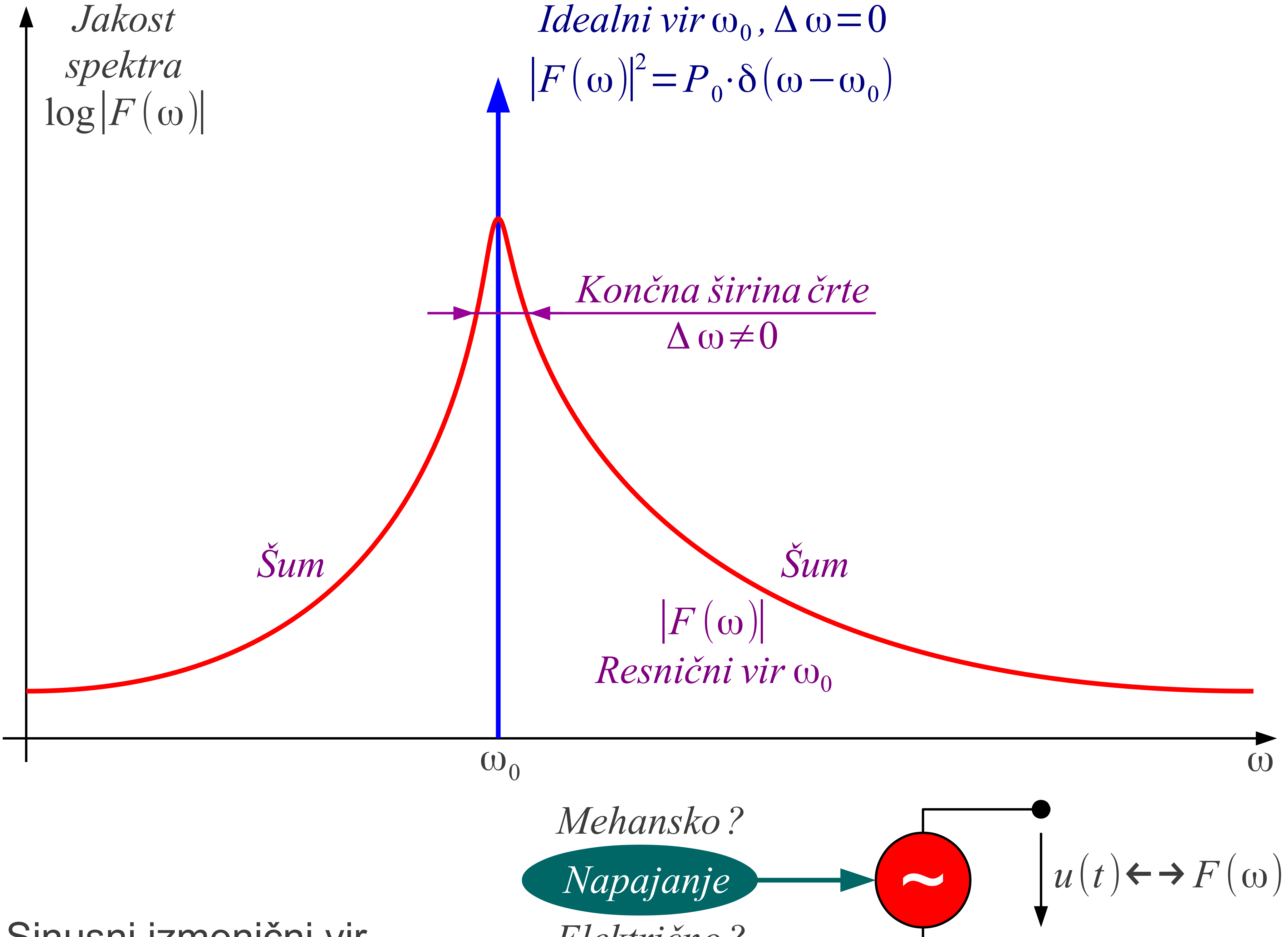
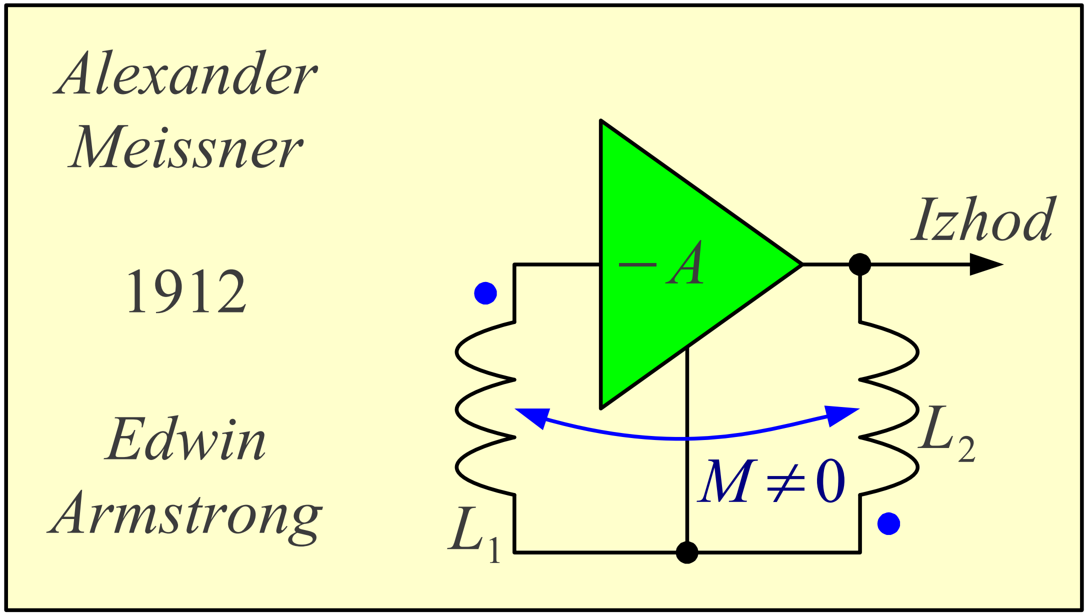
Visokofrekvenčna tehnika

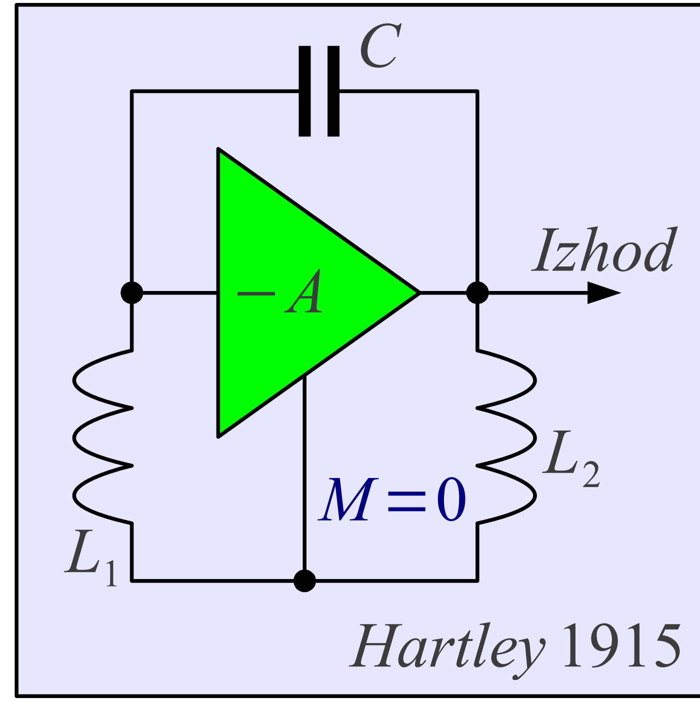
Predavanje 13:

Elektronski oscilator

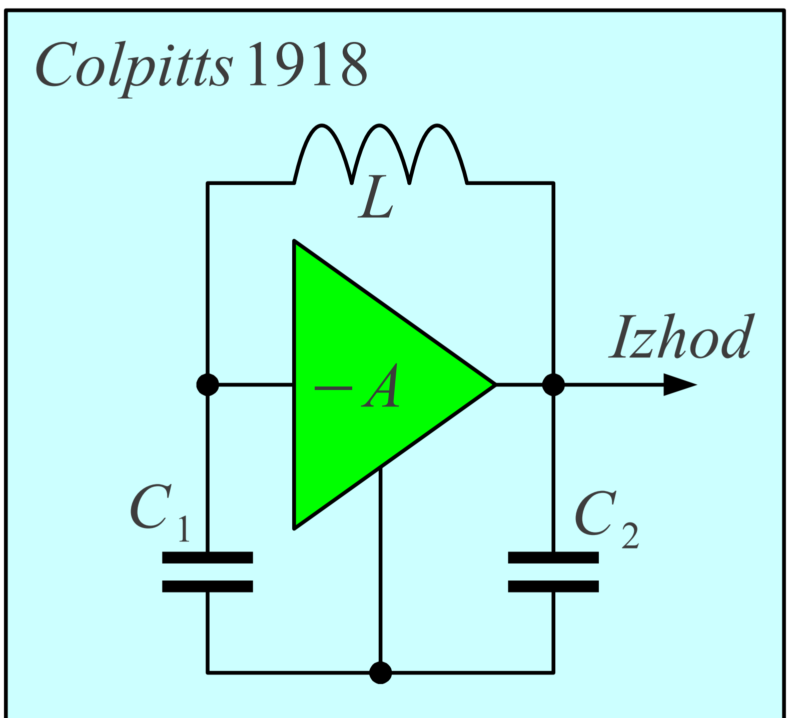


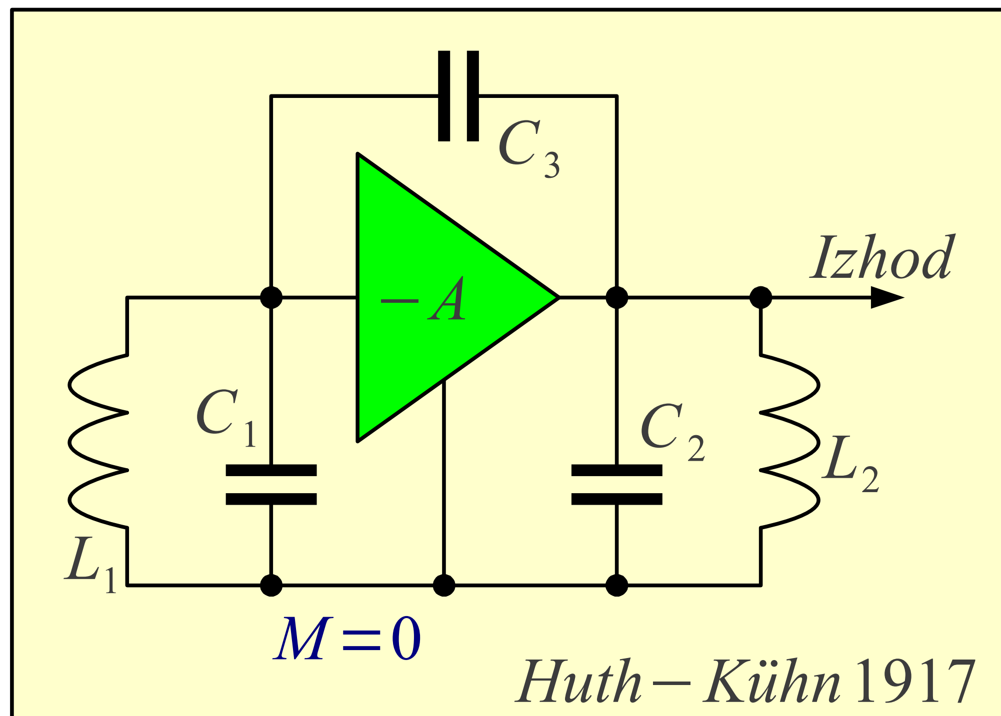
Sinusni izmenični vir





Trioda 1907 *Lee DeForest*





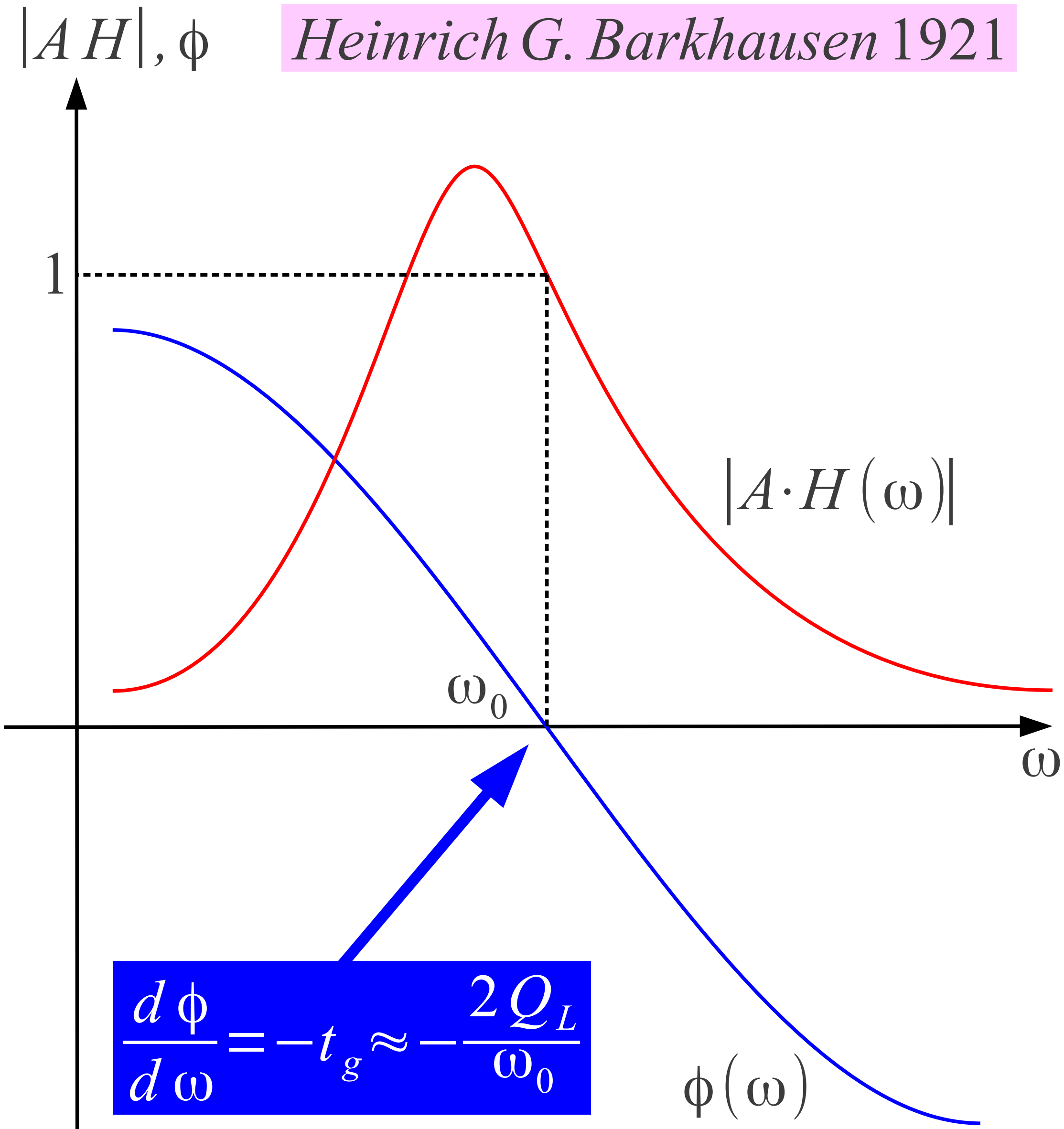
Visokofrekvenčni oscilatorji

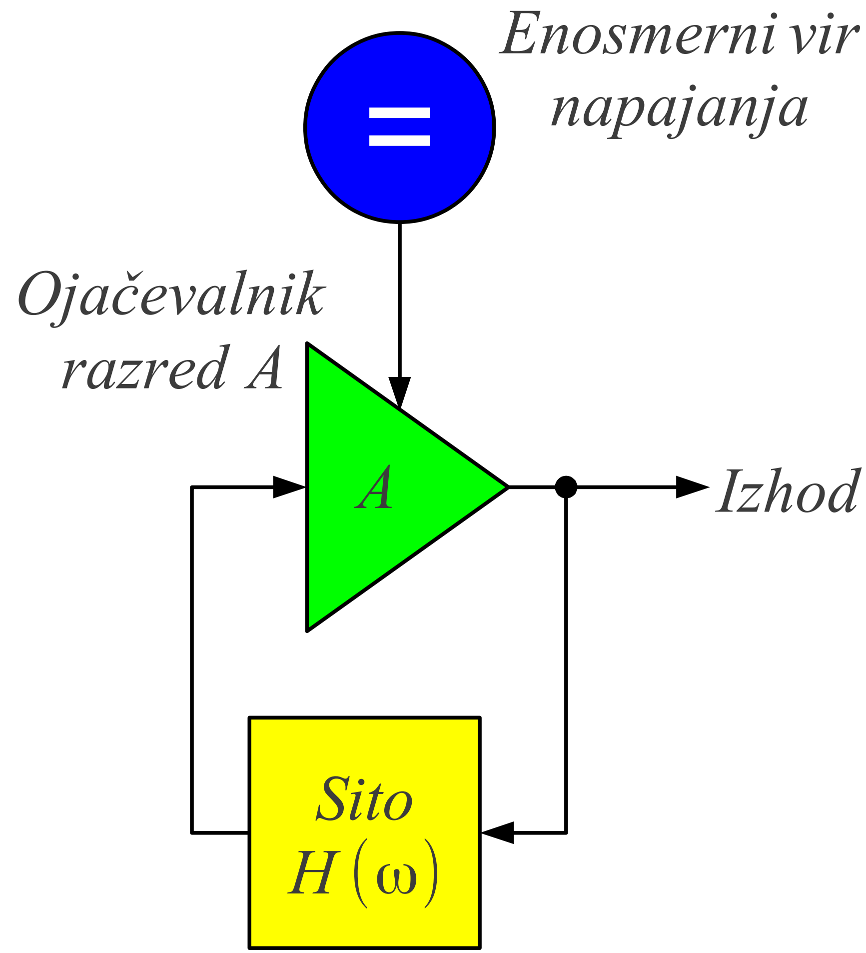
Barkhausenov pogoj

$$\left|A \cdot H(\omega_0)\right| = 1$$

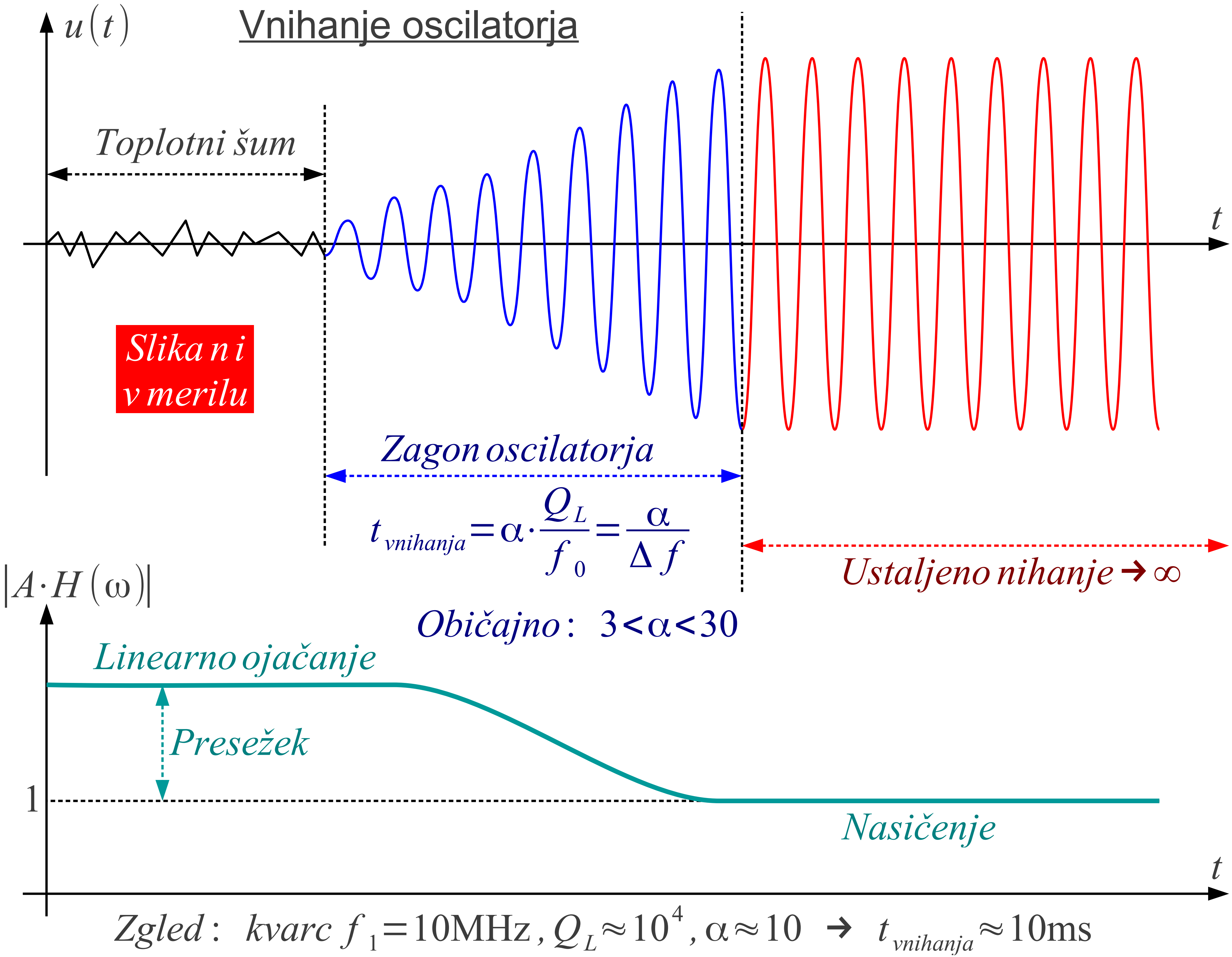
$$\phi(\omega_0) = m \cdot 2\pi \qquad m = 0, 1, 2, 3 \ldots$$

Heinrich G. Barkhausen 1921

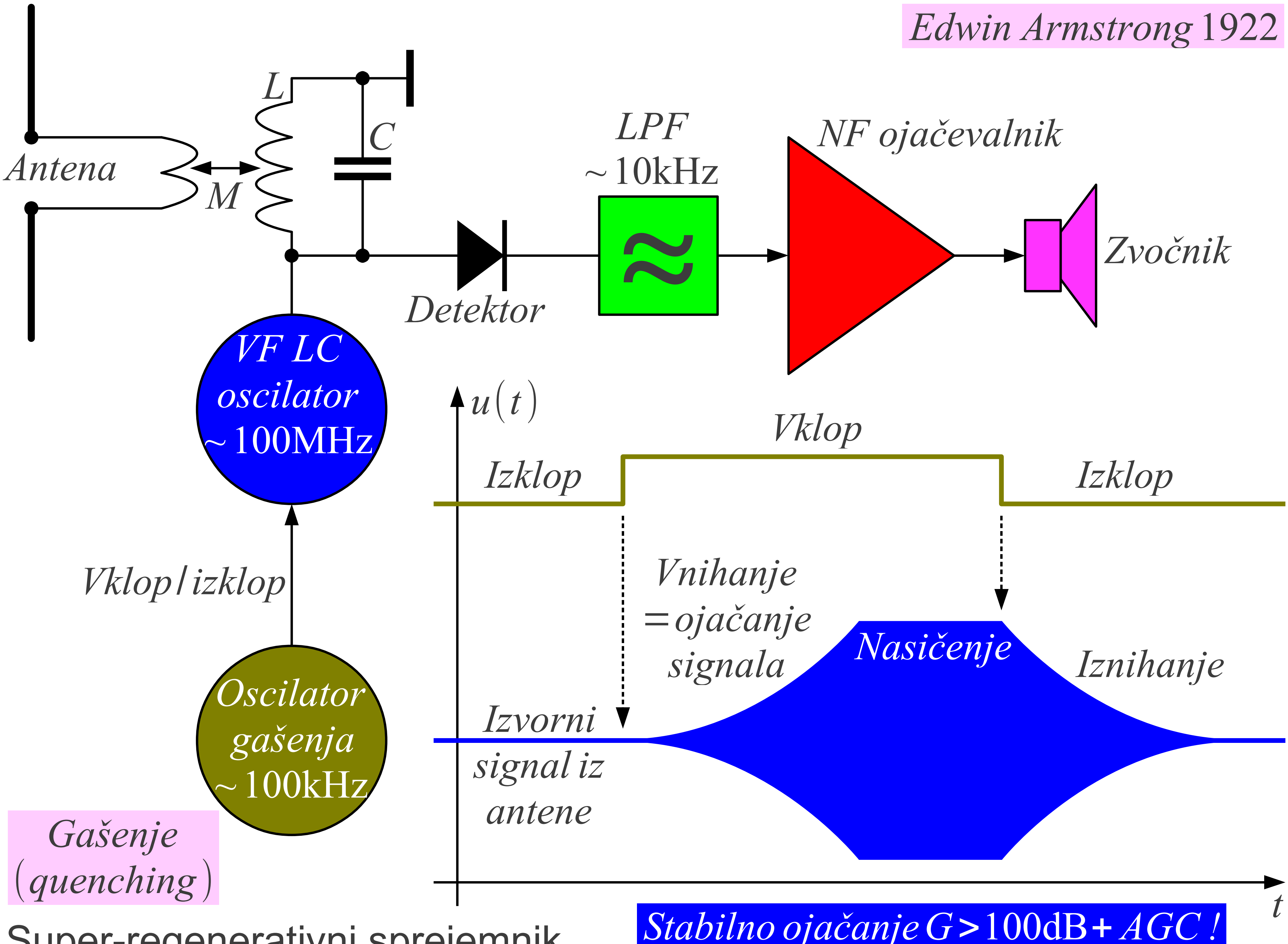




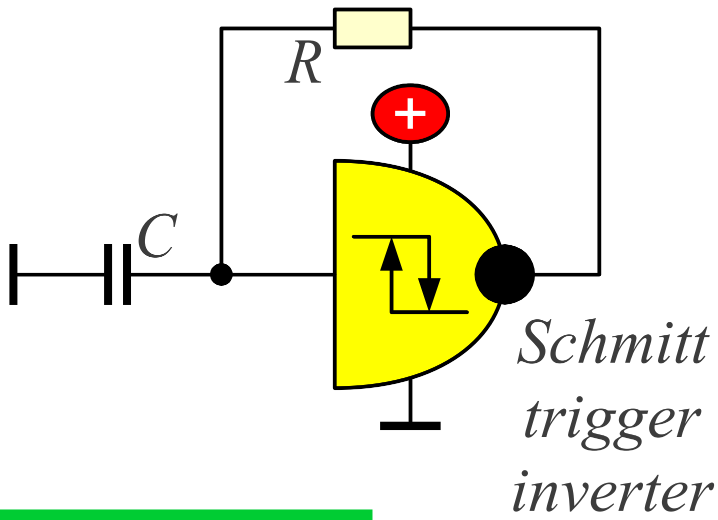
$$A \cdot H(\omega) = \left|A \cdot H(\omega)\right| \cdot e^{j\phi(\omega)}$$



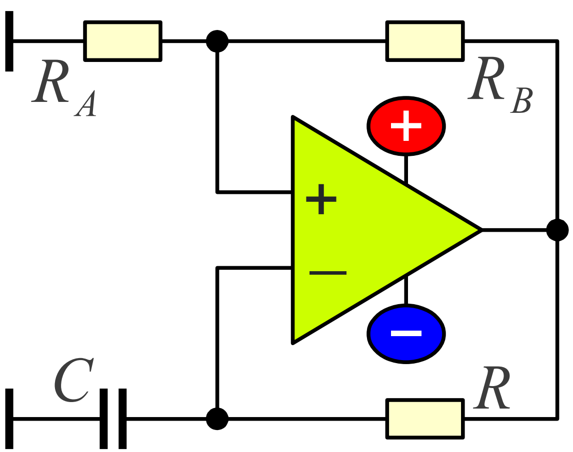
Vnihanje oscilatorja
$u(t)$
Toplotni šum
Slika ni v merilu
t
Zagon oscilatorja
$t_{vnihanja} = \alpha \cdot \frac{Q_L}{f_0} = \frac{\alpha}{\Delta f}$
Ustaljeno nihanje $\rightarrow \infty$
$|A \cdot H(\omega)|$
Običajno: $3 < \alpha < 30$
Linearno ojačanje
Presežek
1
Nasičenje
t
Zgled: kvarc $f_1 = 10\mathrm{MHz}$, $Q_L \approx 10^4$, $\alpha \approx 10$ $\rightarrow$ $t_{vnihanja} \approx 10\mathrm{ms}$



Super-regenerativni sprejemnik

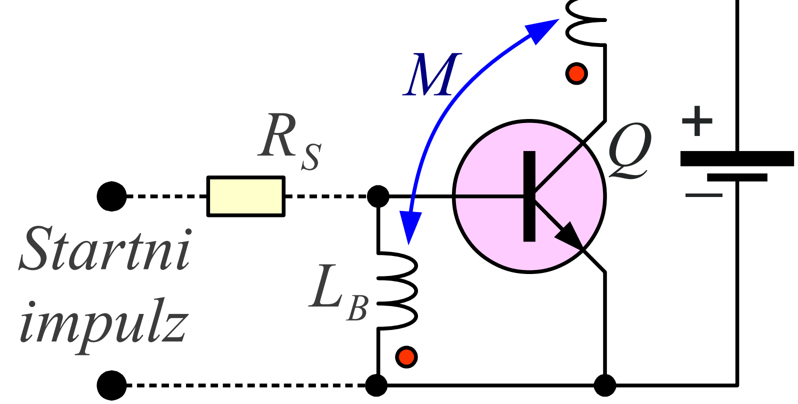


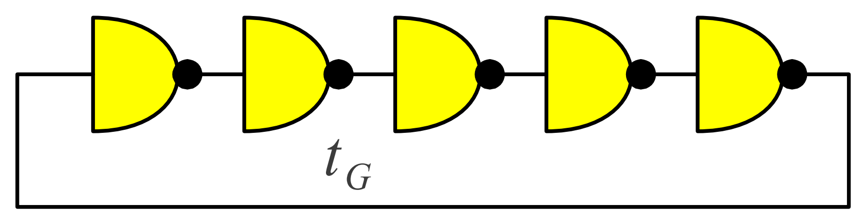
Astabilno vezje zaniha takoj !



Vezja s histerezo so počasna ter šumeča !

Oscilator v razredu C se ne zažene iz šuma !

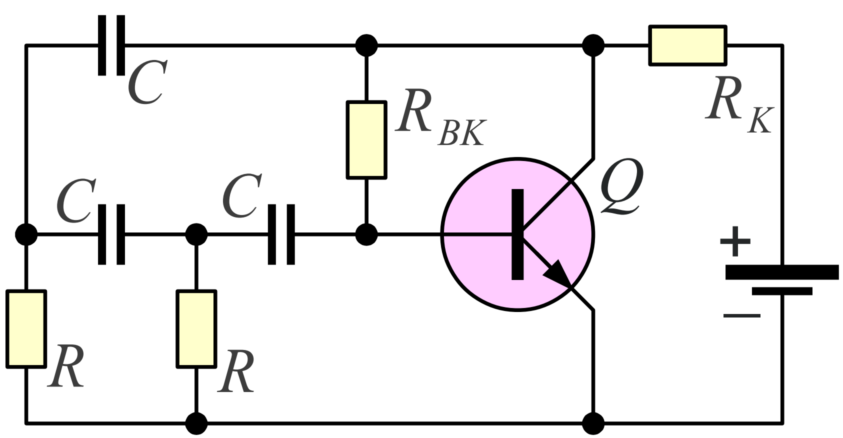




Linearni inverterji $N \geq 3$

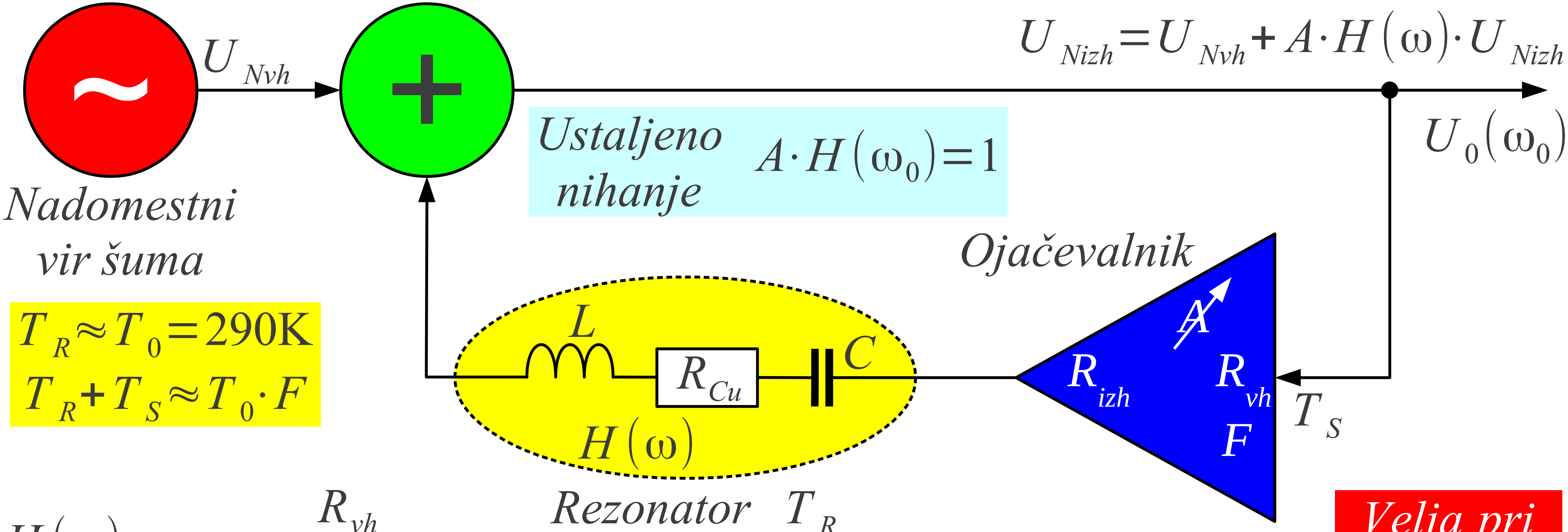
Any odd number of gates always oscillates !

Zagon iz šuma $Q_L \approx 1$



Različice oscilatorjev

Šum v oscilatorju



$$T_R \approx T_0 = 290\mathrm{K}$$
$$T_R + T_S \approx T_0 \cdot F$$

Velja pri $U_{Nizh} \ll U_0$

$$H(\omega) = \frac{R_{vh}}{\Sigma R + j\omega L + \dfrac{1}{j\omega C}}$$

$$Q_L = \frac{\omega_0 L}{\Sigma R}$$

$$\Sigma R = R_{izh} + R_{Cu} + R_{vh}$$

$$\Delta\omega = \omega - \omega_0$$

$$U_{Nizh} = \frac{U_{Nvh}}{1 - A \cdot H(\omega)}$$

$$A \cdot H(\omega) = \frac{\Sigma R}{\Sigma R + j\omega L + \dfrac{1}{j\omega C}} \approx \frac{1}{1 + j 2 Q_L \dfrac{\Delta\omega}{\omega_0}}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$U_{Nizh} \approx \frac{U_{Nvh}}{1 - \dfrac{1}{1 + j 2 Q_L \dfrac{\Delta\omega}{\omega_0}}} = U_{Nvh} \cdot \left(1 + \frac{\omega_0}{j 2 Q_L \Delta\omega}\right)$$

$$U_{Nizh} \approx U_{Nvh} \cdot \left(1 + \frac{\omega_0}{j\,2\,Q_L\,\Delta\omega}\right)$$

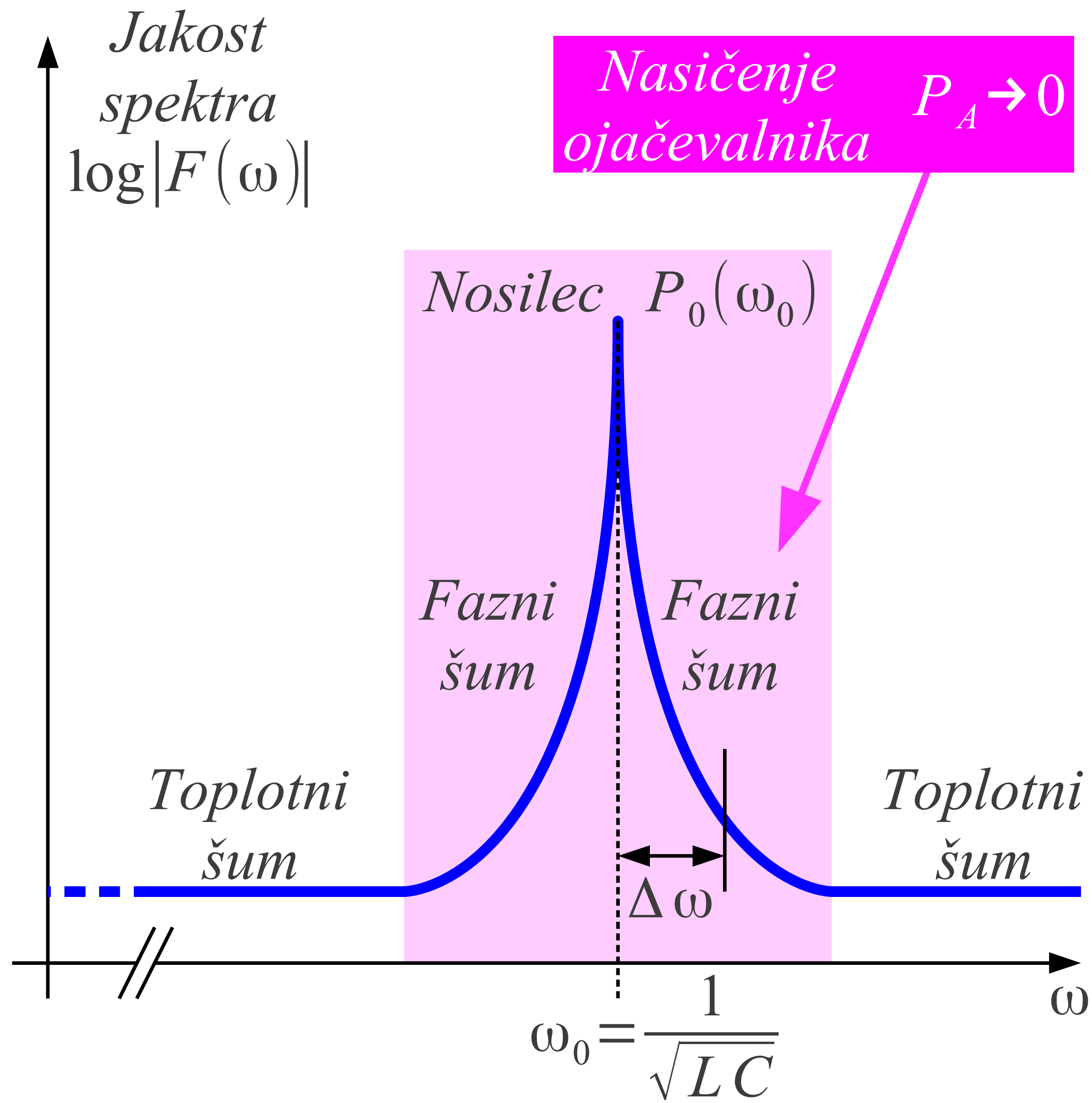
$P = \alpha\,|U|^2$ $\quad$ $|a \pm j\,b|^2 = a^2 + b^2$

$$P_{Nizh} \approx P_{Nvh} \cdot \left[1 + \left(\frac{\omega_0}{2\,Q_L\,\Delta\omega}\right)^2\right]$$

$\omega = 2\pi f \;\rightarrow\; \Delta f = f - f_0$

$$P_{Nizh} \approx P_{Nvh} \cdot \left[1 + \left(\frac{f_0}{2\,Q_L\,\Delta f}\right)^2\right]$$

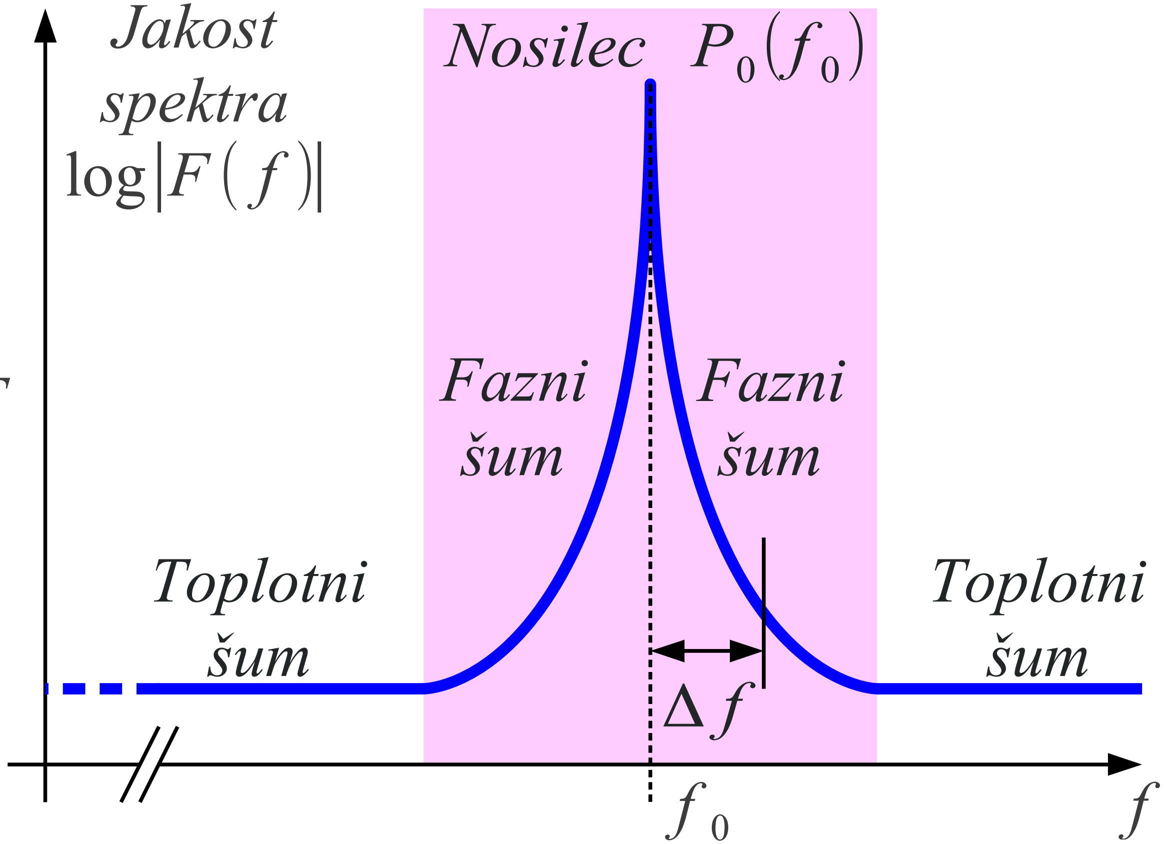
$P_{Nizh} \equiv$ *skupna moč šuma*
$P_A \equiv$ *moč amplitudnega šuma*
$P_\phi \equiv$ *moč faznega šuma*



$$P_\phi = P_A = \frac{P_{Nizh}}{2} \approx \frac{1}{2}\left[1 + \left(\frac{f_0}{2\,Q_L\,\Delta f}\right)^2\right] \cdot P_{Nvh}$$

Fazni in amplitudni šum

$$\text{Relativna gostota faznega šuma}$$
$$L(\Delta f) = \frac{1}{P_0} \cdot \frac{d P_\phi}{d f} \quad [\mathrm{Hz}^{-1}]$$



$$\frac{d P_{Nvh}}{d f} = N_0 = k_B \cdot (T_R + T_S) \approx k_B T_0 F$$

David B. Leeson 1966

Velja pri
$L(\Delta f) \cdot \Delta f \ll 1$

$$L(\Delta f) = \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2 Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0}$$

$Q_L \equiv$ *obremenjeni Q rezonatorja*

$k_B \approx 1.38 \cdot 10^{-23}\ \mathrm{J/K} \equiv$ *Boltzmannova konstanta*

$T_0 \approx 290\mathrm{K} \equiv$ *temperatura vezja*

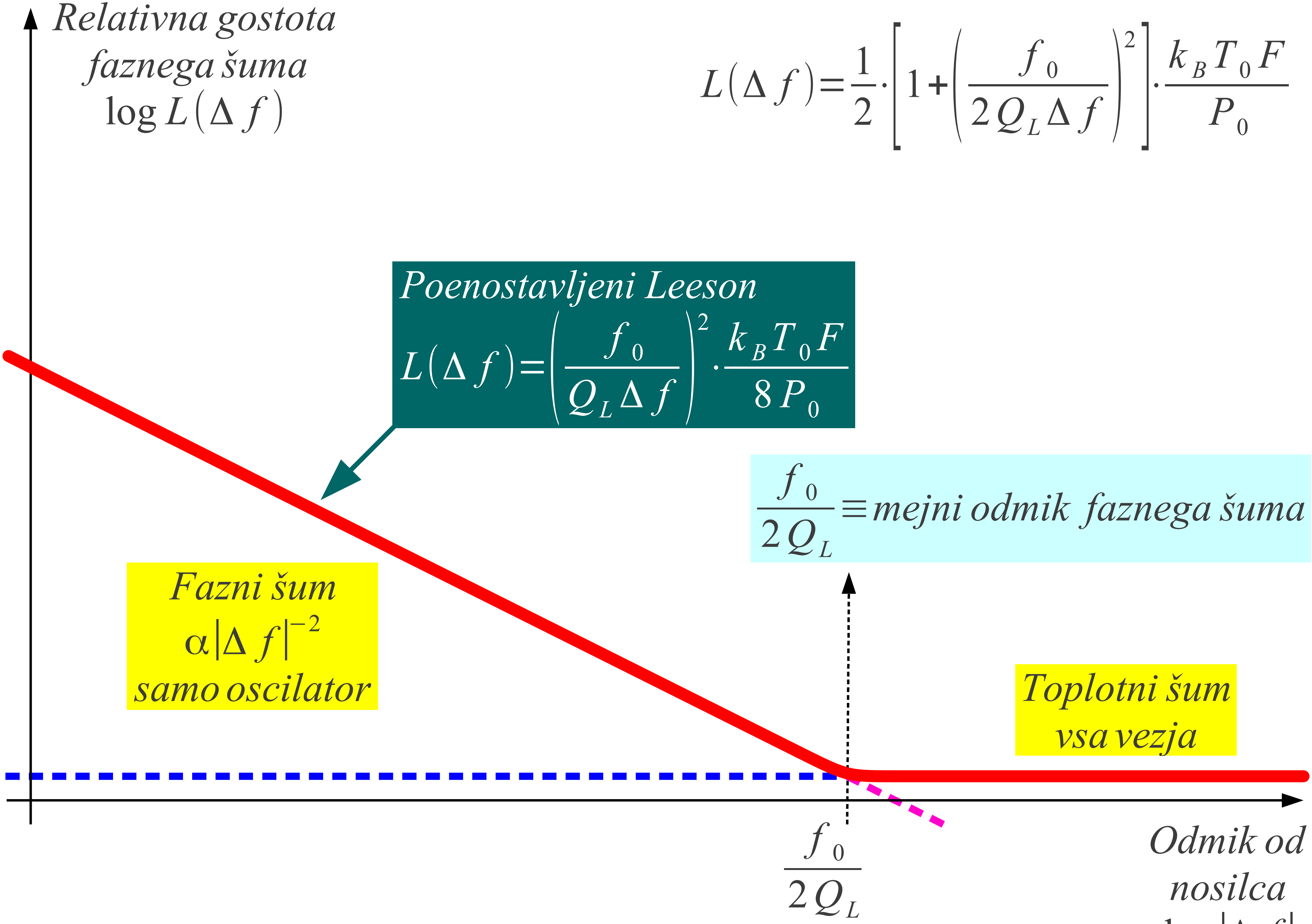
$F \equiv$ *šumno število ojačevalnika @ P_0*

$P_0 \equiv$ *moč nosilca @ f_0*

$$\log L(\Delta f)_{\mathrm{dBc/Hz}} = 10 \log_{10} [L(\Delta f) \cdot 1\mathrm{Hz}]$$

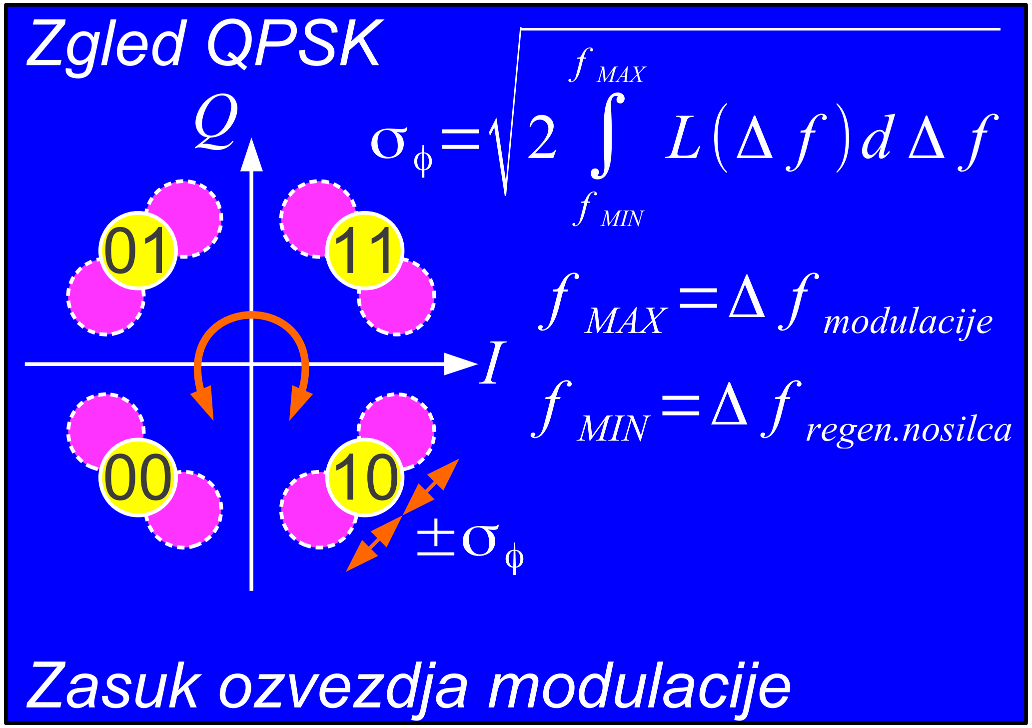
$$\log L(\Delta f)_{\mathrm{dBc/Hz}} = 10 \log_{10} \left\{ \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2 Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0} \cdot 1\mathrm{Hz} \right\}$$

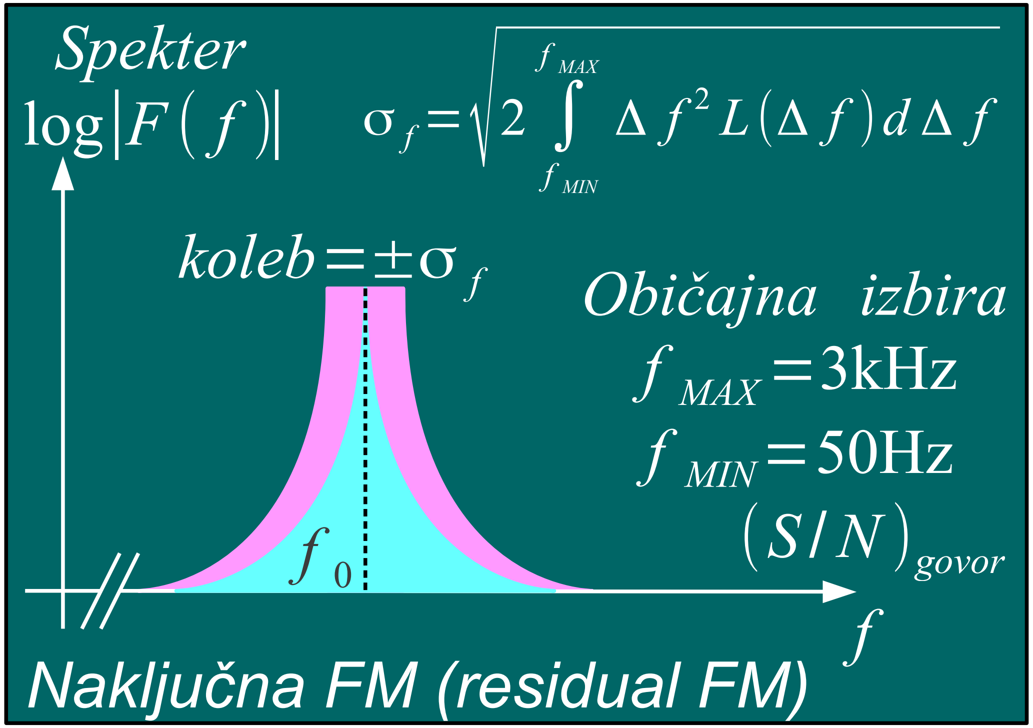
Fazni šum oscilatorja

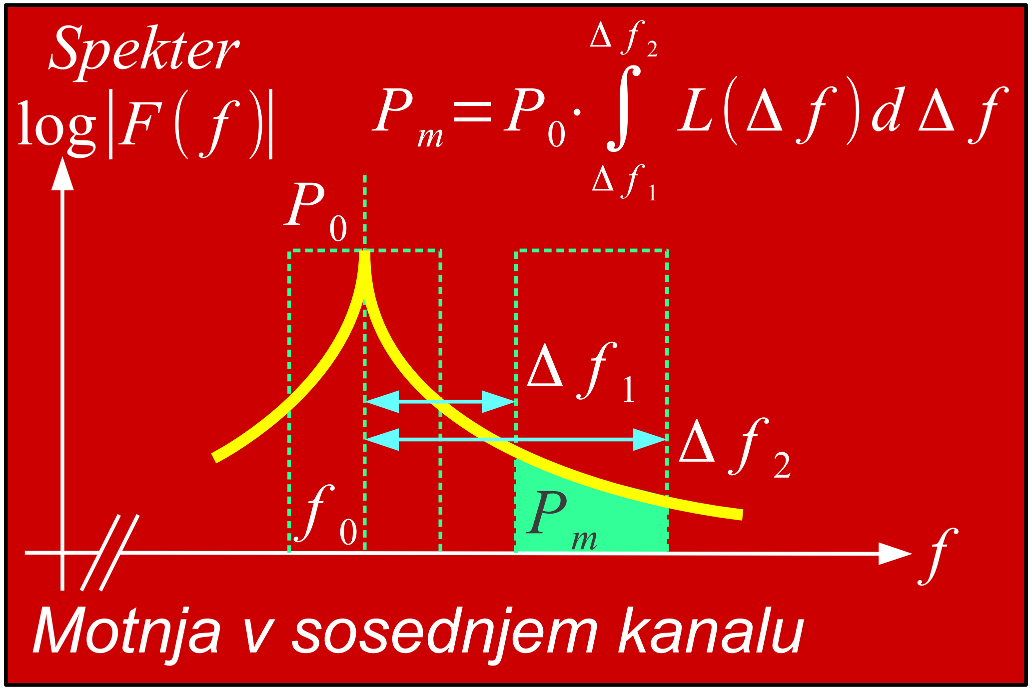


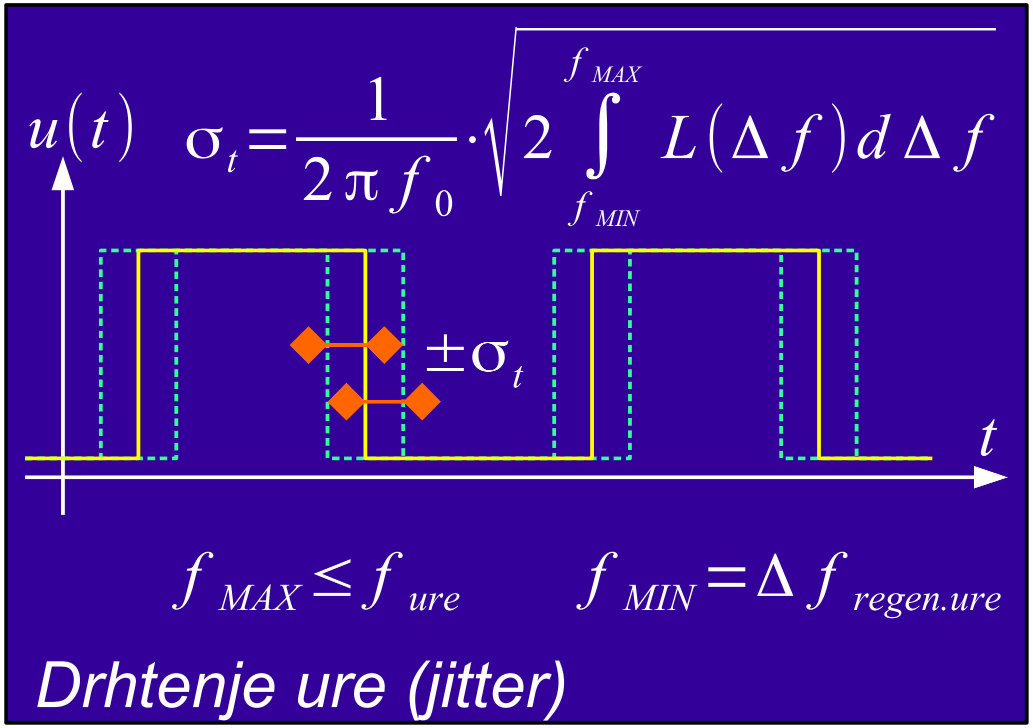
Potek faznega šuma ocilatorja

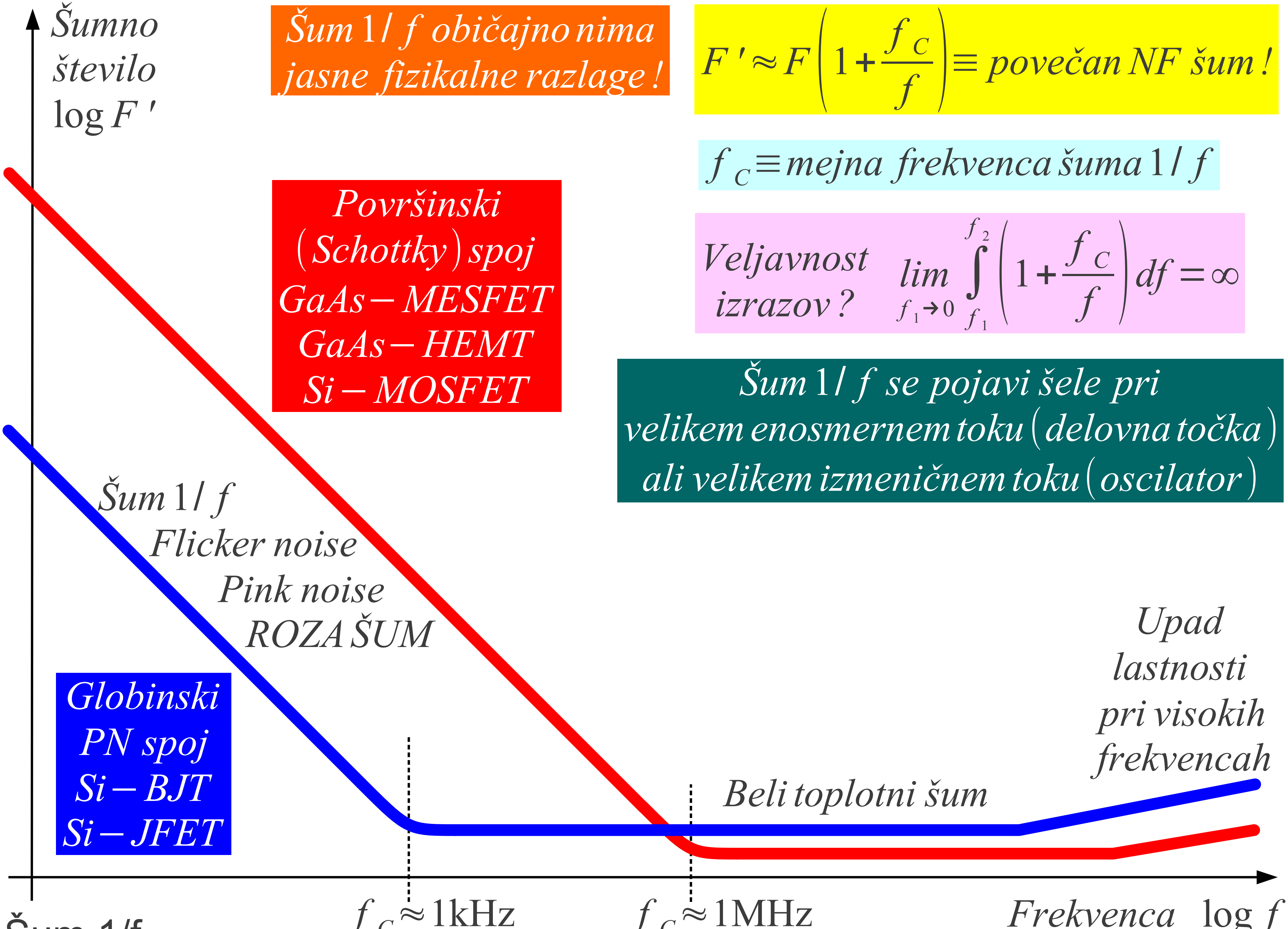
Posledice faznega šuma










Šumno število $\log F'$
Šum $1/f$ običajno nima jasne fizikalne razlage!
$F' \approx F\left(1+\frac{f_C}{f}\right) \equiv$ povečan NF šum!
$f_C \equiv$ mejna frekvenca šuma $1/f$
Veljavnost izrazov? $\lim_{f_1 \to 0} \int_{f_1}^{f_2} \left(1+\frac{f_C}{f}\right) df = \infty$
Površinski (Schottky) spoj
GaAs – MESFET
GaAs – HEMT
Si – MOSFET
Šum $1/f$ se pojavi šele pri velikem enosmernem toku (delovna točka) ali velikem izmeničnem toku (oscilator)
Šum $1/f$
Flicker noise
Pink noise
ROZA ŠUM
Upad lastnosti pri visokih frekvencah
Globinski PN spoj
Si – BJT
Si – JFET
Beli toplotni šum
$f_C \approx 1\text{kHz}$
$f_C \approx 1\text{MHz}$
Frekvenca $\log f$

Šum 1/f

Dopolnjeni šum oscilatorja

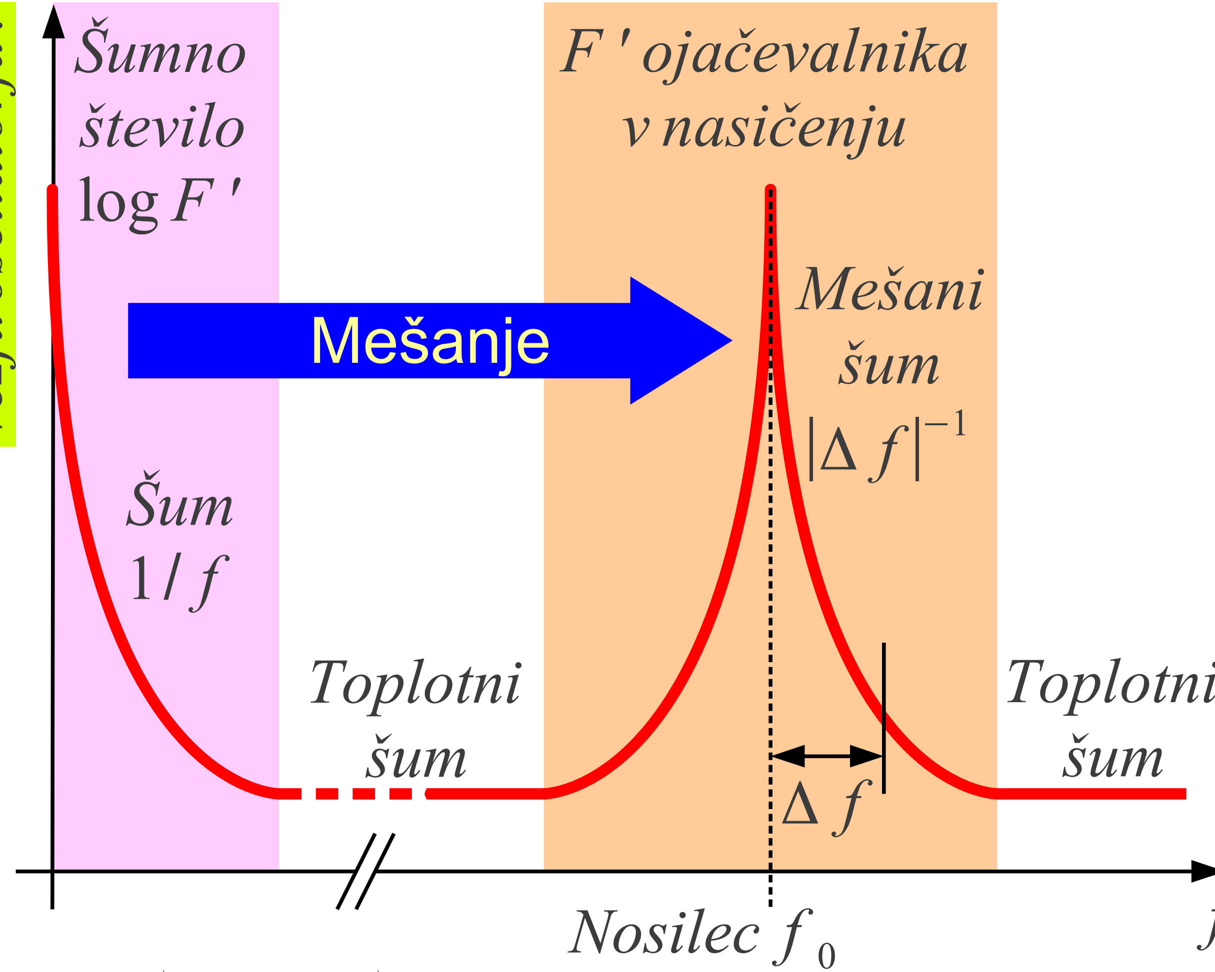
Upoštevanje šuma $1/f$

$$F' = F \cdot \left(1 + \frac{f_C}{|\Delta f|}\right)$$

$$\frac{d\,P_{Nvh}}{d\,f} \approx k_B \cdot T_0 \cdot F'$$

$$\frac{d\,P_{Nvh}}{d\,f} \approx k_B \cdot T_0 \cdot F \cdot \left(1 + \frac{f_C}{|\Delta f|}\right)$$

F' tranzistorja v vezju oscilatorja!



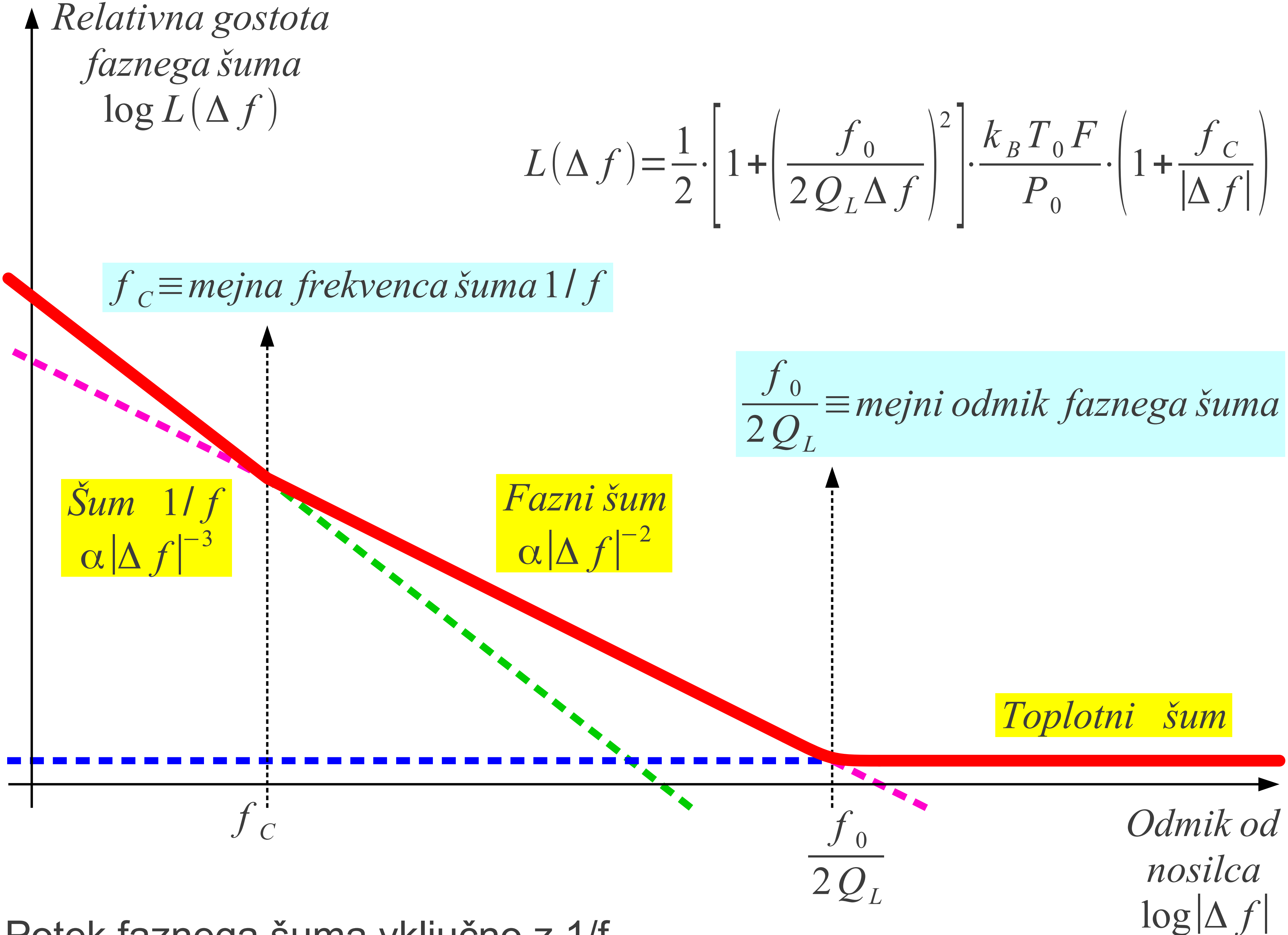
Dopolnjeni Leeson za šum $1/f$

$$L(\Delta f) = \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2 Q_L \Delta f}\right)^2\right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left(1 + \frac{f_C}{|\Delta f|}\right)$$

Velja pri
$L(\Delta f) \cdot \Delta f \ll 1$

Globinski
PN spoj
$Si - BJT$
$Si - JFET$

$$\log L(\Delta f)_{\mathrm{dBc/Hz}} = 10 \log_{10} \left\{ \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2 Q_L \Delta f}\right)^2\right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left(1 + \frac{f_C}{|\Delta f|}\right) \cdot 1\mathrm{Hz} \right\}$$

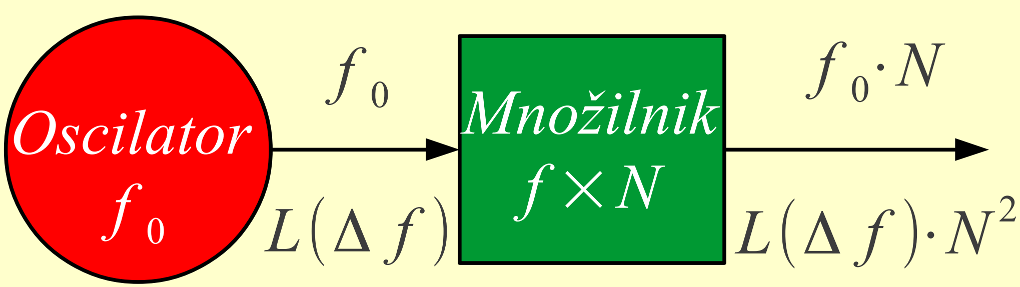


Potek faznega šuma vključno z 1/f

Kvaliteta obremenjenega rezonatorja Q_L je ključnega pomena za fazni šum!

$$L(\Delta f)=\frac{1}{2}\cdot\left[1+\boxed{\left(\frac{f_0}{2Q_L\Delta f}\right)^2}\right]\cdot\frac{k_B T_0 F}{P_0}\cdot\left(1+\frac{f_C}{|\Delta f|}\right)$$

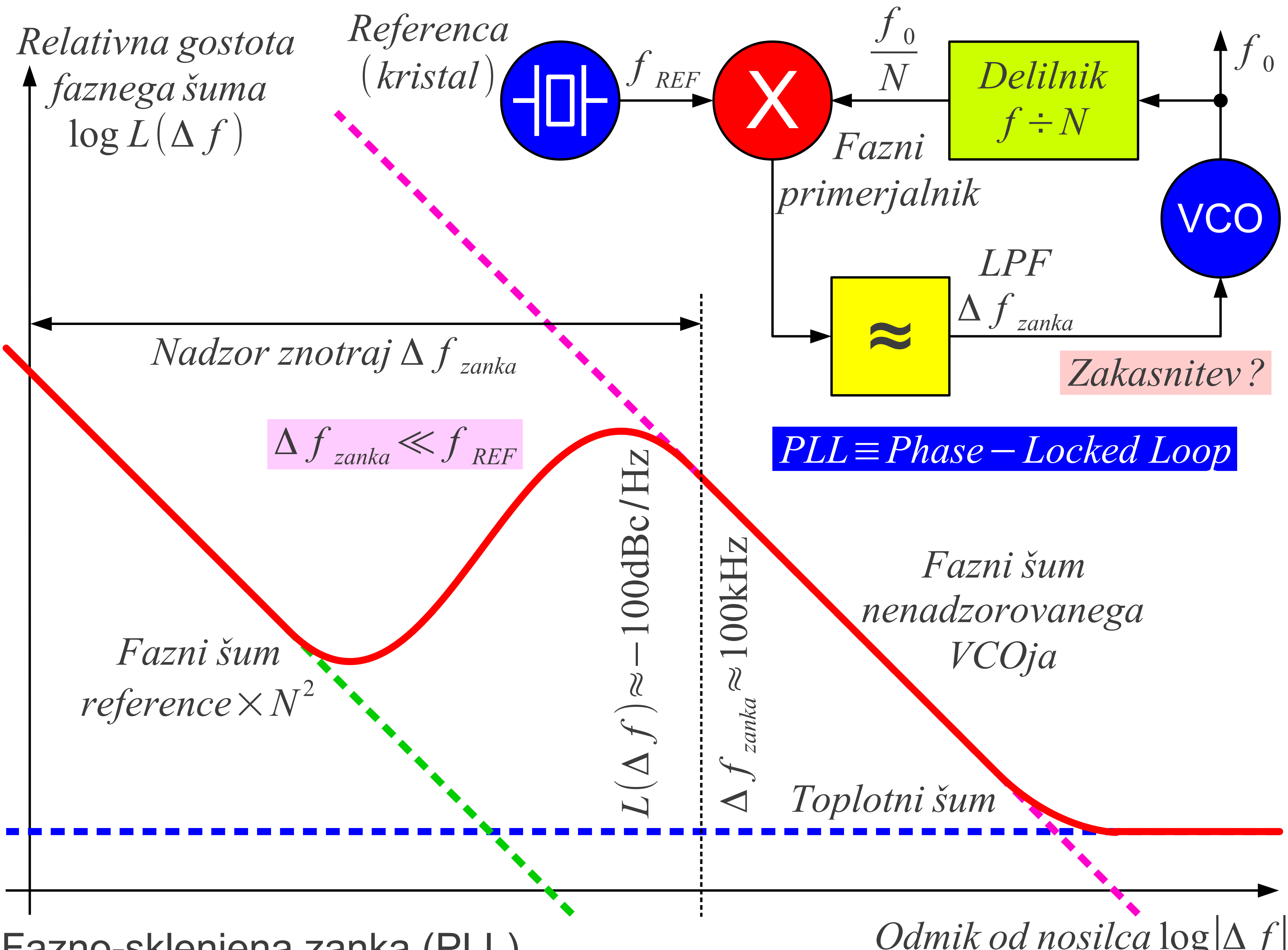
Frekvenčno nastavljivi oscilatorji	Q_L
RC VCO	~1
Cev BWO	~1
Varikap LC VCO	10↔30
YIG ($Y_3Fe_5O_{12}$) oscilator	300↔1000



Moč faznega šuma se množi s kvadratom množenja frekvence! Vloga Q_L ostaja nepsremenjena!

Oscilatorji fiksne frekvence	Q_L
RC oscilator	~1
LC nihajni krog	30↔100
Votlinski rezonator	1000↔3000
Keramični dielektrični rezonator	1000↔3000
AT kremenov kristal (osnovna rezonanca)	3000↔10000
AT kremenov kristal (tretji/peti overton)	10000↔30000
Elektro-optični zakasnilni vod ($)	$\sim 10^5$
Safirjev dielektrični rezonator ($$$)	$\sim 3\cdot 10^5$
Rdeč HeNe LASER	$\sim 10^8$

<u>Kvaliteta rezonatorja</u>



Fazno-sklenjena zanka (PLL)

Oscilator s šumom $A \cdot H(\omega_0) = 1 - \epsilon \qquad 0 < \epsilon \ll 1$

$$A \cdot H(\omega) \approx \frac{1-\epsilon}{1 + j2Q_L \frac{\Delta\omega}{\omega_0}}$$

$$U_{Nizh} = \frac{U_{Nvh}}{1 - A \cdot H(\omega)} \approx \frac{U_{Nvh}}{1 - \frac{1-\epsilon}{1 + j2Q_L \frac{\Delta\omega}{\omega_0}}} = U_{Nvh} \frac{1 + j2Q_L \frac{\Delta\omega}{\omega_0}}{j2Q_L \frac{\Delta\omega}{\omega_0} - \epsilon}$$

$$\frac{dP_{Nvh}}{df} \approx k_B T_0 F$$

Blizu ω_0 $\rightarrow \left| 2Q_L \frac{\Delta\omega}{\omega_0} \right| \ll 1 \rightarrow U_{Nizh} \approx \frac{U_{Nvh}}{j2Q_L \frac{\Delta\omega}{\omega_0} - \epsilon} \rightarrow P_{Nizh} \approx \frac{P_{Nvh}}{\epsilon^2 + \left(2Q_L \frac{\Delta\omega}{\omega_0}\right)^2}$

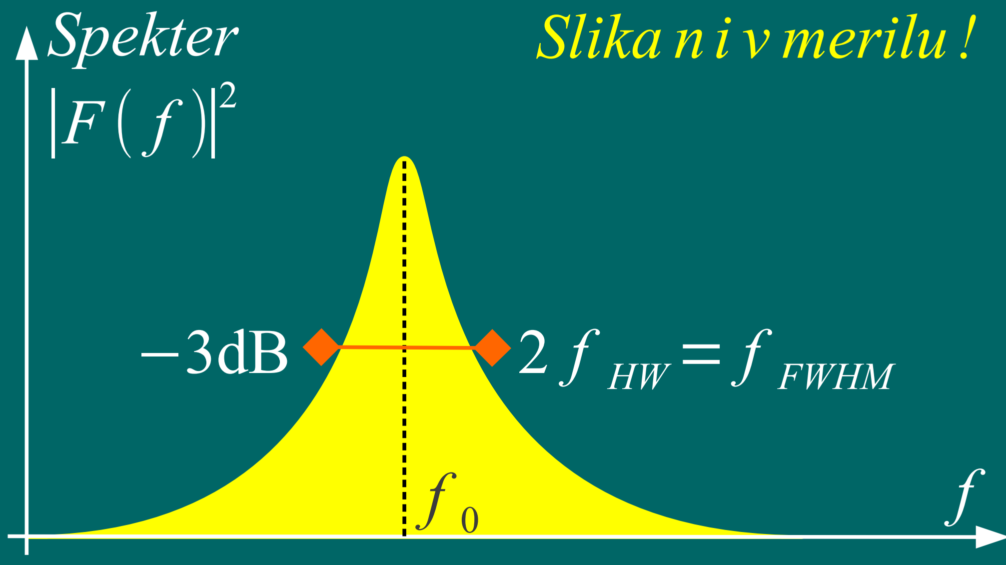
$$P_\phi = \frac{P_{Nizh}}{2} \approx \frac{P_{Nvh}/2}{\epsilon^2 + \left(2Q_L \frac{\Delta f}{f_0}\right)^2} = \frac{P_{Nvh} f_0^2}{8Q_L^2} \cdot \frac{1}{\left(\frac{\epsilon f_0}{2Q_L}\right)^2 + \Delta f^2}$$

Polovična širina

$$f_{HW} = \frac{\epsilon f_0}{2Q_L}$$

$$L(\Delta f) = \left(\frac{f_0}{Q_L}\right)^2 \cdot \frac{1}{f_{HW}^2 + \Delta f^2} \cdot \frac{k_B T_0 F}{8P_0} = \frac{C}{f_{HW}^2 + \Delta f^2} \equiv \text{Lorentzova spektralna črta}$$

Izpeljava Lorentzove črte



Lorentzova spektralna črta

$$L(\Delta f) = \left(\frac{f_0}{Q_L}\right)^2 \cdot \frac{1}{f_{HW}^2 + \Delta f^2} \cdot \frac{k_B T_0 F}{8 P_0}$$

$$f_{HW} \equiv f_{HALF-WIDTH}$$
$$f_{FWHM} \equiv f_{FULL-WIDTH-HALF-MAXIMUM}$$

$$L(\Delta f) = \frac{C}{f_{HW}^2 + \Delta f^2}$$

$$\epsilon = \frac{2 Q_L f_{HW}}{f_0}$$

$$\int_{-f_0}^{\infty} L(\Delta f)\, d\Delta f = 1 \approx \int_{-\infty}^{\infty} \frac{C}{f_{HW}^2 + \Delta f^2}\, d\Delta f = \left[\frac{C}{f_{HW}} \cdot \arctan \frac{\Delta f}{f_{HW}}\right]_{\Delta f = -\infty}^{\Delta f = \infty} = \frac{\pi C}{f_{HW}}$$

$$f_{HW} \approx \pi C = \frac{\pi k_B T_0 F}{8 P_0} \cdot \left(\frac{f_0}{Q_L}\right)^2$$

$$C = \frac{k_B T_0 F}{8 P_0} \cdot \left(\frac{f_0}{Q_L}\right)^2 \approx \frac{f_{HW}}{\pi}$$

$$L(\Delta f) \approx \frac{f_{HW}/\pi}{f_{HW}^2 + \Delta f^2}$$

Zgled $f_0 = 3\text{GHz}$

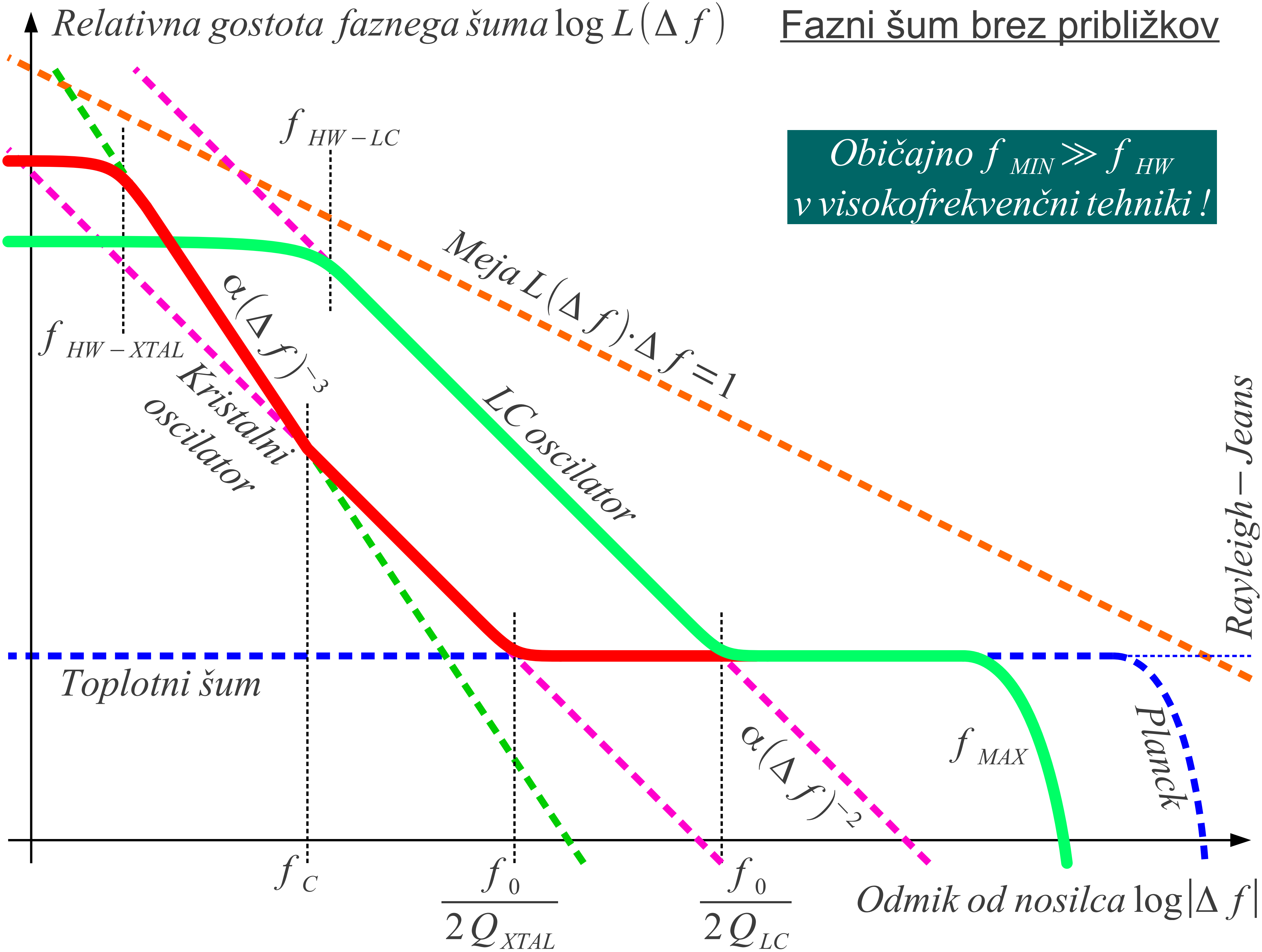
$Q_L = 10 \quad P_0 = 0.1\text{mW} \quad F = 10\text{dB}$

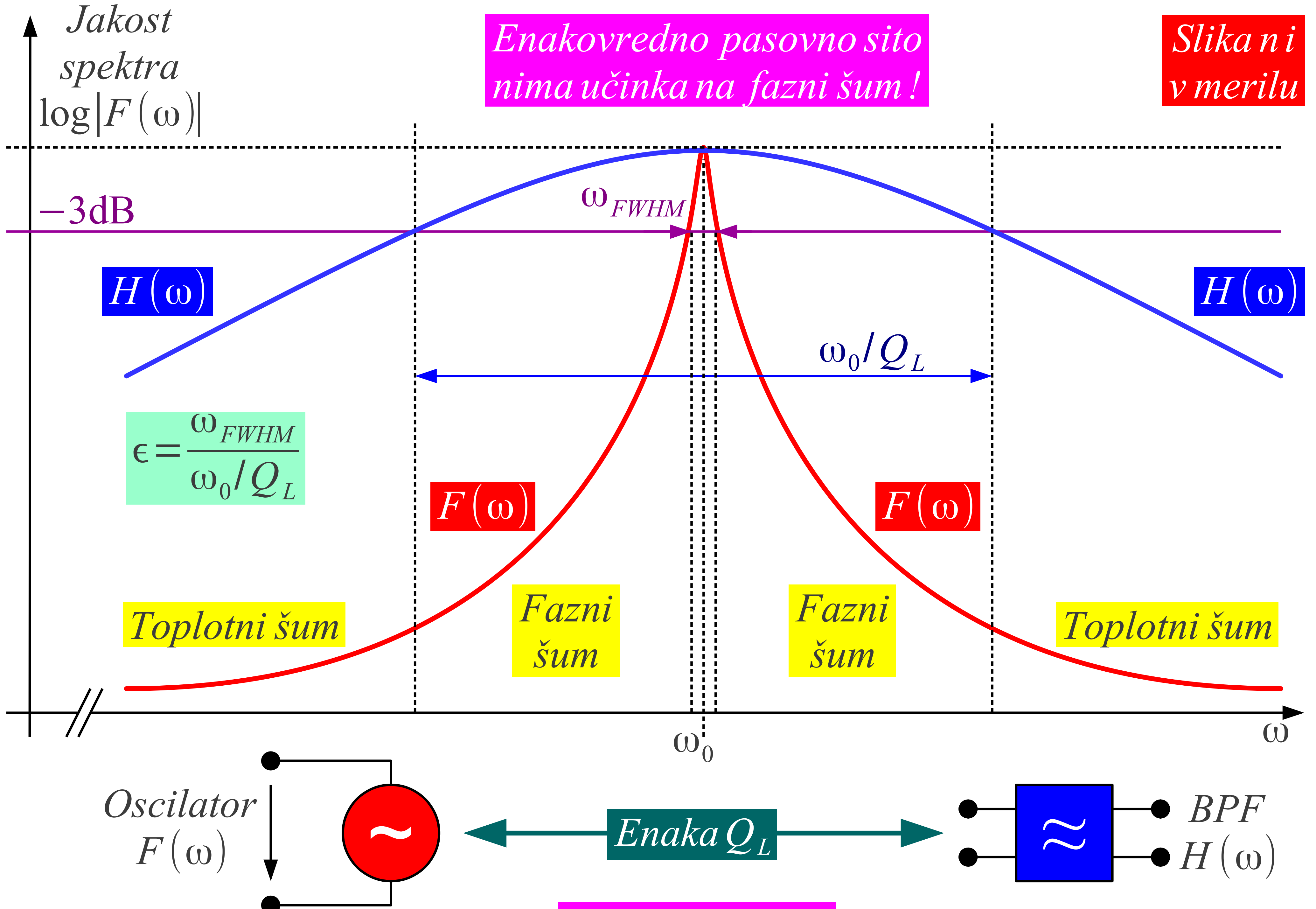
$f_{HW} \approx 14\text{Hz} \quad f_{FWHM} \approx 28\text{Hz} \quad \epsilon \approx 10^{-7}$

Brez upoštevanja šuma $1/f$ *!*

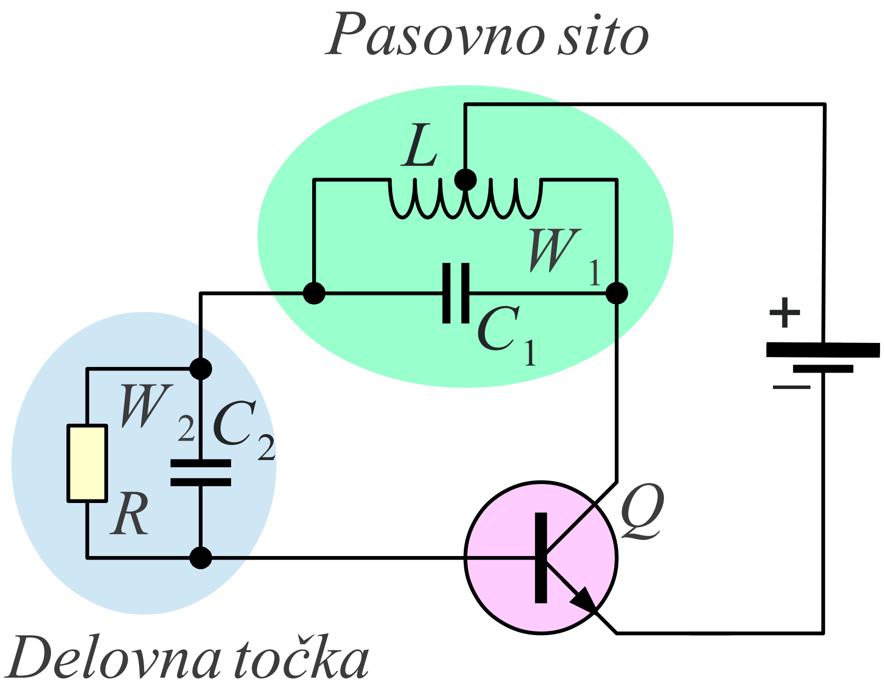
Širina Lorentzove spektralne črte

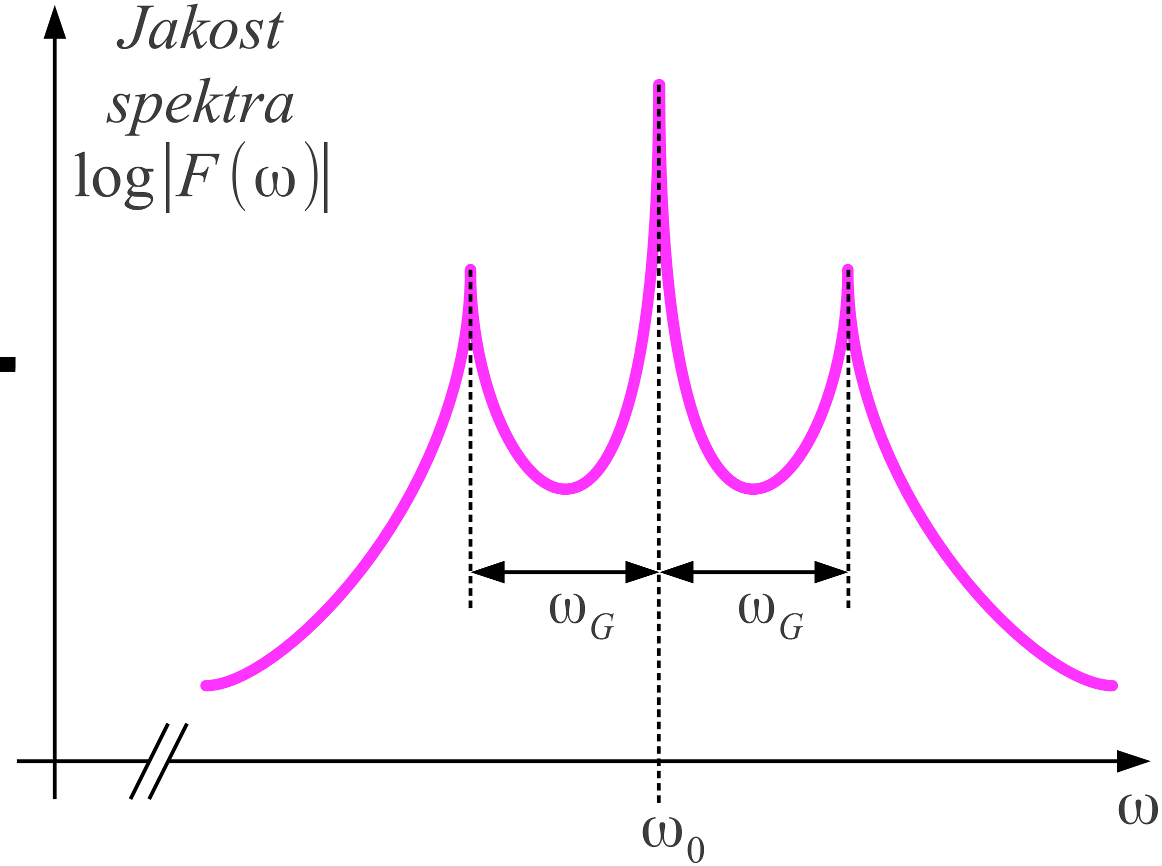
Fazni šum brez približkov





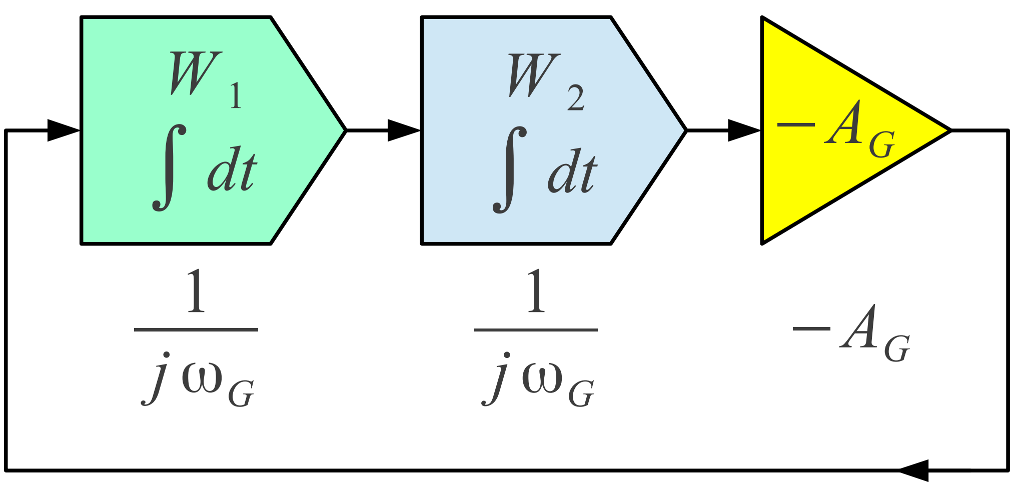
Primerjava oscilator↔BPF





Gašenje (quenching) ?

Povratna vezava nasičenja



Neprimeren (velik) C_2

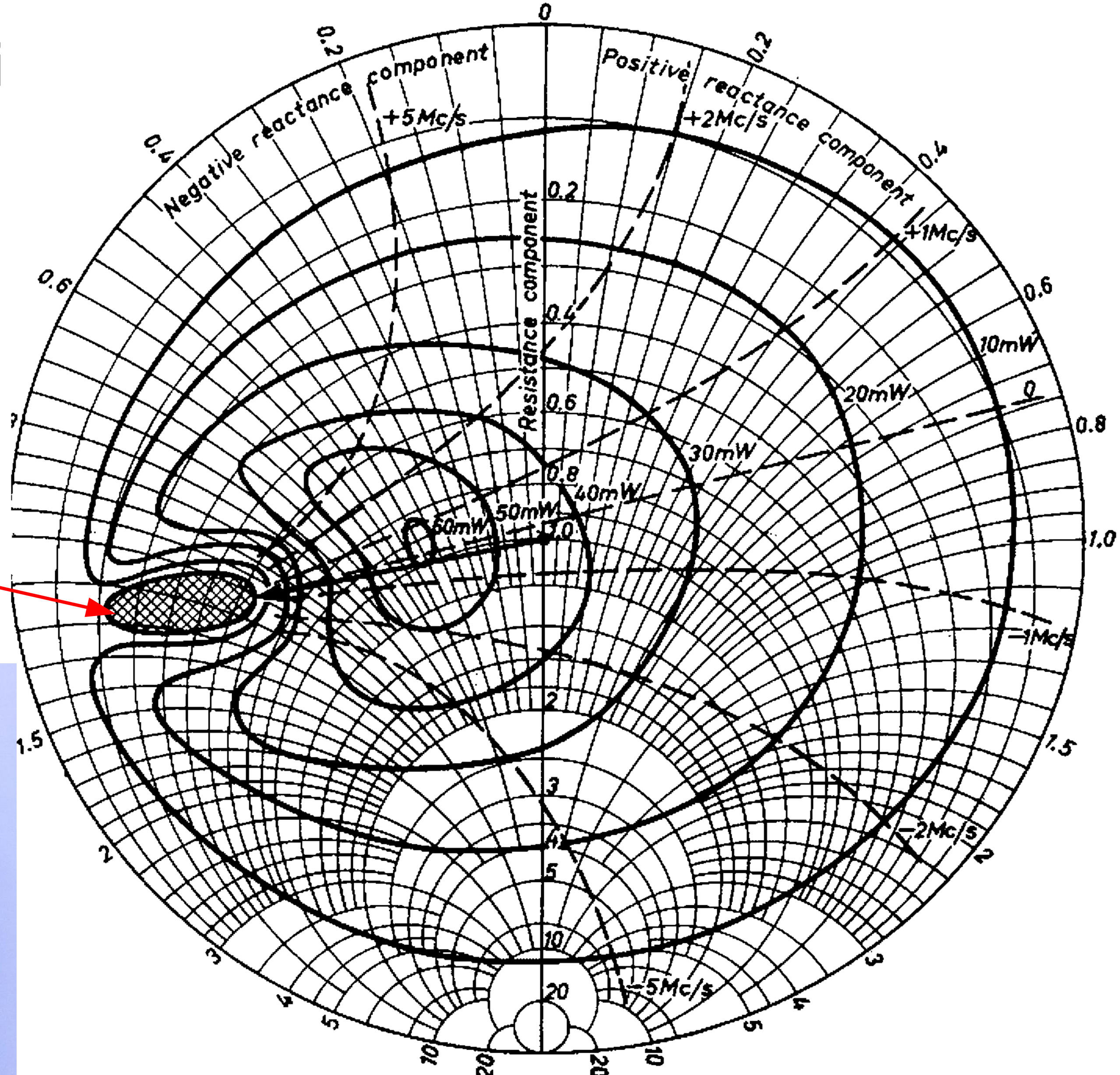
$$\frac{1}{j\omega_G}\cdot\frac{1}{j\omega_G}\cdot(-A_G)=1$$

$$\omega_G=\sqrt{A_G}$$

Nestabilno nasičenje in gašenje

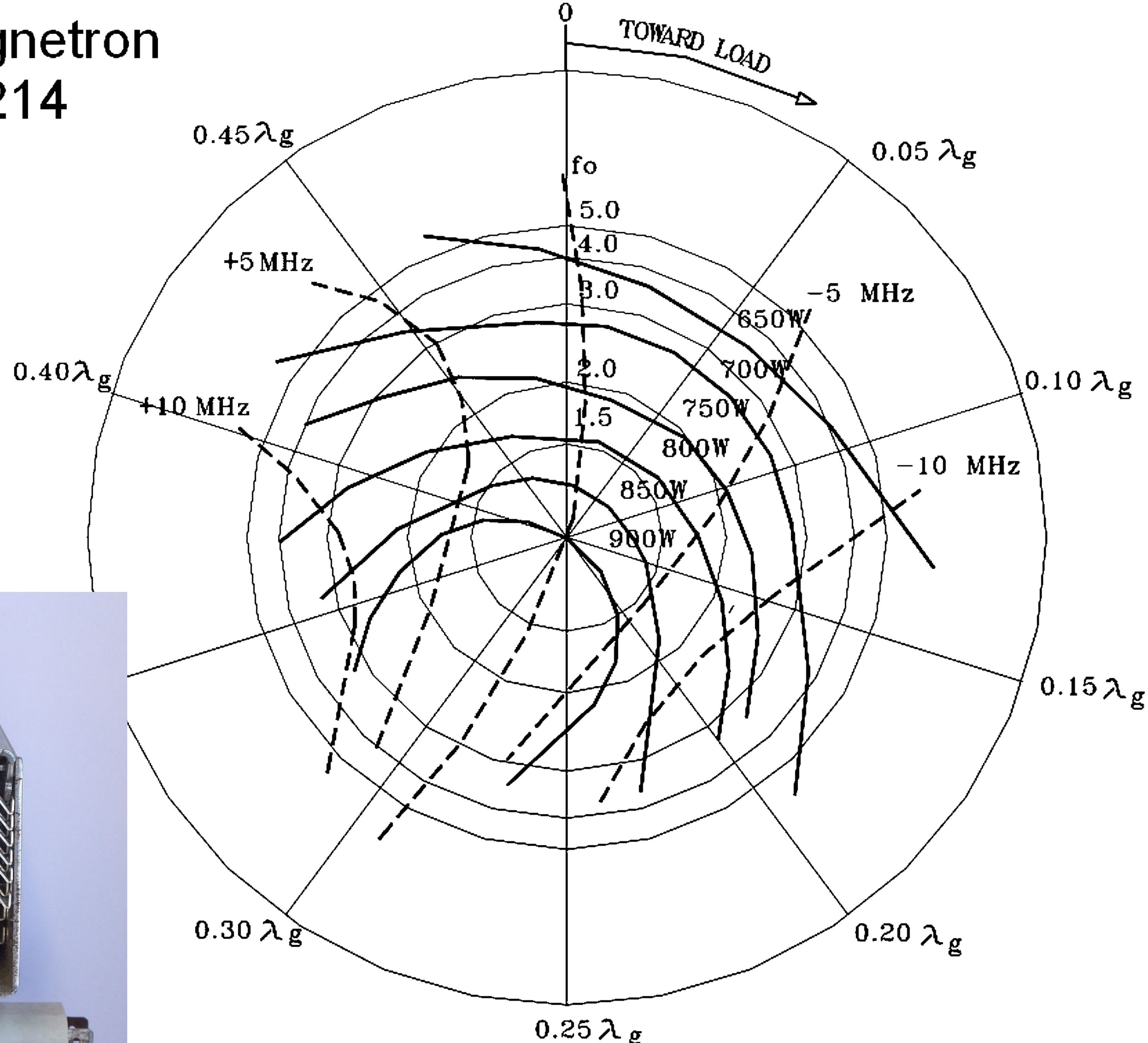
Refleksni klistron 2K25

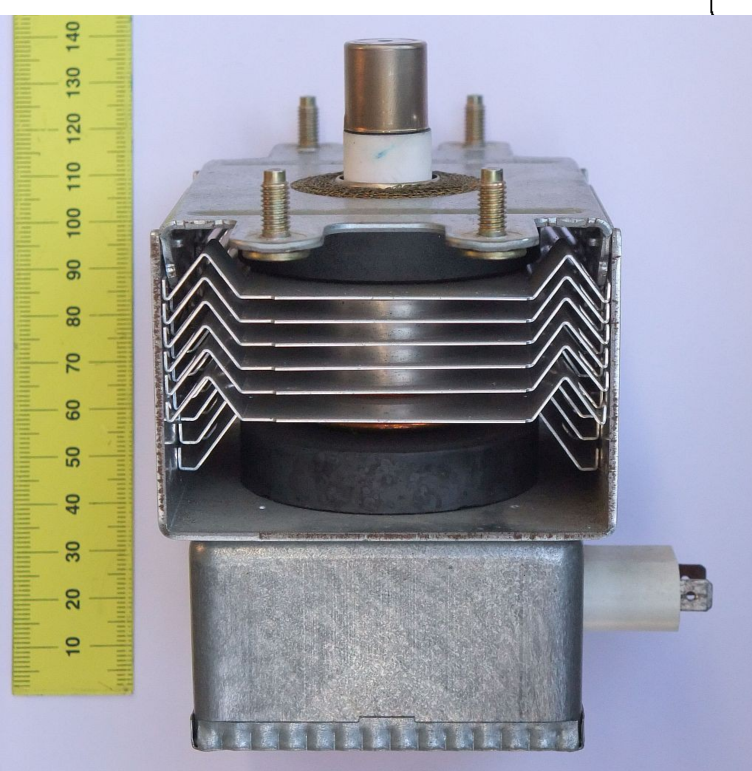
Oscilator ugasne



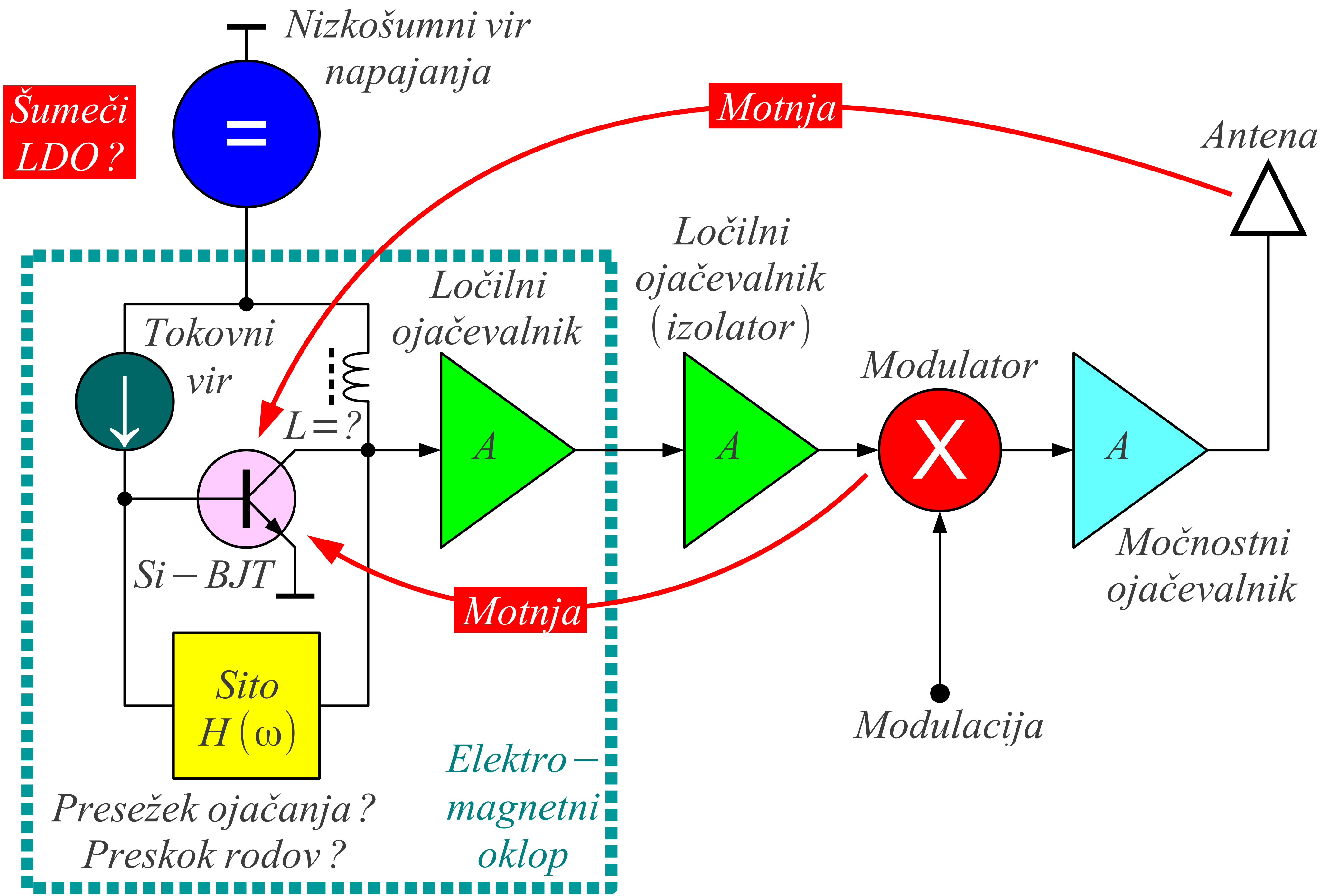
Riekejev diagram 2K25

Magnetron 2M214





Riekejev diagram 2M214



Pravila načrtovanja oscilatorja