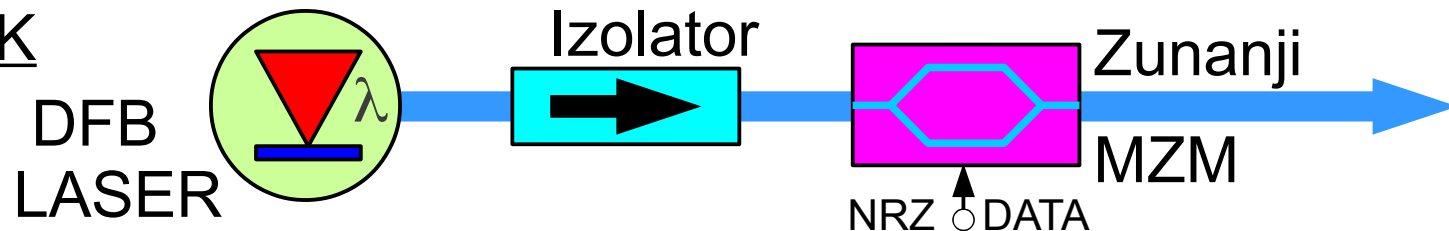
Dostopovni ASK  
(spekter nepomemben)



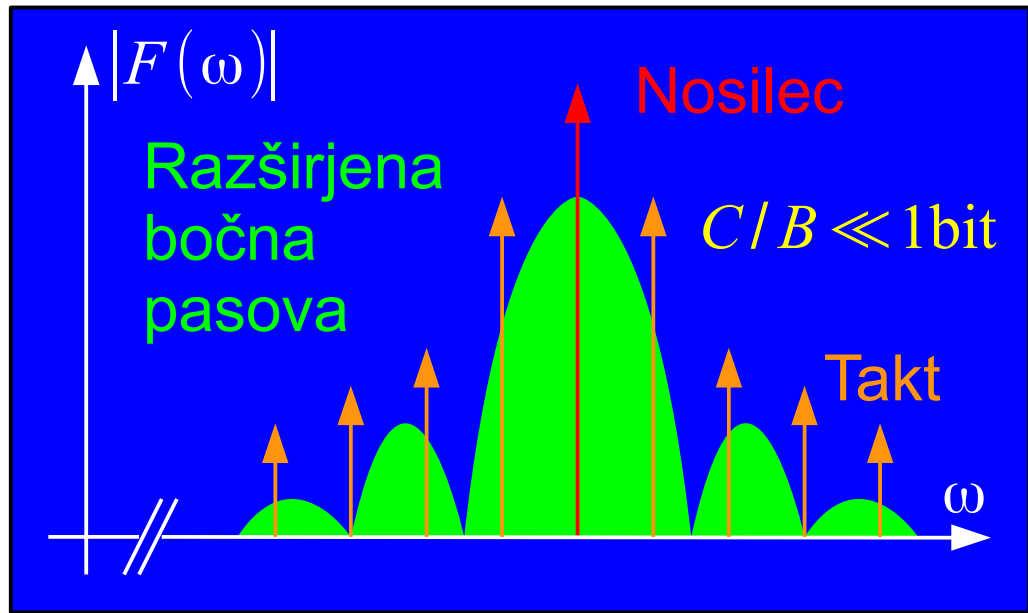
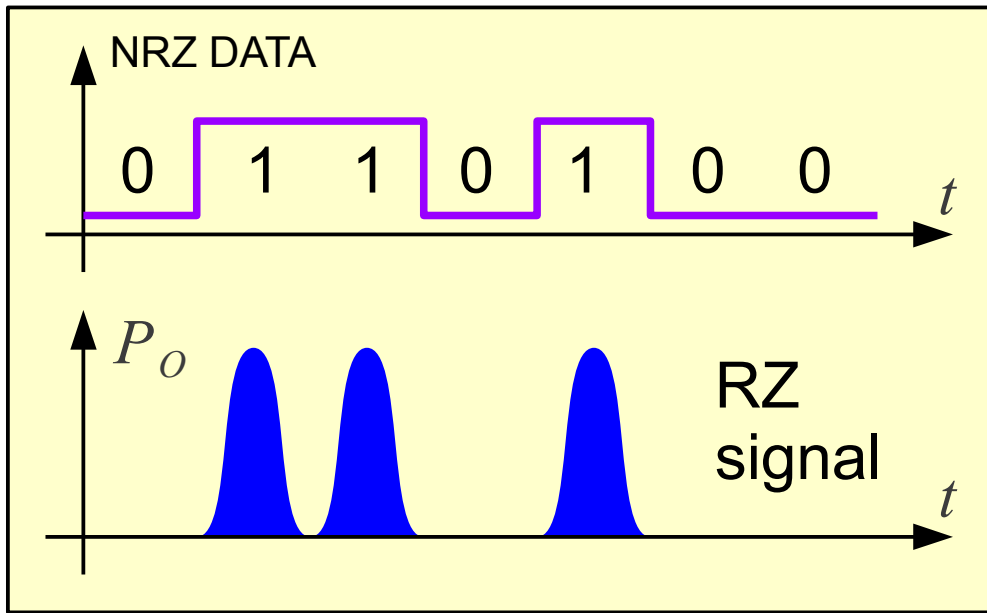
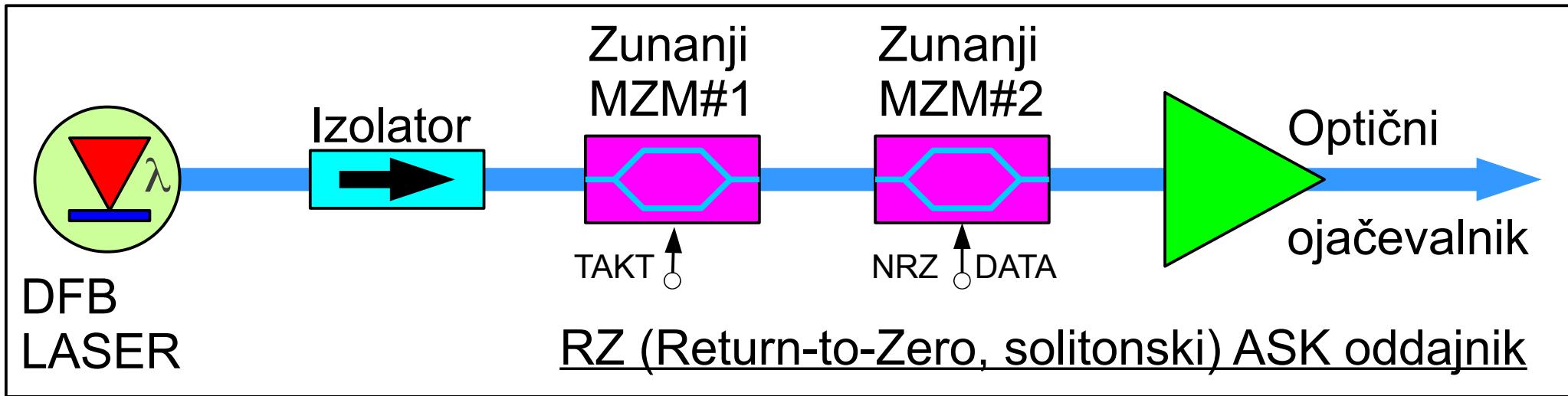
Medkrajevni ASK  
(malo FM)



Prekooceanski ASK  
(brez FM)



Preprosta jakostna modulacija ON/OFF ali ASK (Amplitude Shift Keying)

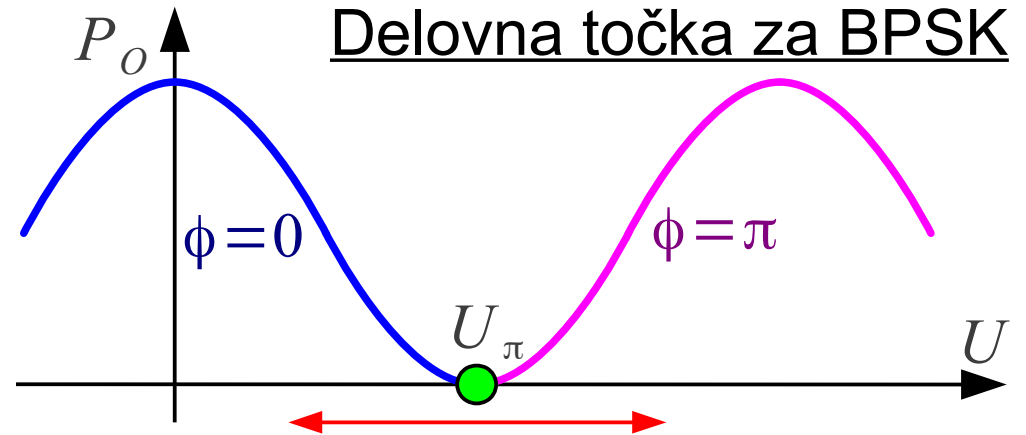
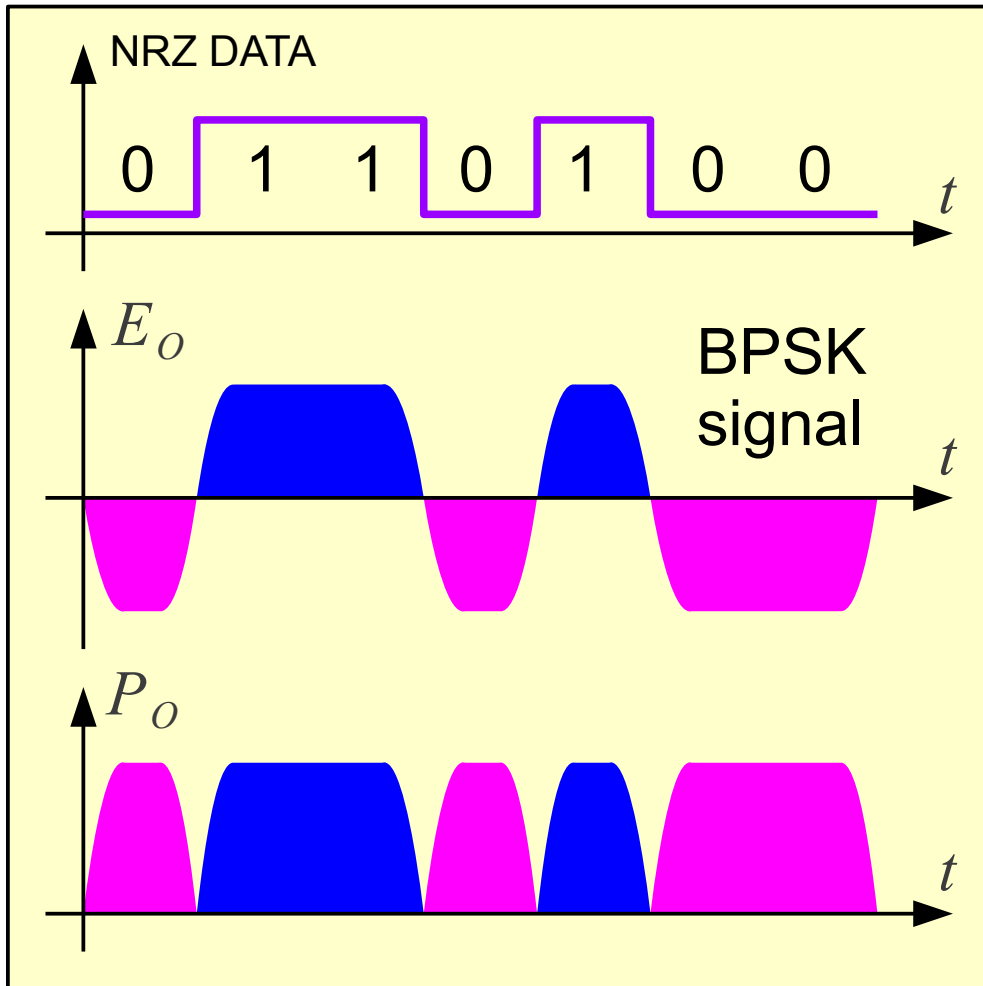
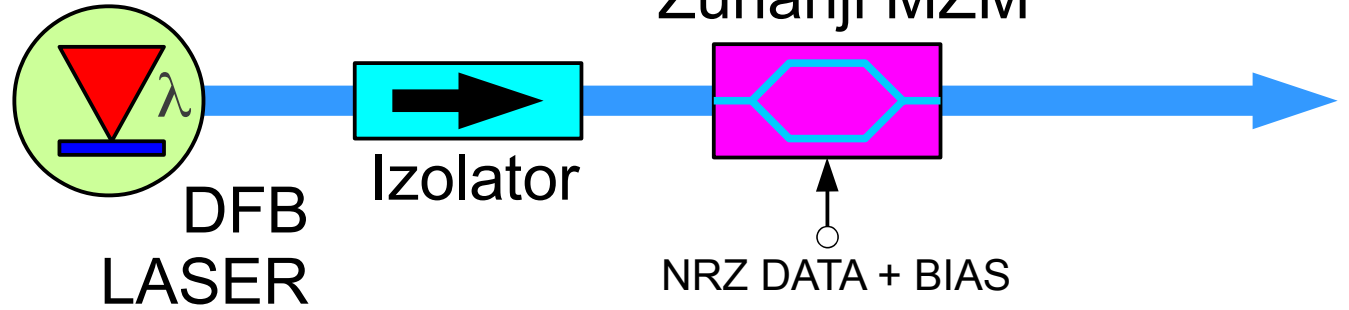


Namen: kompenzacija linearnih in nelinearnih popačenj pri najzahtevnejših visokozmogljivih zvezah.  
 Velika vlaganja v razvoj, danes brez praktične uporabe!

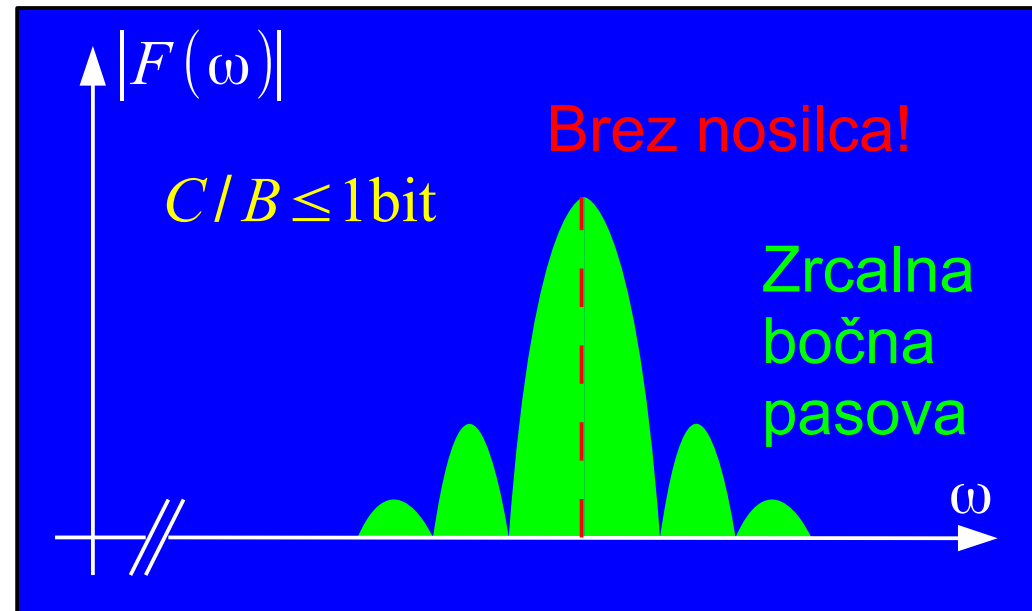
# Simetrični BPSK (Bi-Phase Shift Keying) (AM brez nosilca)

Strogo brez FM !!!

$$\Delta f_{\text{vira}} \ll B_{\text{modulacije}}$$



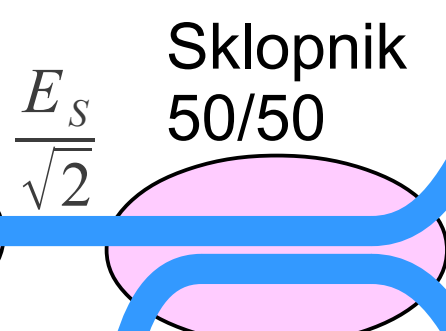
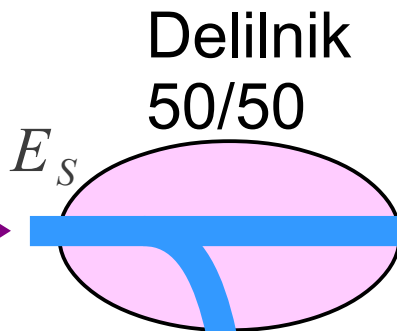
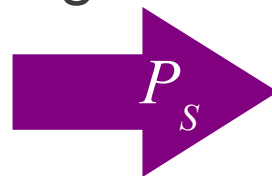
## Delovna točka za BPSK



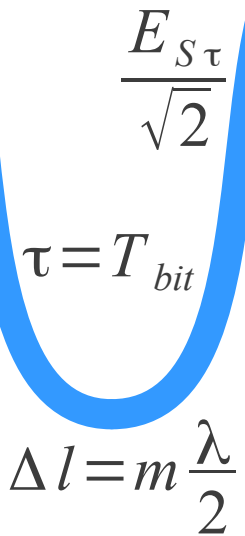
## Dvofazna modulacija BPSK

*Neodvisen od polarizacije!*

BPSK svetlobni signal



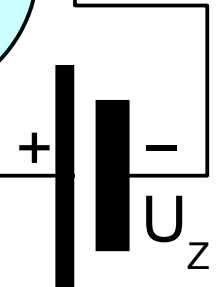
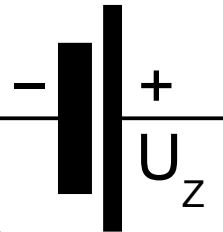
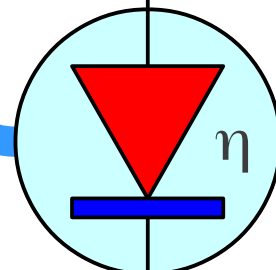
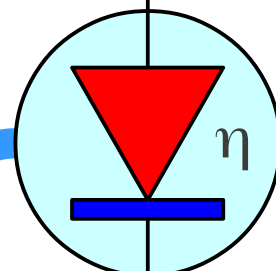
Kasilni vod



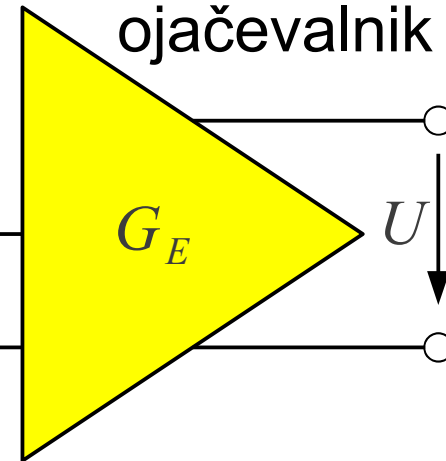
Planarno optično vezje + termostat!

*Dodatni pogoj:*  
 $\omega \tau = m \pi$   
 $m = 0, 1, 2, 3, 4, 5 \dots$

Dve enaki fotodiodi



Električni ojačevalnik



**$S/N - 3\text{dB}!!!$**

$C = 1/T_{bit}$

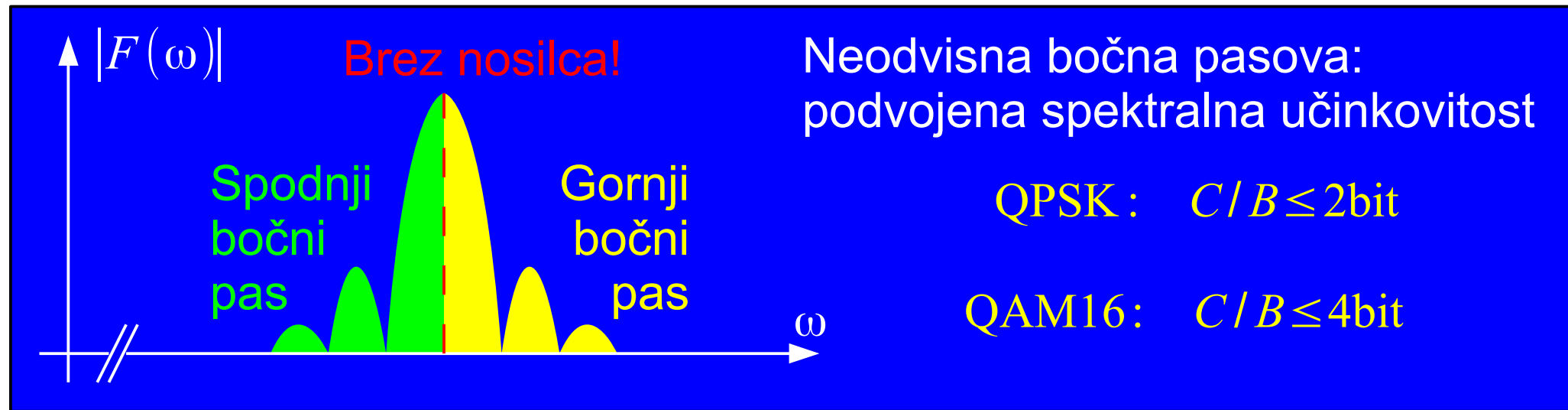
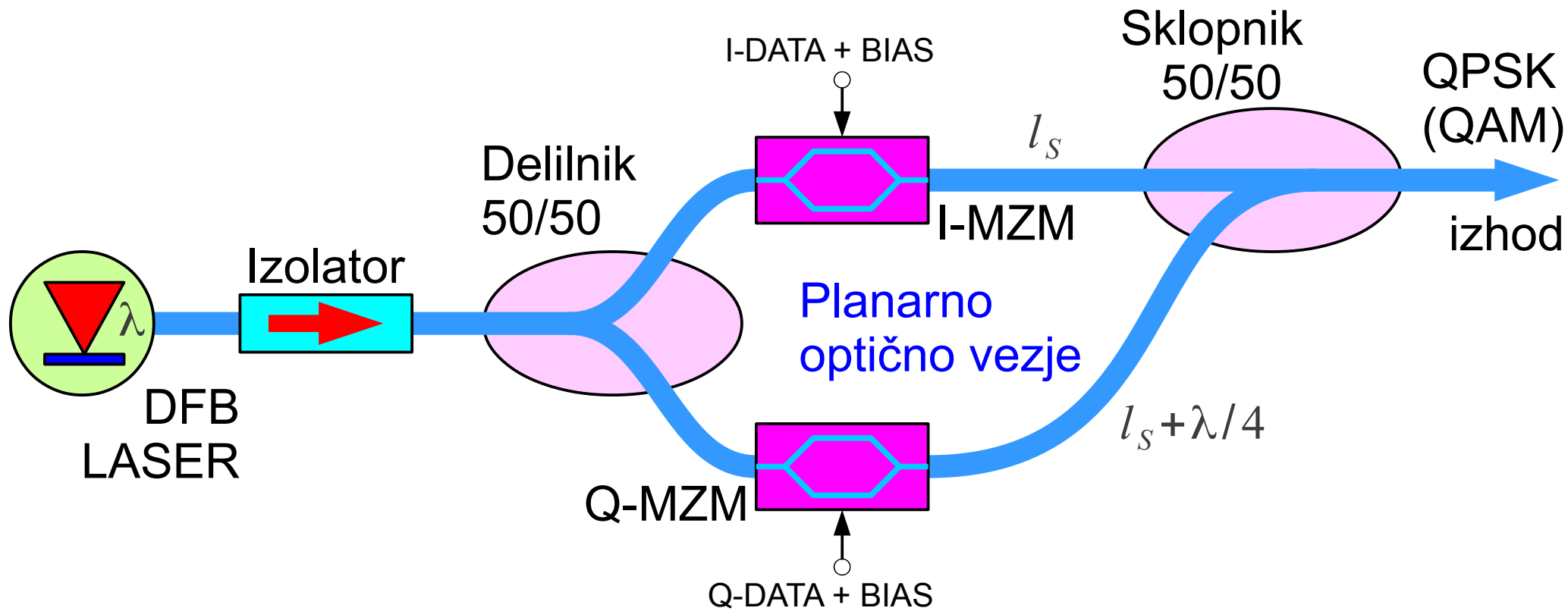
**$\Delta f < \frac{C}{10} = 4\text{GHz} \quad @ C = 40\text{Gbit/s}$**

$$U = \frac{\alpha}{4} \left[ |\vec{E}_S + \vec{E}_{S\tau}|^2 - |\vec{E}_S - \vec{E}_{S\tau}|^2 \right]$$

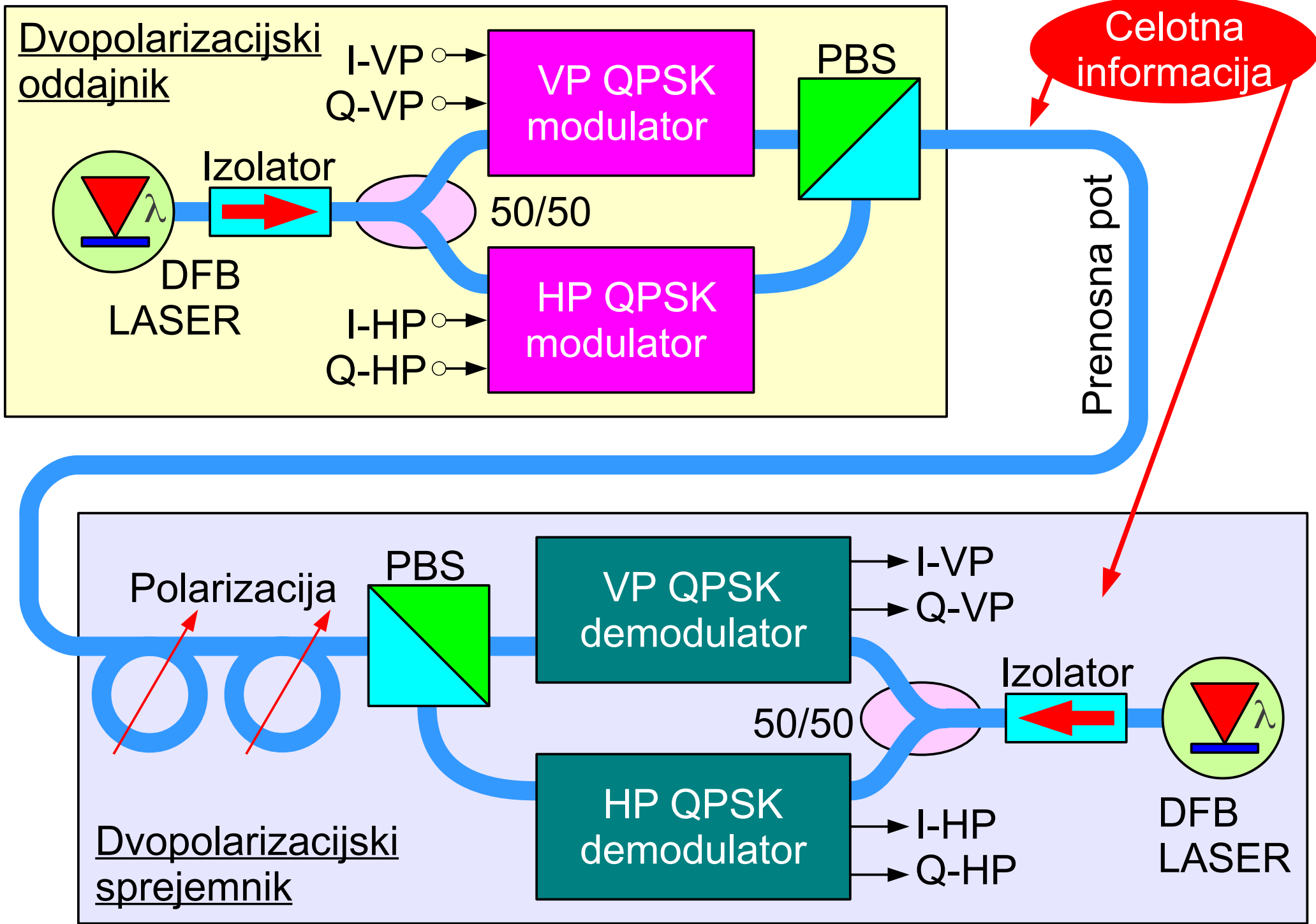
$U = \alpha \cdot \text{Re} \left[ \vec{E}_S \cdot \vec{E}_{S\tau}^* \right]$

Diferencialna demodulacija BPSK

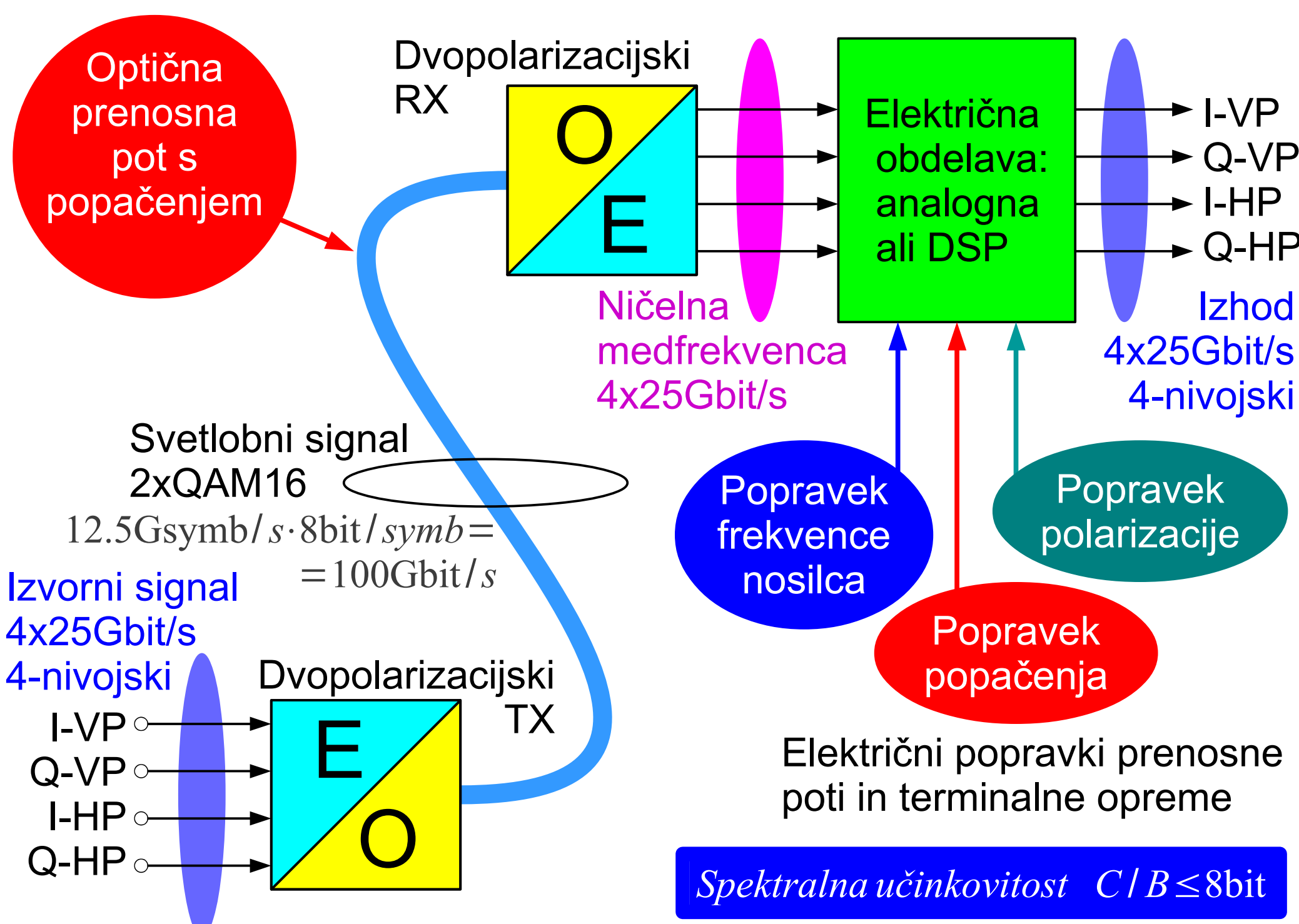




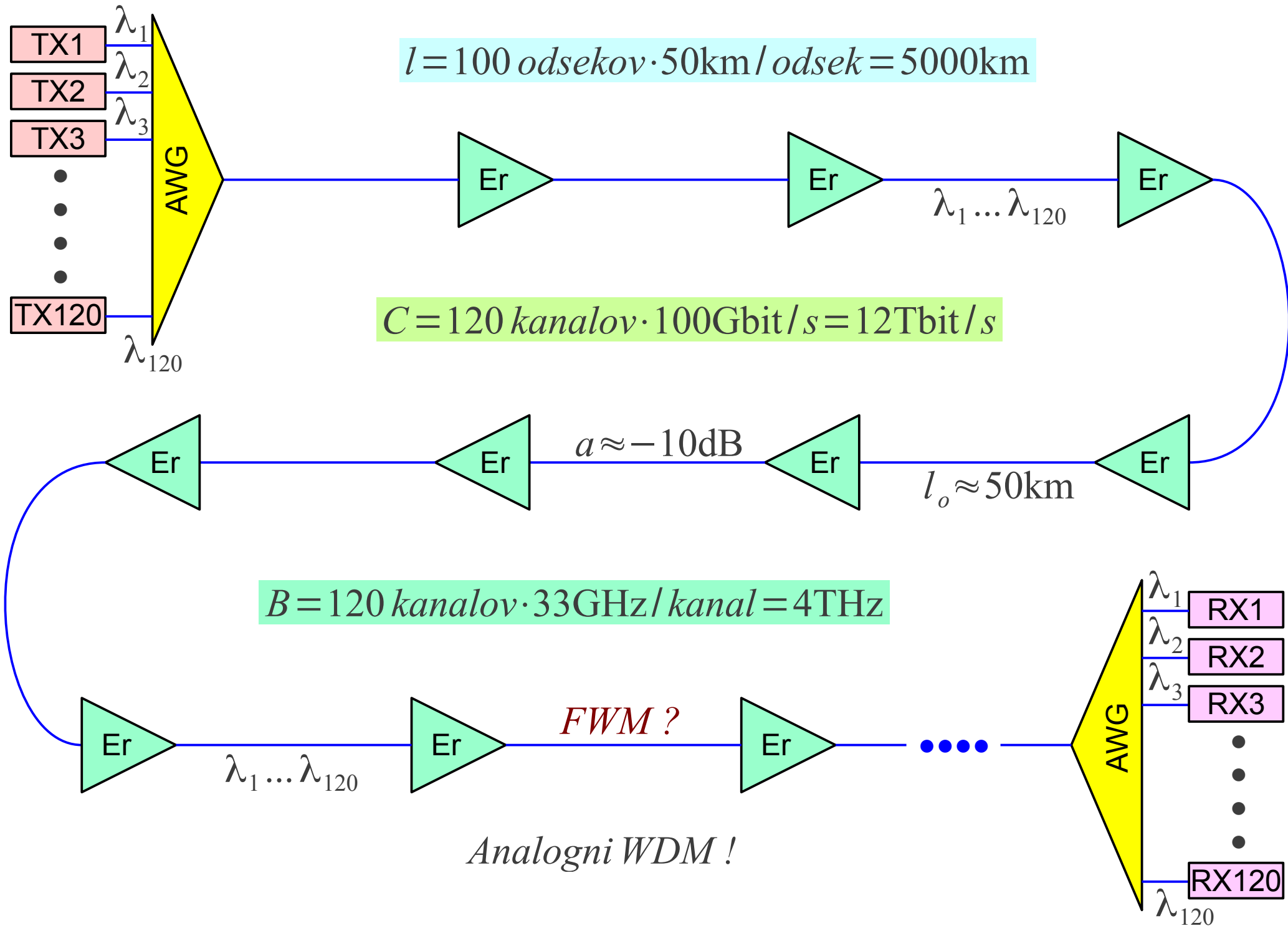
Štirifazna modulacija QPSK (Quadri-Phase Shift Keying)  
ali QAM (Quadrature Amplitude Modulation)



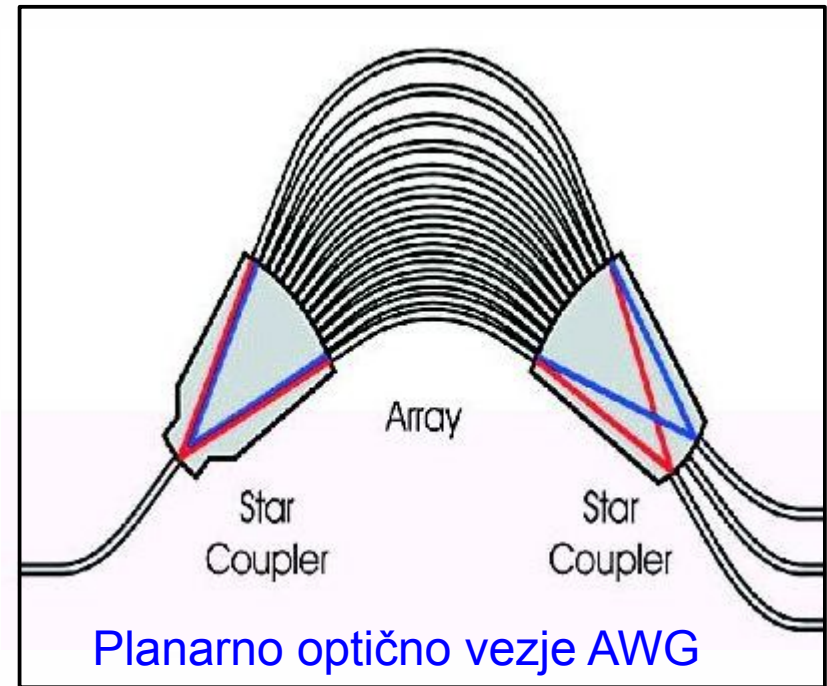
QPSK (QAM) polarizacijski multipleks (MIMO 2x2)



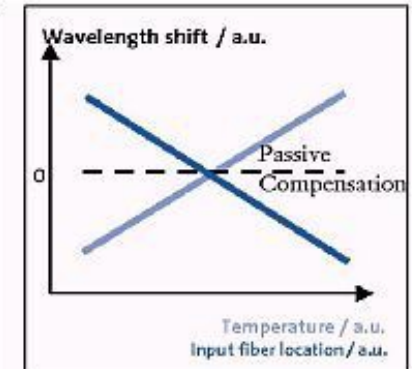
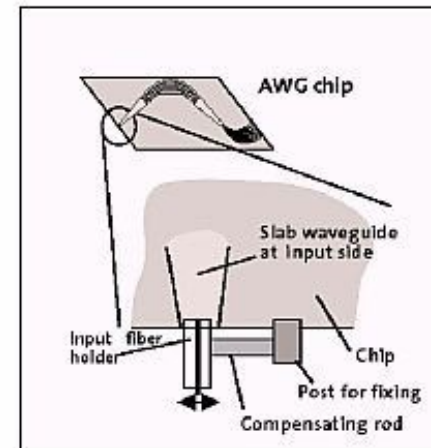
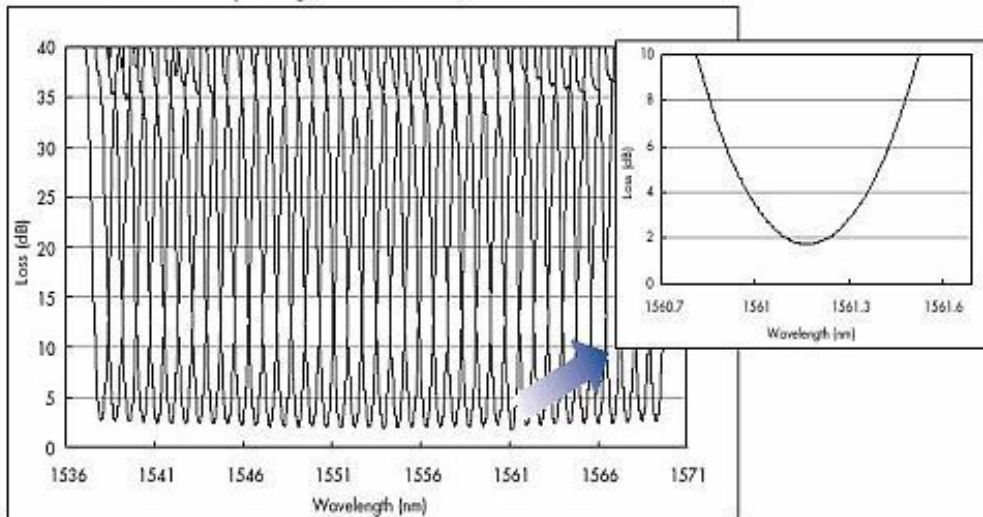
Ničelna medfrekvenca (ZIF) za 100Gbit/s 2xQAM16 (MIMO 2x2)



Preoceanski kabel 120 kanalov po 100Gbit/s 2xQAM16

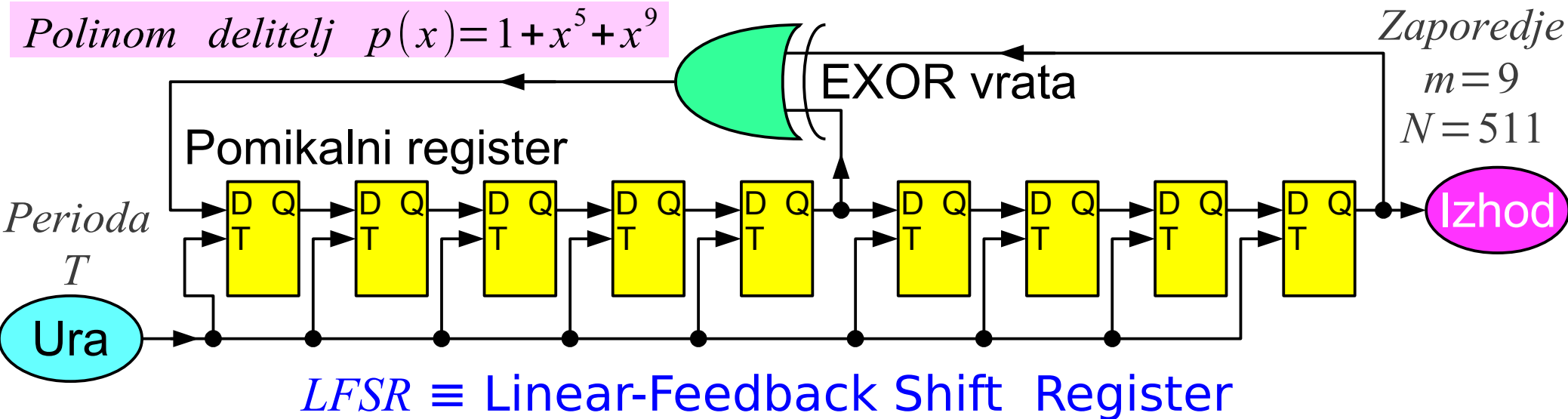


100 GHz Spacing, 40 channels, Gaussian



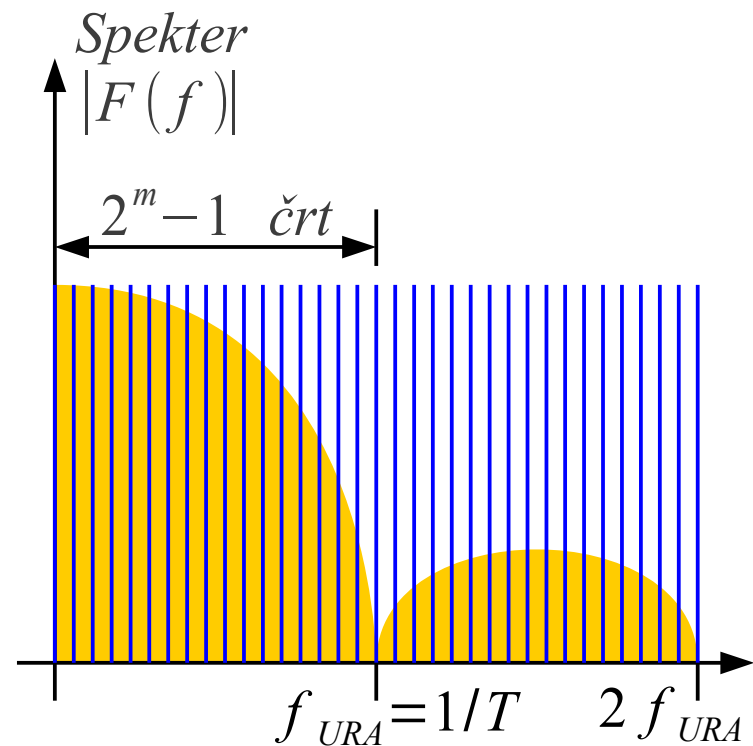
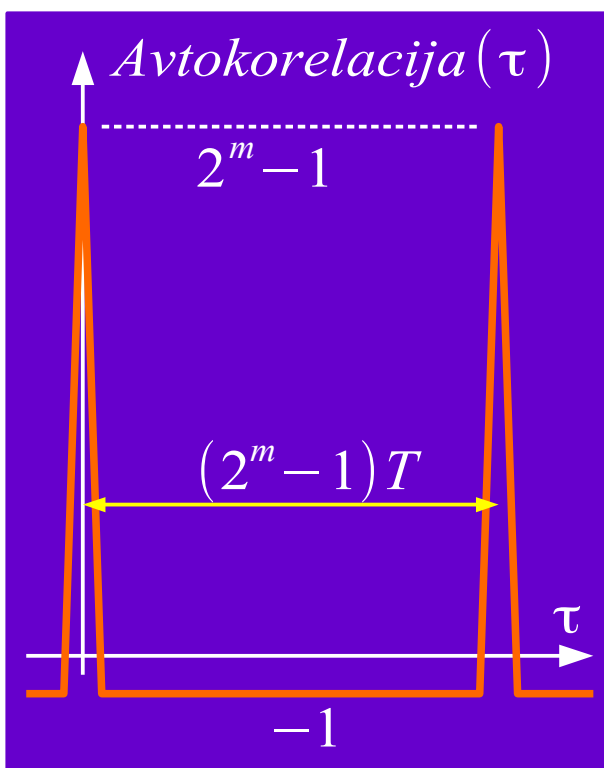
## Kretnice z valovodno razvrstitveno strukturo AWG (Arrayed Waveguide Grating)

Polinom delitelj  $p(x) = 1 + x^5 + x^9$



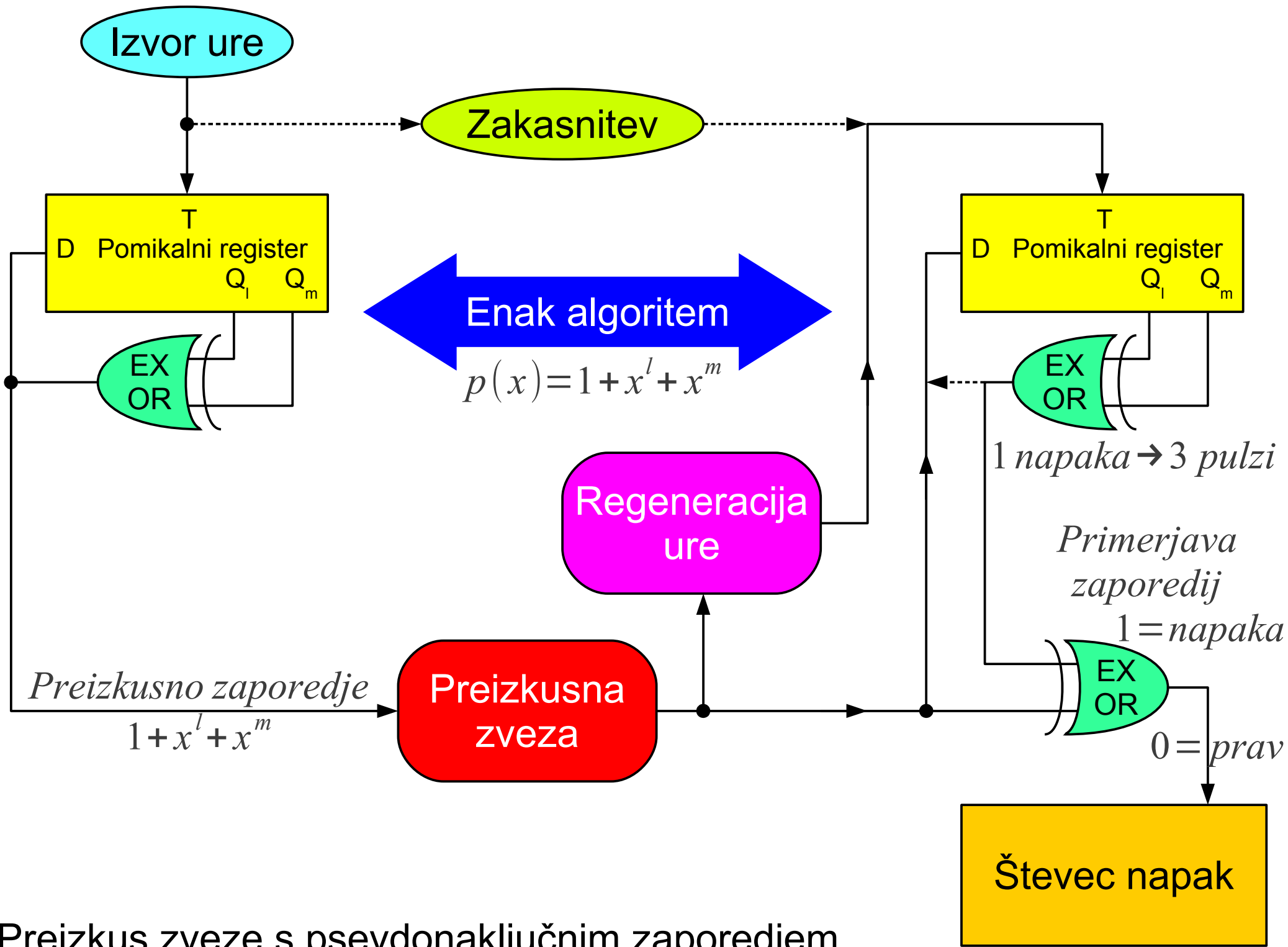
Nerazcepni polinom  $p(x) = 1 + x^l + x^m \rightarrow$  zaporedje dolžine max  $N = 2^m - 1$

- $2^{m-1}$  enic in  $2^{m-1} - 1$  ničel razporejenih v skupine
- 1X m enic, m-1 ničel
- 1X m-2 enic in ničel
- 2X m-3 enic in ničel
- 4X m-4 enic in ničel
- .....
- $2^{m-5}$  skupin 111 in 000
- $2^{m-4}$  skupin 11 in 00
- $2^{m-3}$  posamičnih 1 in 0

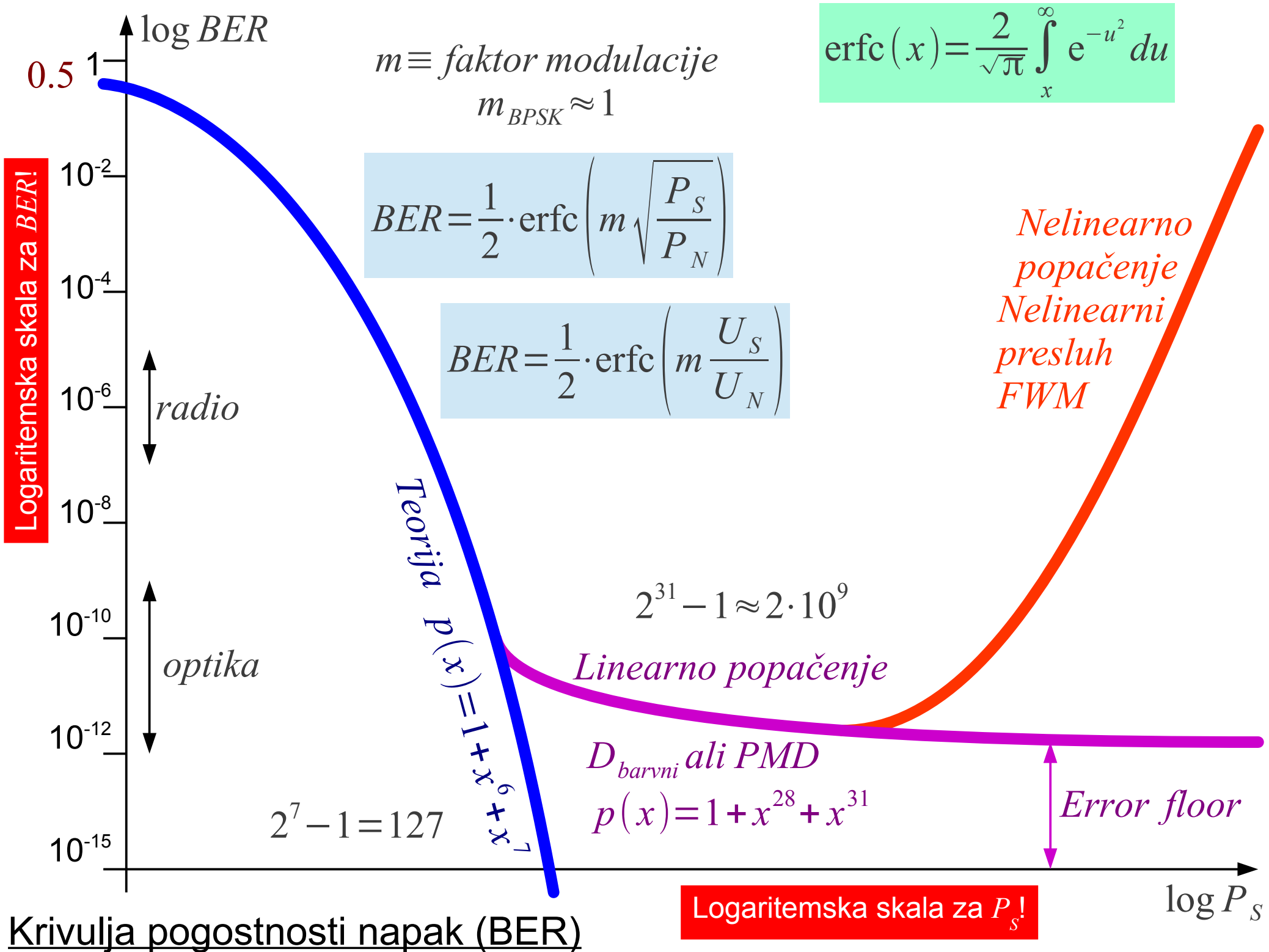


Sliši in vidi se kot beli šum!

Psevdonaključna zaporedja LFSR

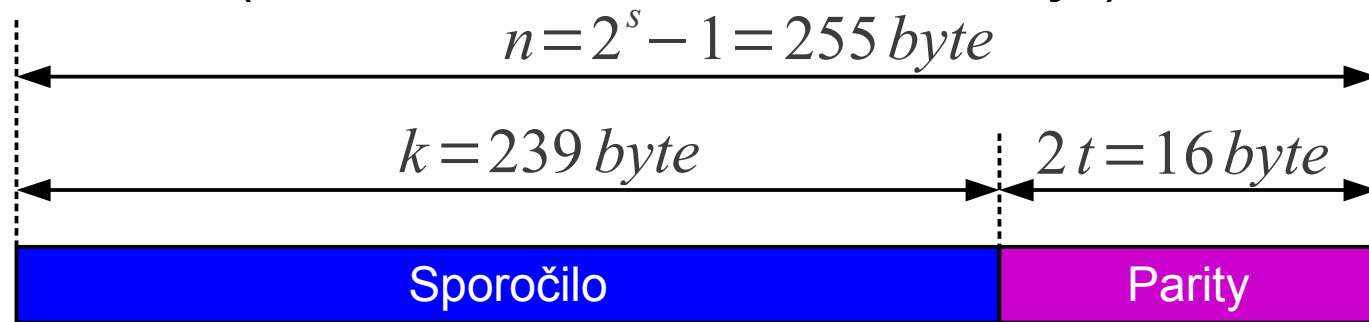


Preizkus zveze s psevdonaključnim zaporedjem





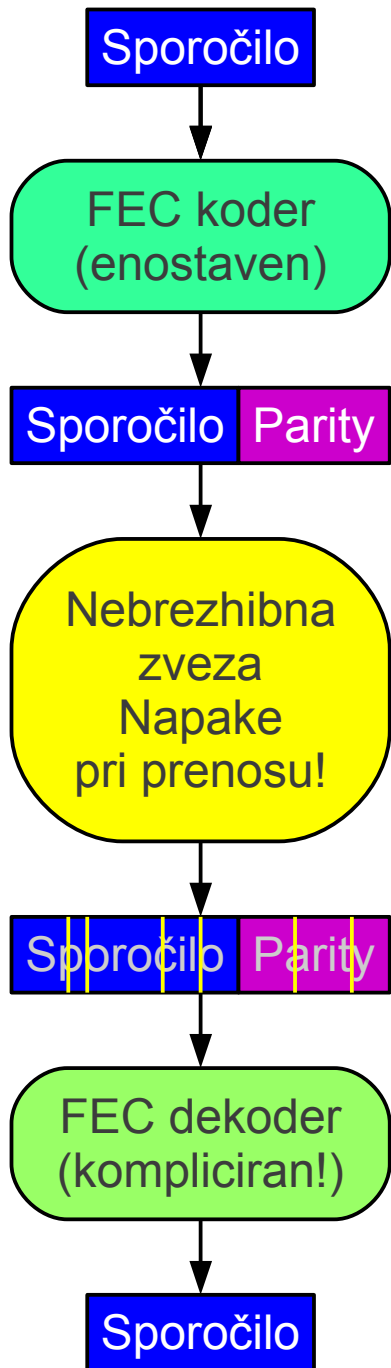
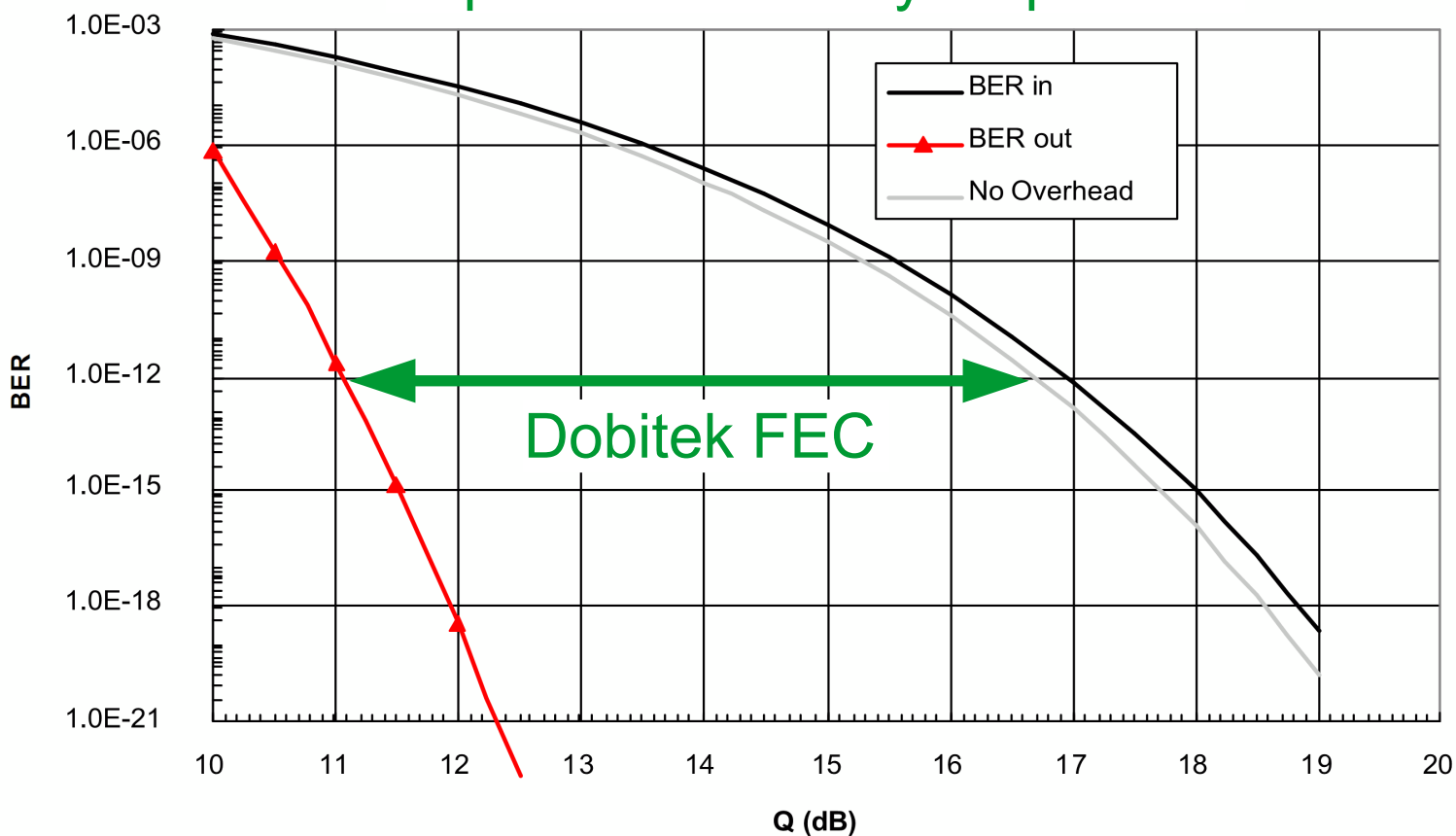
# ITU priporočilo G.709 FEC Reed-Solomon (255,239) (blokovna koda, trdo odločanje)



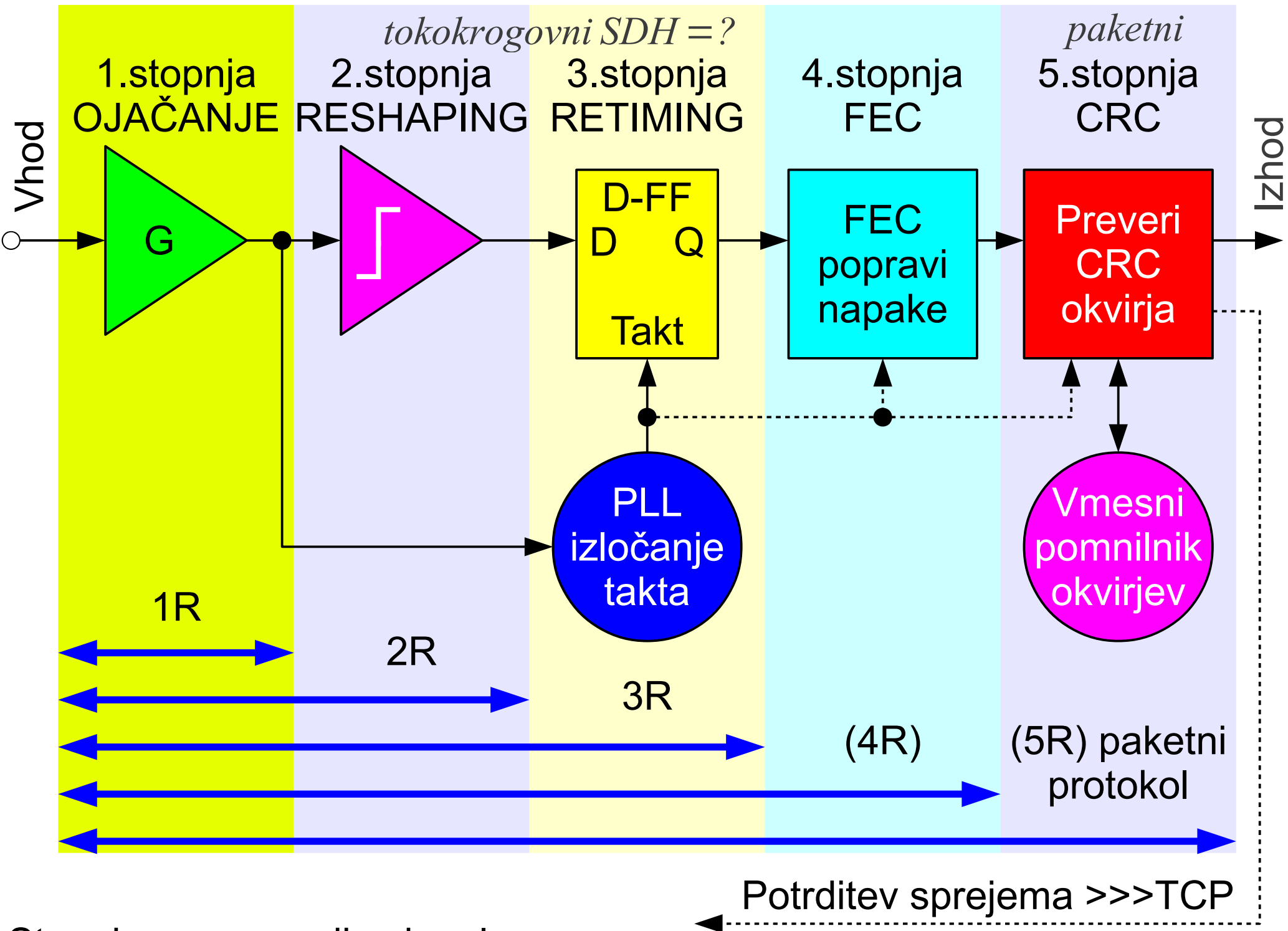
$s = 8 \text{ bit}$

BER vs Q for R-S 255 Code ( $t = 8$ )

Popravek do  $t=8 \text{ byte/sporočilo}$



Vnaprejšnje popravljane napak FEC (Forward Error Correction)



Stopnje regeneracije signala