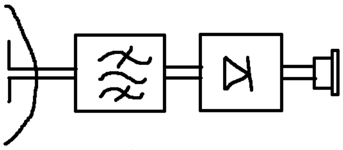
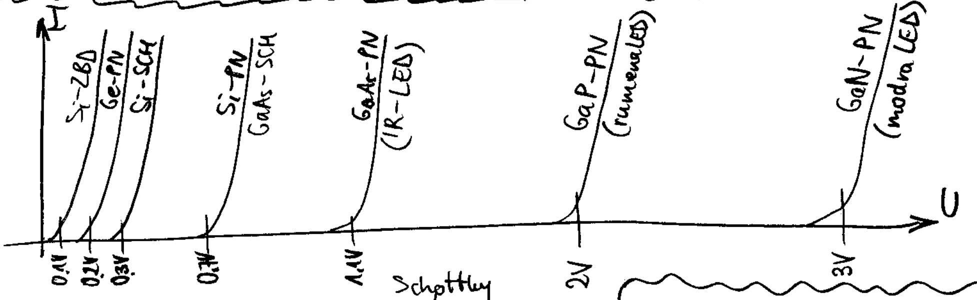
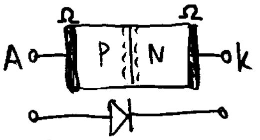
Visokofrekvenčna tehnika #1 5/10/2018

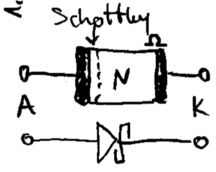


Visokofrekvenčni gradniki: ojačevalnik, frekvenčno sito, nelinearne naloge

Polprevodnik	$\Delta W = Q_e dU$
Si	1,11eV
Ge	0,67eV
GaAs	1,43eV
InP	1,344eV
InAs	0,354eV
GaP	2,26eV
GaN	3,4eV
6H-SiC	3,05eV
PbS	0,37eV
Diamant(C)	5,5eV





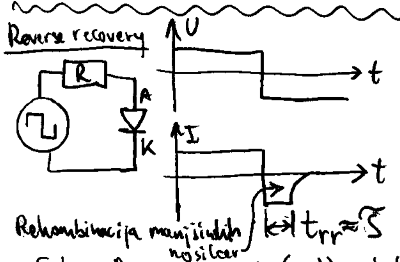


Prevodni režim

Schottky PIN $1 \leq n \leq 2$

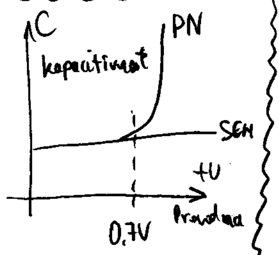
$$I = I_s\left(e^{\frac{qU}{nk_0T}} - 1\right)$$

Reverse recovery

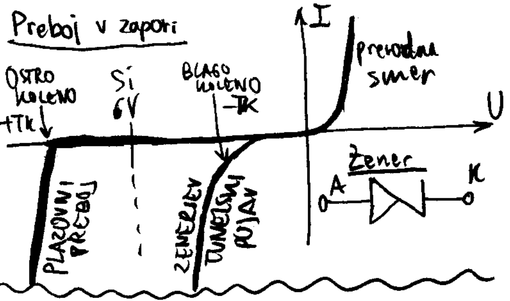


Step-Recovery Diode (SRD) – hiter preklop

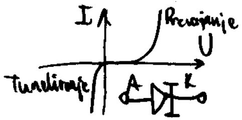
DIODA	$\tau \approx t_{rr}$
Si-PN	~1μs
SiPNthin	~ 1ns
Schottky	0!



Preboj v zapori

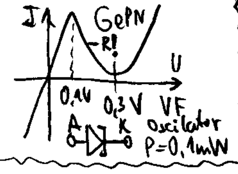


Back dioda

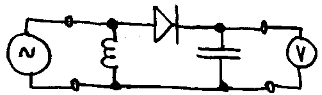


Občutljiv VF detektor

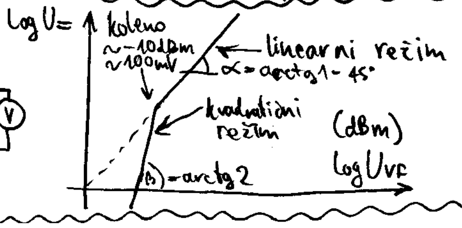
Tunelska dioda



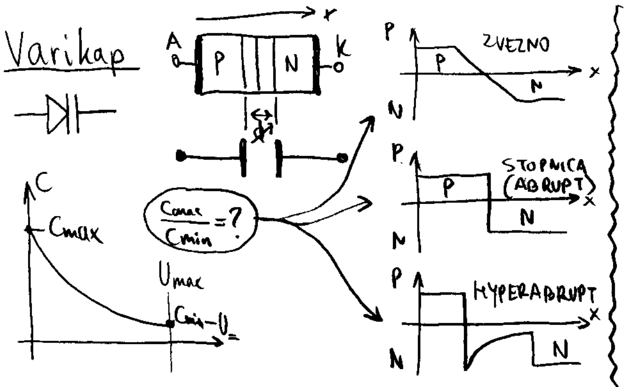
Diodni detektor VF

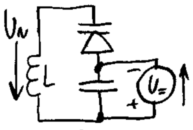


$\omega L \gg R \gg \frac{1}{\omega C}$



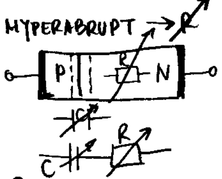
Varikap

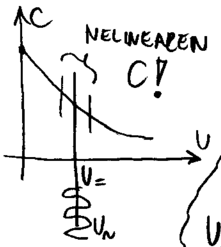




$C \gg C_d$

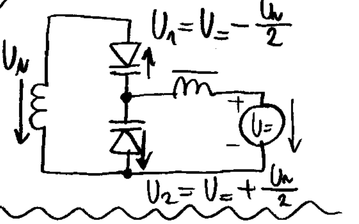
$Q = \omega \frac{W}{P} = ?$



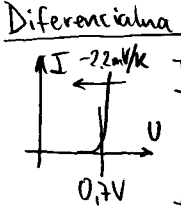


$U = U_= + U_\sim$

Zmanjševanje nelinearnosti
2 varikap zaporedno



Diferencialna upornost diode



$$I = I_s\left(e^{\frac{qU}{nk_0T}} - 1\right)$$

$$U_T = \frac{k_B T}{q} = 26mV$$

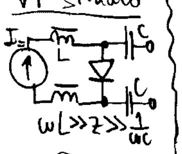
$$I \approx I_s e^{\frac{U}{U_T}} = I_s e^{\frac{U}{n26mV}}$$

$$R = \frac{\Delta U}{\Delta I} = \frac{dU}{dI} = \frac{nU_T}{I} = \frac{n26mV}{I}$$

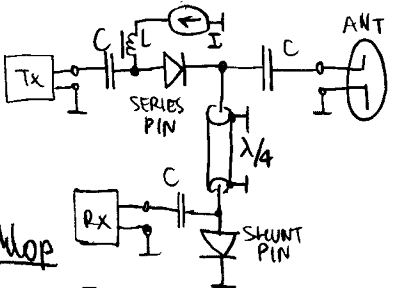
$$\frac{dI}{dU} = \frac{I_s}{nU_T} e^{\frac{U}{nU_T}} = \frac{I}{nU_T} = \frac{I}{n26mV}$$

I	R
1mA	40Ω
10mA	4Ω

VF stikalo



$\omega L \gg Z \gg \frac{1}{\omega C}$



Antenski preklop

Diferencialna kapacitivnost manjšinskih nosilcev

$C = C_s + C_m$

kap. spoja

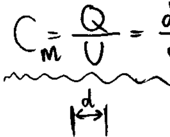
kap. manjšinskih

Rekombinacija $t_{rr} \approx \tau$

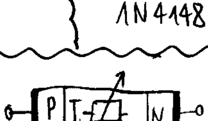
Skupni naboj $Q = I\tau$

$$C_m = \frac{Q}{U} = \frac{dQ}{dU} = \tau\frac{dI}{dU} = \frac{\tau I}{nU_0} = \frac{\tau I}{n26mV}$$

DIODA	C_s	τ	C_m@I=1mA	$\frac{1}{j\omega C}$@100MHz
1N4007	30pF	10μs	250nF	−j 6.3mΩ
BAR81	0.3pF	100ns	2.5nF	−j 0.63Ω
1N4148	4pF	5ns	150pF	−j 11 Ω

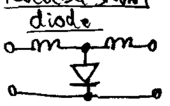


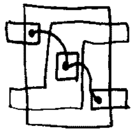
d=3μm	SWITCH	τ=100ns
d=100μm	VF R	τ=1μs



I=10mA → R~3Ω

Izvedba SHUNT diode



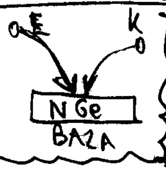


Visoko frekvenčna tehnika # 2 12/10/2018

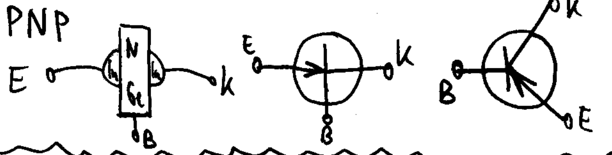
1948 → Bipolarni Ge PNP

Shockley

$\alpha = I_K / I_E$



Ge PNP



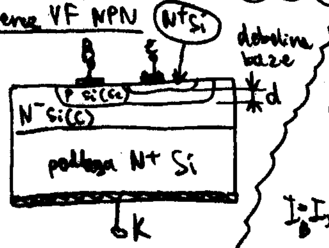
Tranzistorji

→ bipolarni: NPN, PNP

→ N/P kanal, poljski: JFET, MOSFET

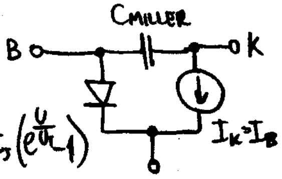
$\mu_{elektronov} > 3\mu_{vrzeli}$ v Si!

Prerez VF NPN



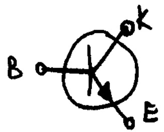
Nadomestno vezje $h_{FE} = \beta \equiv$ tokovno ojačenje

$\beta = 10 \ldots 1000 < \frac{|N^+|}{|P|}$

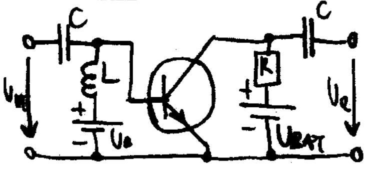


$I_B = I_S \left(e^{\frac{U}{U_T}} - 1\right)$

$I_K = I_B \beta$



VF ojačevalnik

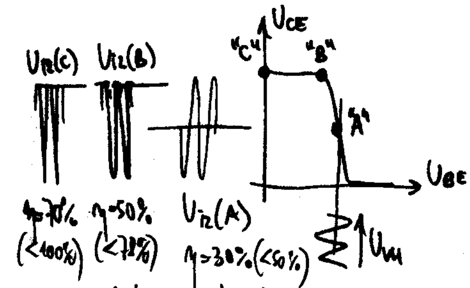


BAZNI TOK=?

TOPLOTNI POBEG?

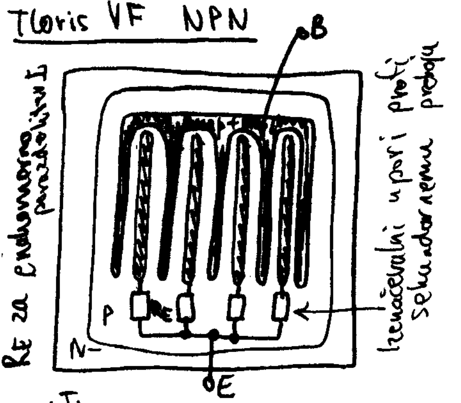
(THERMAL RUNAWAY)

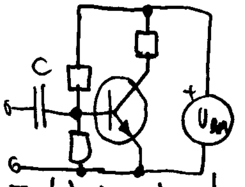
TK_{BE} −2,2mV/K



IZBira delovne točke

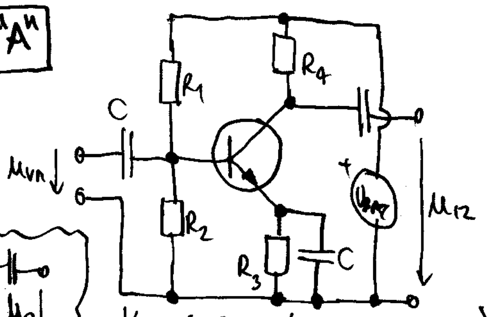
Tloris VF NPN



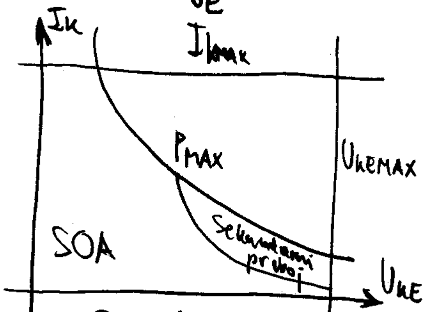


Toplotni pobeg!

Razred "A"

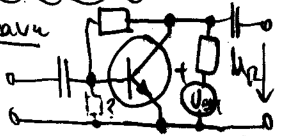


Komplicirano (izgubni tokovi Ge)

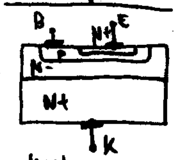


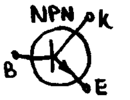
Secondary breakdown

Povratna vezava preprosto!



VF bipolarni

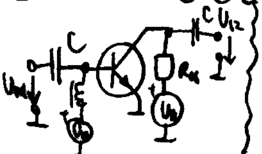




$\frac{I_K}{I_B} = \beta = B = h_{FE}$

$\frac{|N^+|}{|P|} > \beta \gg \beta_{OBRATNI}$ ← zamenjan E/K

$U_{BRKB} \approx 10\text{–}100V > U_{BREB} \sim 2\text{–}6V$



$R_{VH} = \frac{nU_T}{I_B} = \frac{n\,26mV}{I_B}$

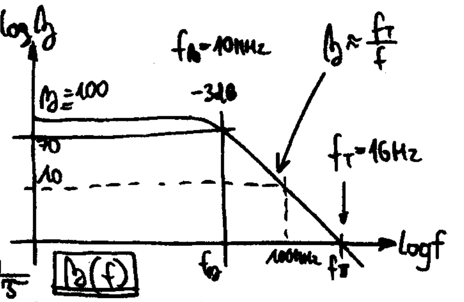
$\frac{U_{iz}}{U_{vh}} = \frac{I_K R_K}{I_B R_{vh}} = \beta \frac{R_K I_B}{nU_T} = \frac{I_K R_K}{nU_T}$

Zgled: razred "A"

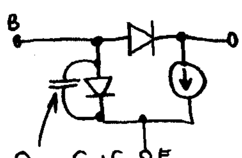
$I_K R_K = \frac{U_K}{2}$

$\frac{U_{iz}}{U_{vh}} = \frac{U_K}{2nU_T}$

$U_K = 12V \rightarrow \frac{U_{iz}}{U_{vh}} = 200$

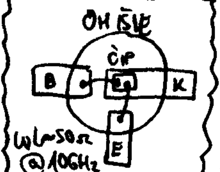


$f_\beta = \frac{1}{2\pi R_{EB} C_{EB}} = \frac{1}{2\pi \tau}$ $\boxed{\beta(f)}$

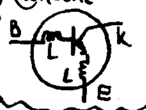


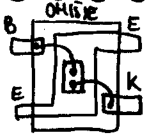
$C_{EB} = C_S + C_M$

$C_{EB} \approx \frac{\tau I_B}{nU_T} = \frac{\tau I_B}{n26mV}$

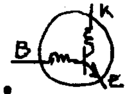


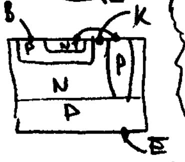
L≈1–5nH @1GHz





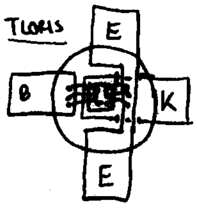
CE tranzistor



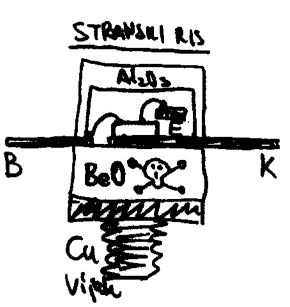


Močnostni VF bipolarni tranzistor

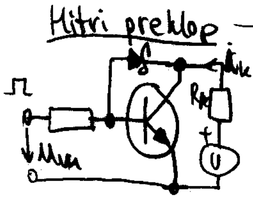
TLORIS

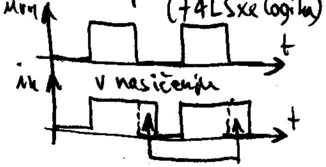


STRANSKI RIS



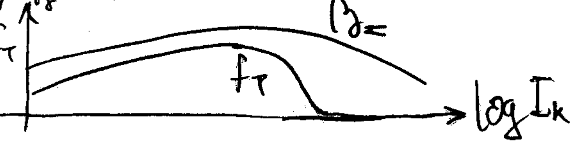
Hitri preklop → Schottky tranzistor (74LSxx logika)





τ manjšinskih v Bazi

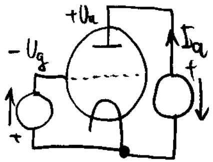
Učinek upornosti baze



Visokofrekvenčna tehnika # 3 18/10/2013

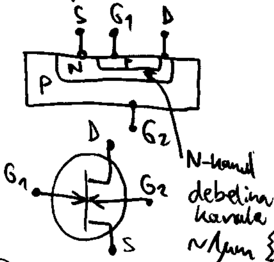
Zgodovina:

1907 — TRIODA

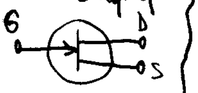


1912 — sprejemnik!

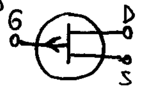
Spojni FET = JFET

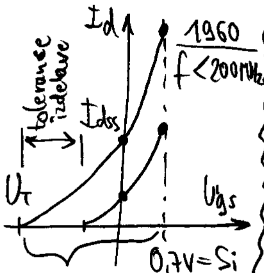


$G_1 \| G_2$ vezana skupaj



P-kanal



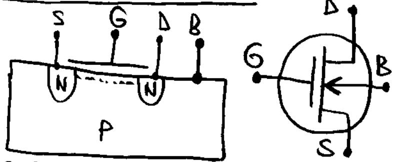


1960
f < 200MHz

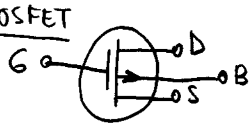
$I_d = k(U_{gs} - U_T)^2$

N-kanalni MOSFET

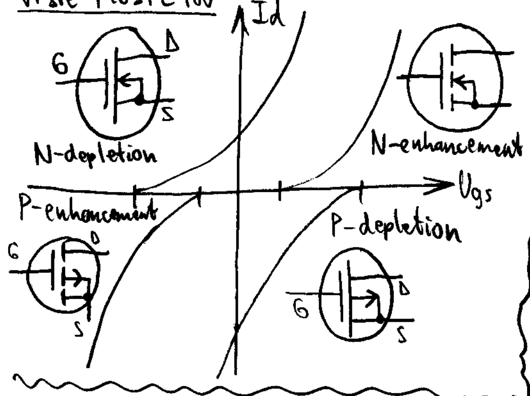
(1970: f<200MHz)



P-kanalni MOSFET



Vrste MOSFETov

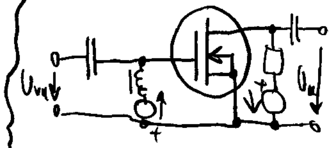


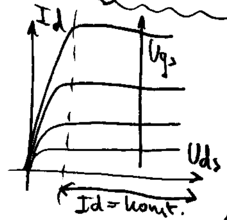
Razvoj 1970 → 2010

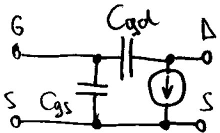
l = 20µm → l = 20nm

f = 100MHz → f = 100GHz

Ojačevalnik





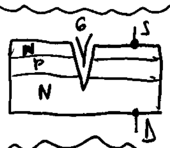


$I_D = k(U_{gs} - U_T)^2$

$R_{kanala} = +\alpha T$!

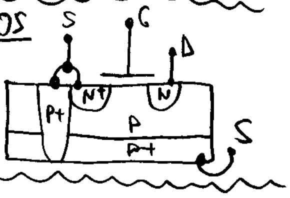
VMOS

NF

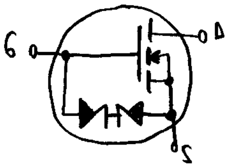


LDMOS

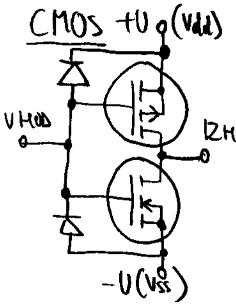
VF
3GHz
100W

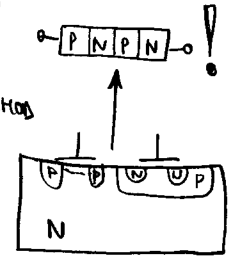


Zaščita pred statiko



CMOS





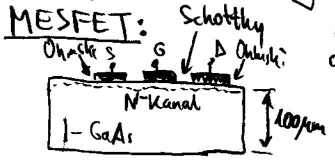
Polprevodniki 3-5?

Si: $\mu_e = 1300 cm^2/Vs$

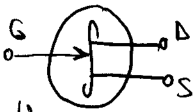
GaAs: $\mu_e = 5000 cm^2/Vs$

ΔW = 1,42eV

MESFET:



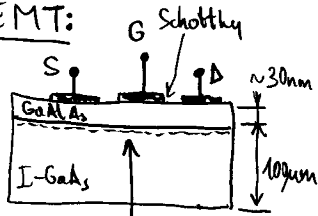
Dolžina kanala (vrat):
1975 → 1µm, 10GHz
2013 → 0,1µm, 100GHz



MESFET VF stikala!

$U_{DS\,max} \sim 10V$

HEMT:

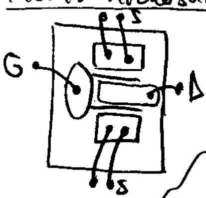


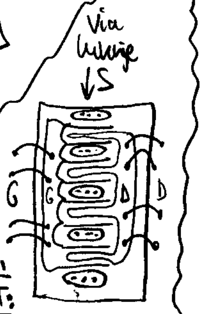
2D oblak elektronov
$\mu > 10000 cm^2/Vs$

GaAs → nizek šum

InP → visoka frekvenca

Tloris nizkošumni HEMT:





Močnostni HEMT:

SiC:

250 kristalnih oblik

3 uporabne za polprevodnike

4H-SiC $\mu_e = 260 cm^2/Vs$

$E_{max} = 3.5 \cdot 10^6 V/cm = 12 E_{Si}$ ΔW=3,2eV

SiC MESFET (2005):

10W, 2GHz, 28V

GaN:

ΔW=3.4eV

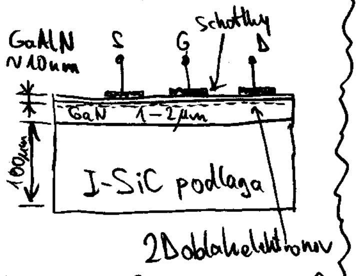
$\mu_e = 1500 cm^2/Vs$

$E_{max} = 2 \cdot 10^6 V/m = 7 E_{max\,Si}$

$T_{max} = 700°C$

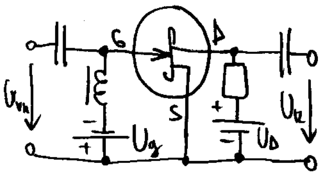
$U_{DS\,max} > 100V$

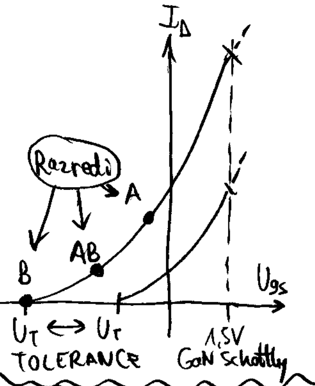
GaN / GaAlN HEMT:



2D oblak elektronov

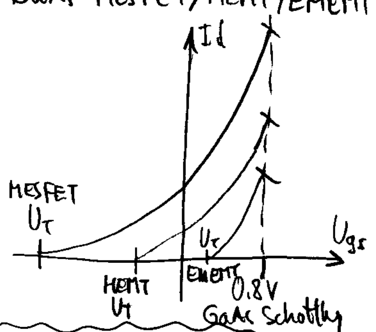
GaN/GaAlN ojačevalnik:



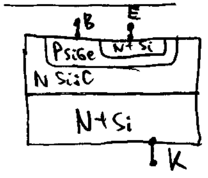


Primerjava:

GaAs MESFET/HEMT/EHEMT

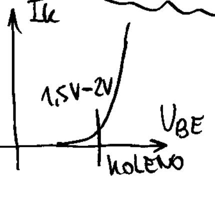


SiGe HBT



GaAsP HBT

InP HBT

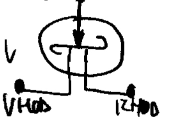


GaAs MESFET stikalo

- dolg kanal
- široka vrata

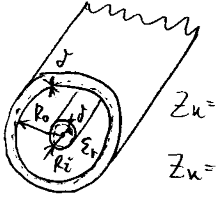
- preklop VF signalov

$P_{max} < 10W$



Visoko frekvenčna tehnika # 4 25/10/2013

Koaksialni kabel: $Z_u = \sqrt{\frac{L/l}{C/l}}$



$\delta_{Cu} \sim 7\mu m @ 100MHz$

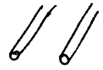
$$Z_u = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}}\ln\frac{R_o}{R_{\check{z}}}$$

$$Z_u = \frac{60\Omega}{\sqrt{\varepsilon_r}}\ln\frac{R_o}{R_{\check{z}}}$$

$\left(\frac{R_o}{R_{\check{z}}}\right)_{opt} = 3{,}511\ldots \rightarrow Z_u = 50\Omega\,(60\Omega)$

$20\Omega < Z_u < 93\Omega$

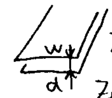
Žični dvovod:



$(Z_K)_{max} \sim 600\Omega$

UTP: $Z_K = 100\Omega$

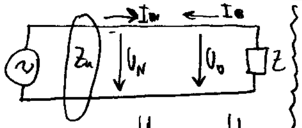
Ploščati dvovod:



$w \gg d$

$Z_u = \frac{d}{w}\sqrt{\frac{\mu_0}{\varepsilon_0}}$

$Z_u > 10\Omega$

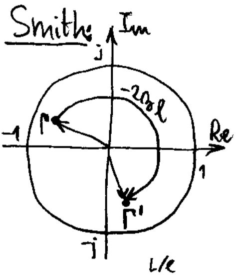


$$Z_u = \frac{U_N}{I_N} = -\frac{U_O}{I_O}$$

$$\Gamma = \frac{Z - Z_u}{Z + Z_u}$$

$$Z = Z_u\frac{1+\Gamma}{1-\Gamma}$$

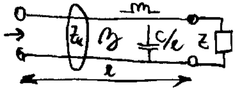
Smith:



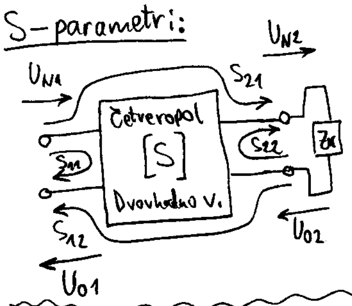
① $\Gamma = \frac{Z - Z_u}{Z + Z_u}$

② $\Gamma' = \Gamma e^{-j2\beta l}$

③ $Z' = Z_u\frac{1+\Gamma'}{1-\Gamma'}$



S-parametri:



$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}\begin{bmatrix} U_{N1} \\ U_{O2} \end{bmatrix} = \begin{bmatrix} U_{O1} \\ U_{N2} \end{bmatrix}$$

$S_{11} \approx \Gamma_{VHODNI}$

$S_{21} \approx \frac{U_{N2}}{U_{N1}} \sim$ ojačanje

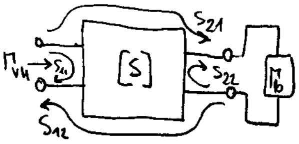
Simetrija: $S_{11} = S_{22}$

Recipročnost: $S_{21} = S_{12}$

Prilagojenost:

$S_{11} \longrightarrow 0$

$S_{22} \longrightarrow 0$

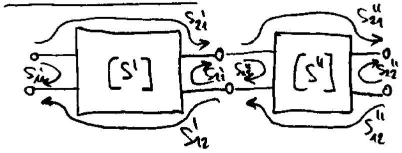


$\Gamma_{VH} = S_{11} + S_{21}\Gamma_b S_{12} + S_{21}\Gamma_b S_{22}\Gamma_b S_{12} + \ldots$

$\Gamma_{VH} = S_{11} + S_{21}\Gamma_b S_{12}(1 + \Gamma_b S_{22} + \Gamma_b^2 S_{22}^2 + \Gamma_b^3 S_{22}^3 + \ldots)$

$$\boxed{\Gamma_{VH} = S_{11} + \frac{S_{21}\Gamma_b S_{12}}{1 - \Gamma_b S_{22}}}$$

Verižna vezava:

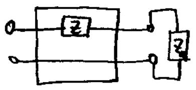


$$S_{11} = S'_{11} + \frac{S'_{21}S''_{11}S'_{12}}{1 - S''_{11}S'_{22}}$$

$$S_{22} = S''_{22} + \frac{S''_{12}S'_{22}S''_{21}}{1 - S'_{22}S''_{11}}$$

$$S_{21} = \frac{S'_{21}S''_{21}}{1 - S''_{11}S'_{22}} \qquad S_{12} = \frac{S''_{12}S'_{12}}{1 - S'_{22}S''_{11}}$$

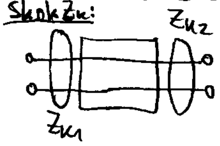
Zaporedna impedanca Z:



$$S_{11} = S_{22} = \frac{Z}{Z + 2Z_u}$$

$$S_{21} = S_{12} = \frac{2Z_u}{Z + 2Z_u}$$

Skok Z_u:



$$S_{11} = \frac{Z_{u2} - Z_{u1}}{Z_{u2} + Z_{u1}}$$

$$S_{22} = \frac{Z_{u1} - Z_{u2}}{Z_{u1} + Z_{u2}}$$

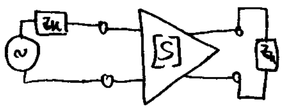
Moči: $P_{N2} = P_{N1} - P_{O1} = P_{N1}(1 - |\Gamma|^2)$

$$S_{21} = \frac{U_{N2}}{U_{N1}} = \sqrt{\frac{P_{N2}}{P_{N1}}} = \sqrt{1 - |\Gamma|^2} = \sqrt{1 - S_{11}^2}$$

$S_{12} = S_{21}$

Vstavitveno ojačanje G:

(insertion gain)



$$G = \frac{P_{N2}}{P_{N1}} = \left|\frac{U_{N2}^2}{U_{N1}^2}\right| = |S_{21}|^2$$

$G_{dB} = 10\log G = 20\log|S_{21}|$

Rollett-ova stabilnost: (1962)

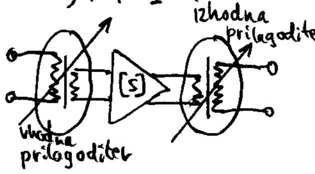
$|S_{11}| < 1$; $|S_{22}| < 1$ ≡ predpogoj

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{21}S_{12}|} > 1$$

$$\Delta = S_{11}S_{22} - S_{21}S_{12}\ ;\ |\Delta| < 1$$

Brezpogojno stabilni ojačevalnik:

$K > 1$; $|\Delta| < 1$ ≡ Unconditional Stability



Maximum Available Gain: $MAG = (K - \sqrt{K^2 - 1})\frac{|S_{21}|}{|S_{12}|}$

(razpoložljivo ojačanje)

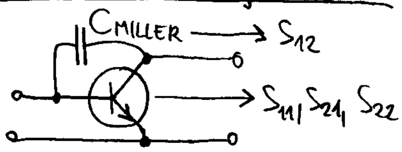
Pogojno stabilni ojačevalnik:

$K < 1$

Maximum Stable Gain: $MSG = \frac{|S_{21}|}{|S_{12}|}$

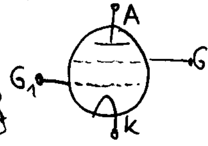
(stabilno ojačanje

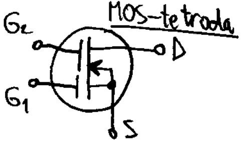
Glavni vzrok $K < 1$ je $S_{12} \neq 0$!



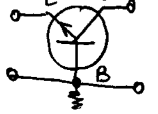
Protiukrep #1: znižanje C_{MILLER}

Tetroda: W. Schottky 1915

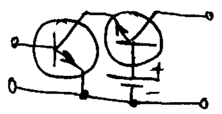




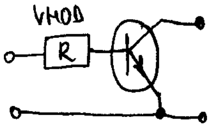
Ozemljena baza

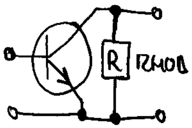


Kaskada

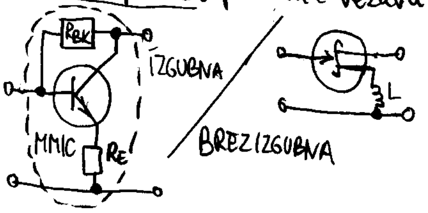


Protiukrep #2: obremenitev

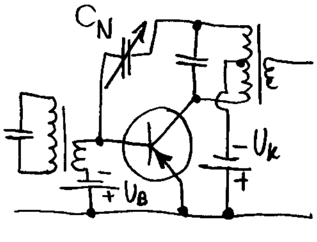


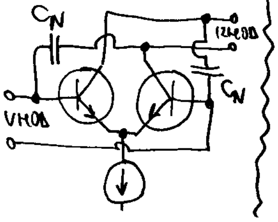


Protiukrep #3: povratna vezava

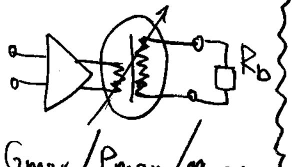


Protiukrep #4: nevtralizacija



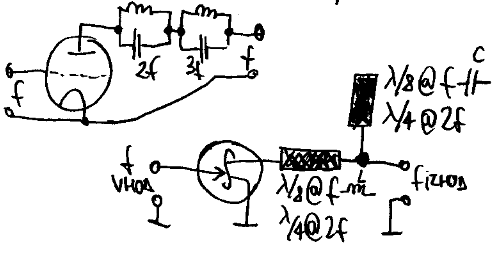


Močnostni ojačevalnik:



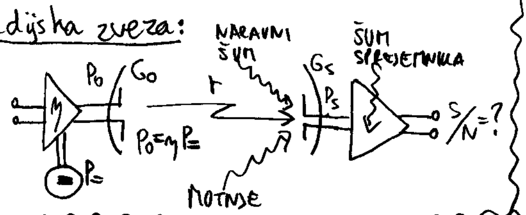
$G_{max} / P_{max} / \eta_{max}$

Prilagoditev harmonikov: $\eta\uparrow$

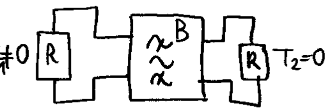


Visokofrekvenčna tehnika #5   8/11/2013

Radijska zveza:



Toplotno ravnovesje



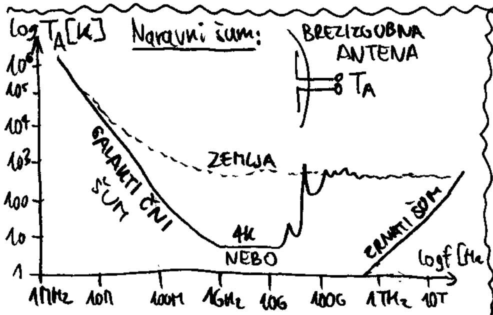
$\longrightarrow P_N=Bk_BT_1$

$$\boxed{k_B=1.3806488\cdot 10^{-23}\,J/K}$$

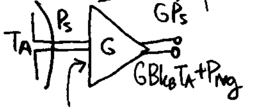
$T\,[k]$ $T_0=293K=20°C$

$B\,[Hz]$ $k_BT_0=-173{,}93dBm/Hz$

Naravni šum:



Šum sprejemnika:

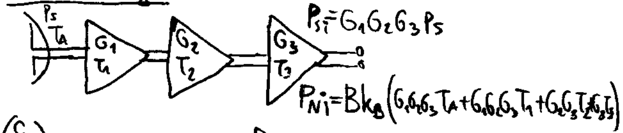


Šum preračunan na vhod!

$$S/N=\frac{GP_S}{GBk_B(T_A+T_S)}$$

Šum nekoreliran → vsota moči

Šum verige:



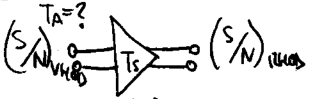
$P_{Si}=G_1G_2G_3P_S$

$P_{Ni}=Bk_B(G_1G_2G_3T_A+G_1G_2G_3T_1+G_2G_3T_2+G_3T_3)$

$$\left(S/N\right)_{izhod}=\frac{P_S}{Bk_B\left(T_A+T_1+\frac{T_2}{G_1}+\frac{T_3}{G_1G_2}\right)}$$

$$T_S=T_1+\frac{T_2}{G_1}+\frac{T_3}{G_1G_2}+\frac{T_4}{G_1G_2G_3}+\dots$$

Nesmiselna definicija F:



$$1\leq F=\frac{(S/N)_{VHOD}}{(S/N)_{IZHOD}}=1+\frac{T_S}{T_A}$$

Smiselna definicija F:

$$\boxed{F=1+\frac{T_S}{T_0}}\;;\;T_0=293K\,(=T_A)$$

$$F_{dB}=10\log F=10\log\left(1+\frac{T_S}{T_0}\right)$$

$$T_S=T_0\left(10^{\frac{F_{dB}}{10}}-1\right)=T_0(F-1)$$

F verige: (lin. enote) $F=F_1+\frac{F_2-1}{G_1}+\frac{F_3-1}{G_1G_2}+\frac{F_4-1}{G_1G_2G_3}+\dots$

Neskončna veriga: $F_\infty=1+(F-1)\left(1+\frac{1}{G}+\frac{1}{G^2}+\frac{1}{G^3}+\dots\right)=1+\frac{F-1}{1-1/G}$

Zgled: $G=10dB=10$, $F_e=4dB=2{,}5$ $F_\infty=1+\frac{2{,}5-1}{1-1/10}=\underline{\underline{2{,}67=4{,}3dB}}$

Slabilec (izgubni kabel):

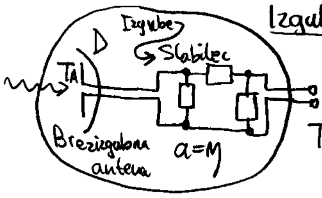
$$S/N=\frac{P_SaG}{GBk_B(aT_A+(1-a)T_K+T_S)}$$

$$\boxed{T_S'=\left(\frac{1}{a}-1\right)T_K+\frac{T_S}{a}}$$

$$F'=1+\left(\frac{1}{a}-1\right)\frac{T_K}{T_0}+\frac{F-1}{a}$$

Učinki:
① slabi signal $P_S'=P_Sa$
② slabi $T_A'=T_Aa$
③ seva lasten šum $T_K\neq 0$ $T_K=T_0\rightarrow\boxed{F'=\frac{F}{a}\;;\;F'_{dB}=F_{dB}-a_{dB}}$

Izgubna antena:



$G=\eta D$

$T_A'=\eta T_A+(1-\eta)T_0$

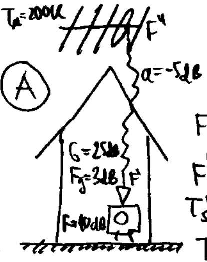
REF

$F'_{dB}=F_{dB}-a_{dB}$

$F'_{dB}=15dB$

$T_S'=8973K$

$T=T_A+T_S'=\underline{\underline{9173K}}$



$G=25dB=\underline{316}$

$F_g=3dB=\underline{2}$

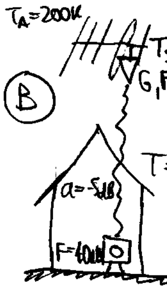
$F=10dB=\underline{10}$

$F'=F_g+\frac{F-1}{316}=2{,}03=\underline{3{,}07dB}$

$F''=F'-a=\underline{8{,}07dB}$

$T_S''=\underline{1587K}$

$T=T_A+T_S''=\underline{\underline{1787K}}$



$T_S'',F''=F_g+\frac{F'-1}{G}=\underline{2{,}1=3{,}2dB}$

$\underline{T_S''=321K}$

$T=T_A+T_S=\underline{\underline{521K}}$

Primerjava:

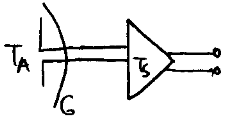
Primerjava:	ΔF_{dB}	$\Delta(S/N)_{dB}=10\log\frac{T_1}{T_2}$
REF → A	$15dB-8{,}07dB=\underline{6{,}93dB}$	$10\log\frac{9173}{1787}=\underline{7{,}12dB}$
REF → B	$15dB-3{,}2dB=\underline{11{,}8dB}$	$10\log\frac{9173}{321}=\underline{12{,}5dB}$

$F_1=1dB\rightarrow T_1=76K$ $T_1+T_N=96K$

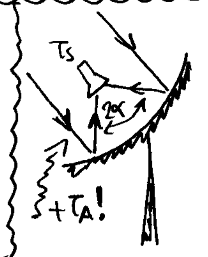
$F_2=0{,}5dB\rightarrow T_2=36K$ $T_2+T_N=56K$

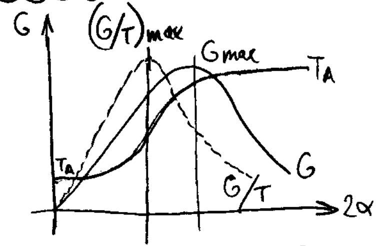
$\underline{\underline{\Delta F=0{,}5dB}}\longrightarrow 10\log\frac{T_1+T_N}{T_2+T_N}=\underline{\underline{2{,}3dB}}$

Satelitski sprejemnik:



$G/T\;[dB/K]$





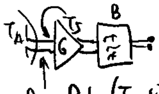
Osvetlitev zrcala:

$G_{max}\rightarrow\sim-10dB$ na robu

$(G/T)_{max}\rightarrow\sim-15\dots-20dB$ na robu

Visokofrekvenčna tehnika #6 15/11/2013

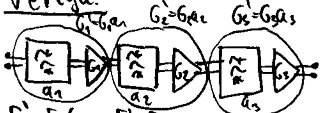
Ponovitev:



$P_N = B k_B (T_A + T_s)$

$F_{dB} = 10 \log_{10}\left(\frac{T_s}{T_0} + 1\right)$

Veriga:

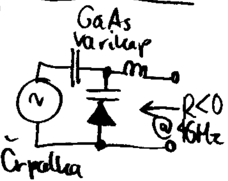


$F_1' = F_1/a_1$ $F_2' = F_2/a_2$ $F_3' = F_3/a_3$

$$F = F_1' + \frac{F_2' - 1}{G_1'} + \frac{F_3' - 1}{G_1' G_2'}$$

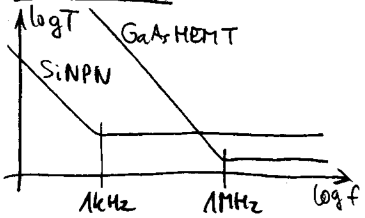
ojačevalnik	G [dB]	T [K]	F [dB]
trioda	15	2000	8
klystron, TWT	50	3000-30000	10-20
Si NPN	15	100-300	1,5-3
GaAs HEMT	15	30-100	0,5-1,5
parametrični	15	30-100	0,5-1,5
hlajeni HEMT	20	10-30	0,15-0,5
MMIC	10-20	1000-2000	5-8
OP.AMP.	~80	$10^4 - 10^7$	15-55

Parametrični:

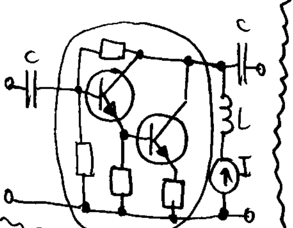


Črpalka ~60 GHz

Šum 1/f:

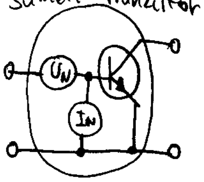


MMIC:



Šumni izvori:

šumeči tranzistor



$$F = F_{min} + 4\frac{R_N}{Z_K} \frac{|\Gamma_g - \Gamma_0|^2}{(1 - |\Gamma_g|^2)|1 + \Gamma_0|^2}$$

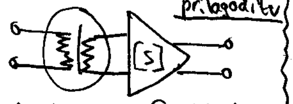
F_{min} ≡ min. šumno število @ Γ_0

Γ_0 ≡ optimalna odbojnost izvora

R_N ≡ šumna upornost → normirana r_N

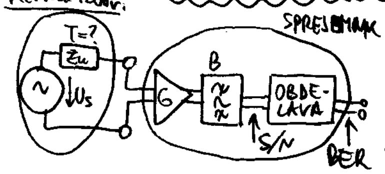
$$F = F_{min} + 4 r_N \frac{|\Gamma_g - \Gamma_0|^2}{(1 - |\Gamma_g|^2)|1 + \Gamma_0|^2}$$

Prilagoditev Z Šumna prilagoditev



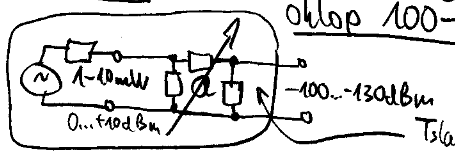
$\Gamma_0 \neq S_{11}$; $G < MAG$

Merilni izvor:



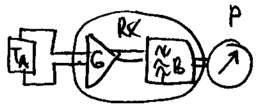
Zahteve izvora:

oklop 100-140dB !!!



$T_{slabilca} = T_0 = 293K$

Meritev T_s:

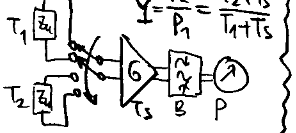


$P = G B k_B (T_A + T_s)$

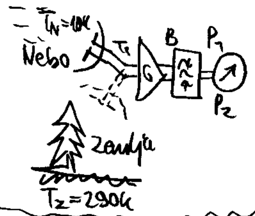
Slabo poznamo G in B!

Vroče/hladno:

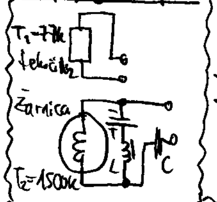
$Y = \frac{P_2}{P_1} = \frac{T_2 + T_s}{T_1 + T_s}$



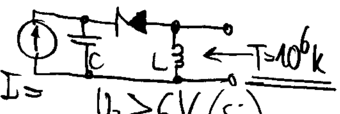
Nebo/Zemlja



Hlajen/gret upor

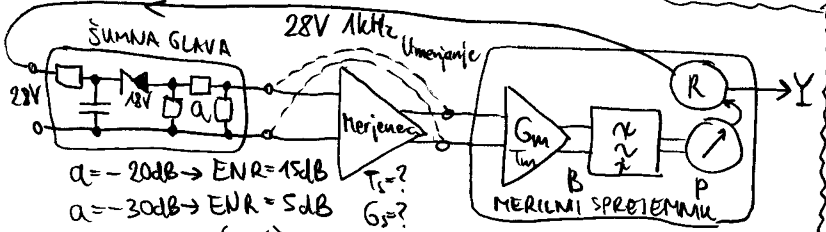


Plazovna dioda:



$U_Z > 6V$ (Si)

$U_Z \sim 18V$



a = -20dB → ENR = 15dB

a = -30dB → ENR = 5dB

$ENR = 10 \log_{10}(T_2/T_0)$

Brez umerjanja:

$$T = \frac{T_2 - Y T_1}{Y - 1}$$

$$T = T_s + \frac{T_m}{G_s}$$

Z umerjanjem:

$P_1 = G_m B k_B (T_1 + T_m)$

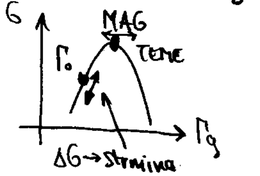
$P_2 = G_m B k_B (T_2 + T_m)$

$P_3 = G_m G_s k_B \left(T_1 + T_s + \frac{T_m}{G_s}\right)$

$P_4 = G_m G_s k_B \left(T_2 + T_s + \frac{T_m}{G_s}\right)$

4 neznanke:
- → T_s
- → G_s
- → T_m
- → $G_m B k_B$

ΔΓ šumne glave: → $\Delta\Gamma_g$ = ?



Naključni signal

$P_N = \langle p_N(t) \rangle$

točnost $\frac{\Delta P_N}{P_N} = \frac{\pm 1}{\sqrt{B t_m}}$

Zgled B = 4MHz t_m = 400μs

$\frac{\Delta P_N}{P_N} = 2{,}5\%$

$\frac{\Delta Y}{Y} = 3{,}5\%$

Povprečenje N

$$\frac{\Delta P_N}{P_N} = \frac{1}{\sqrt{B t_m N}}$$

$$\frac{\Delta P_N}{P_N} = \frac{1}{\sqrt{N}} \left(\frac{\Delta P_N}{P_N}\right)_{N=1}$$

Zasičenje:

$P_N < \frac{1}{10} P_{1dB}$

za napako 1%

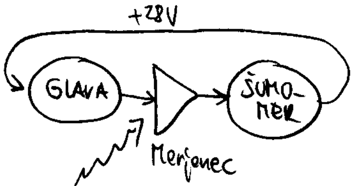
Zgled ENR = 5dB F = 15dB $\frac{\Delta Y}{Y} = 3{,}5\%$

$Y \approx 1{,}06$

$Y = 1.025 \ldots 1.095$

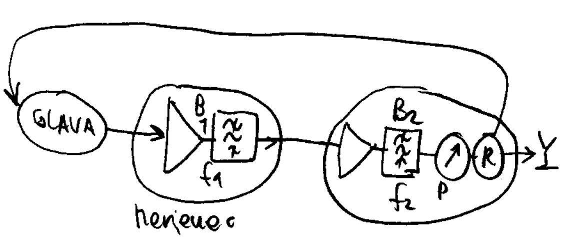
imenovalec $Y - 1 = 0{,}025 \ldots 0{,}095$

→ 380% napake!



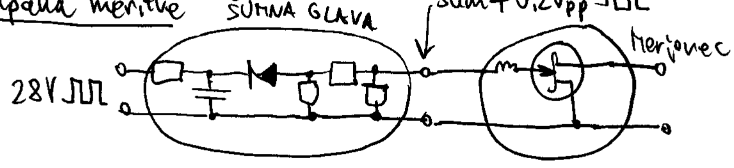
Radijske ~100MHz UKV FM

mobilne ~950MHz GSM



Napaka: $B_1 < B_2$, $f_1 \neq f_2$!

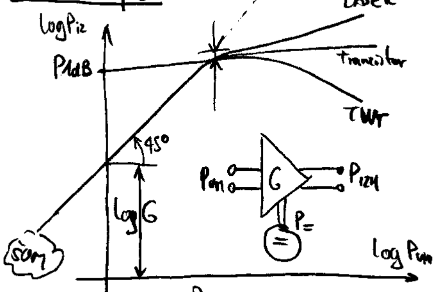
Napaka meritve



Visokofrekvenčna tehnika #7 22/11/2013

Nasičenje:

$G_{1dB} = G_{LIN} - 1dB$



$\eta_{1dB} = \frac{P_{1dB}}{P_=} \approx 30\%$

Zgled: izkoristek OFDM

$<P> = N P_1 \quad N \sim 8192$

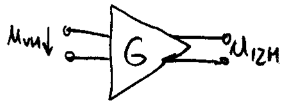
$P_{max} = N^2 P_1$ TEORIJA

$\eta = \eta_{1dB} \frac{<P>}{P_{max}} = \eta_{1dB} \cdot N \approx 0.004\%$

PRAKSA EVM $\rightarrow \frac{P_{max}}{<P>} = 10 \ldots 30$

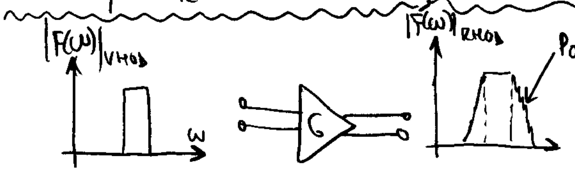
$\eta = \eta_{1dB} \frac{<P>}{P_{max}} = 1\% \ldots 3\%$

Popačenje:



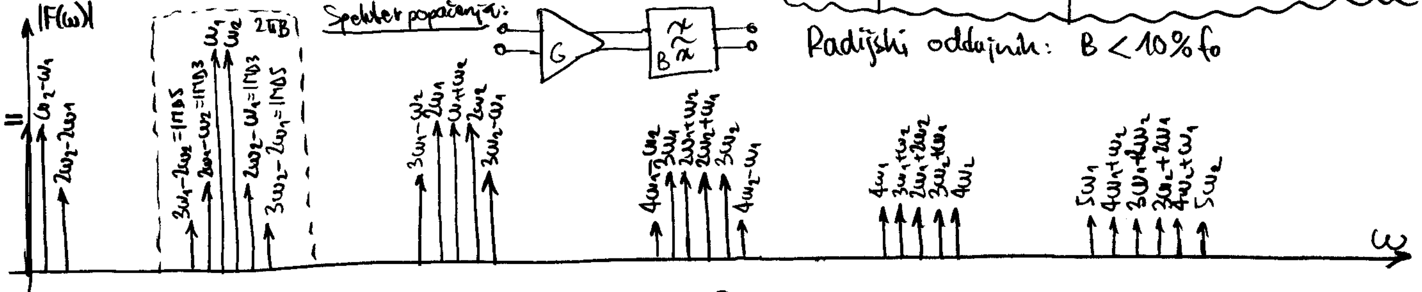
$u_{IZH} = \alpha_0 + \alpha_1 u_{VH} + \alpha_2 u_{VH}^2 + \alpha_3 u_{VH}^3 + \alpha_4 u_{VH}^4 + \alpha_5 u_{VH}^5 + \ldots$

ČLEN	$u_{VH} = U_0 \cos\omega t$	$u_{VH} = \frac{U_0}{2}(\cos\omega_1 t + \cos\omega_2 t)$
α_0	= (BIAS)	=
α_1	ω	ω_1, ω_2
α_2	$\textcircled{=}, 2\omega$ usmerjanje	$=, 2\omega_1, 2\omega_2, \omega_2+\omega_1, \omega_2-\omega_1$
α_3	$\textcircled{\omega}, 3\omega$ nasičenje $\alpha_1 \cdot \alpha_3 < 0$	$\omega_1, \omega_2, 3\omega_1, 3\omega_2, \boxed{2\omega_1-\omega_2}, 2\omega_1+\omega_2, \boxed{2\omega_2-\omega_1}, 2\omega_2+\omega_1$
α_4	$=, 2\omega, 4\omega$	$=, 2\omega_1, 2\omega_2, 4\omega_1, 4\omega_2 \ldots$
α_5	$\omega, 3\omega, 5\omega$	$\omega_1, \omega_2, \ldots 5\omega_1, 5\omega_2 \ldots \boxed{3\omega_1-2\omega_2} \boxed{3\omega_2-2\omega_1}$
α_6	$=, 2\omega, 4\omega, 6\omega$	$=, 2\omega_1 \ldots 6\omega_1, 5\omega_1+\omega_2 \ldots$

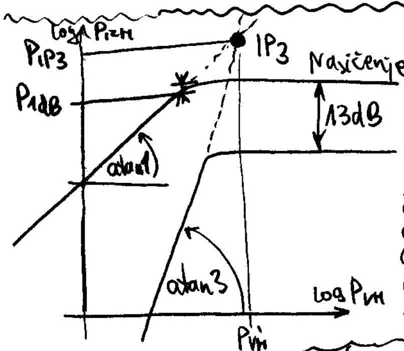


Popačenje odvisno od faze F(ω)!

Spekter popačenja:



Radijski oddajnik: B < 10% fo



Moč IMD:

$P_{LIN} = G P_{VH}$

$P_{IMD3} = G_3 P_{VH}^3$

Premici Pvh'

$\left.\begin{array}{l} P_{IP3} = G P_{VH}' \\ P_{IP3} = G_3 P_{VH}'^3 \end{array}\right\} G_3 = \frac{G^3}{P_{IP3}^2}$

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

$P_{IMD3}[dBm] = 3 P_{LIN}[dBm] - 2 P_{IP3}[dBm]$

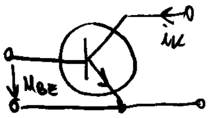
IMD 5, 7, 9, ...

$$\boxed{P_{IMDN} = \frac{P_{LIN}^N}{P_{IPN}^{N-1}}}$$

OBIČAJNO: $\boxed{P_{IMDN} > P_= !}$

$P_{IMDN}[dBm] = N P_{LIN}[dBm] - (N-1) P_{IPN}[dBm]$

P_{IP3} bipolarni T:



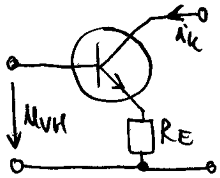
$i_K = \beta I_S \left(e^{\frac{u_{BE}}{26mV}} - 1\right)$

$i_K = \alpha_0 + \alpha_1 u_{BE} + \alpha_2 u_{BE}^2 + \alpha_3 u_{BE}^3 + \ldots$

$\boxed{P_{IP3} \approx 10 P_{1dB}}$

$P_{IP3}[dBm] \approx P_{1dB}[dBm] + 10dB$

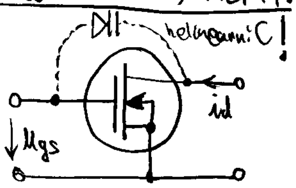
Bipolarni + R_E (MMIC):



$\boxed{P_{IP3} \approx 30 P_{1dB}}$

$P_{IP3}[dBm] \approx P_{1dB}[dBm] + 15dB$

P_{IP3} za MOSFET/HEMT:



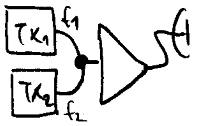
$i_d = k(u_{gs} - U_T)^2$

$i_d = \underset{\alpha_2}{k u_{gs}^2} - \underset{\alpha_1}{\underbrace{2kU_T u_{gs}}} + \underset{\alpha_0}{kU_T^2} \leftarrow$ člena α_3 ni!

$\boxed{P_{IP3} \approx 100 P_{1dB}}$

$P_{IP3}[dBm] \approx P_{1dB}[dBm] + 20dB$

Zgled:



$P_{LIN} = 1W = +30dBm$

$P_{IMD3} = 1\mu W = -30dBm$

$P_{IP3} = \sqrt{\frac{P_{LIN}^3}{P_{IMD3}}} = 1kW!$

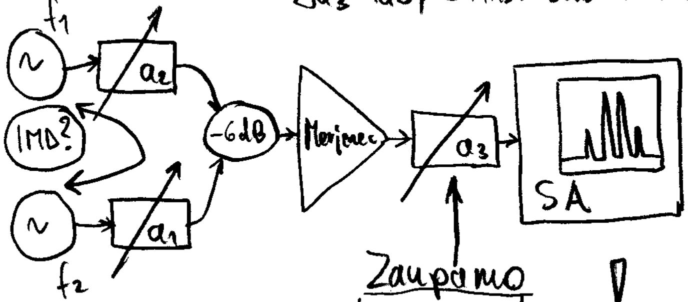
$P_=$ (bipolarni) $\approx 333W$

$P_=$ (MOSFET) $\approx 33W$

Meritev IMD3:

$\Delta a_3 = 1dB, \Delta P_{IMD3} = 1dB \rightarrow$ izvor IMD3 PRED a_3 (merjenec)

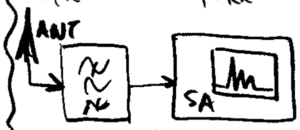
$\Delta a_3 = 1dB, \Delta P_{IMD3} = 3dB \rightarrow$ izvor IMD3 ZA a_3 (SA)



Zaupamo v linearnost a_3!

Zahtevna meritev

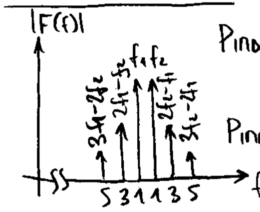
$P_{TX} = +30dBm, P_{RX} = -100dBm$



Pasovno sito izloči TX

Visokofrekvenčna tehnika #8 29/11/2013

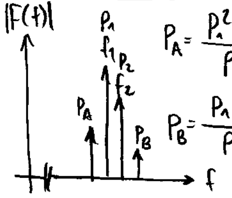
Ponovitev: IMD



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

$$P_{IMD5}=\frac{P_{LIN}^5}{P_{IP5}^4}$$

Različni moči:



$$P_A=\frac{P_1^2P_2}{P_{IP3}^2}$$

$$P_B=\frac{P_1P_2^2}{P_{IP3}^2}$$

Trije signali: f_1, f_2, f_3

9 produktov IMD3:

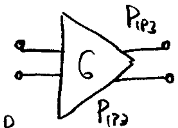
$2f_1-f_2, 2f_2-f_1, 2f_1-f_3,$

$2f_3-f_1, 2f_2-f_3, 2f_3-f_2$

$f_1+f_2-f_3, f_1+f_3-f_2$

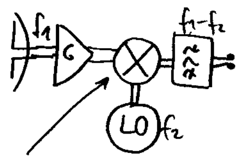
$f_2+f_3-f_1 \rightarrow P_{IMD3}=\frac{P_1P_2P_3}{P_{IP3}^2}$

IMD na vhodu:



$$P_{IIP3}=\frac{P_{IP3}}{G}$$

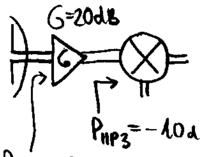
Sprejemnik:



mešalnik: f_1-f_2=mešanje (x^2)

$2f_1-f_2$= IMD3 (x^3)

Škodljivost predojačevalnika:



$P_{IIP3}=-10dBm$

$P_{IIP3}'=P_{IIP3}-G=\underline{\underline{-30dBm}}$

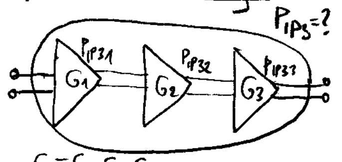
Zgled: $P_S=-40dBm$

$P_{IMD3}=-60dBm$

$P_S/P_{MOTNJA}=\underline{\underline{20dB}}$

Ojačevalna veriga:

$P_{IP3}=?$



$G=G_1G_2G_3$

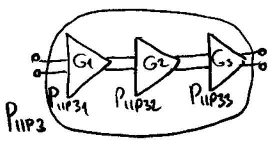
Seštevanje sofaznih kazalcev $(\alpha_1 \cdot \alpha_3 < 0)$

$$\sqrt{P_{IMD3}}=\sqrt{\frac{\left(\frac{P_{LIN}}{G_2G_3}\right)^3}{P_{IP31}^2}+\frac{\left(\frac{P_{LIN}}{G_3}\right)^3}{P_{IP32}^2}+\frac{P_{LIN}^3}{P_{IP33}^2}}$$

$$\frac{1}{P_{IP3}}=\frac{1}{P_{IP31}G_2G_3}+\frac{1}{P_{IP32}G_3}+\frac{1}{P_{IP33}}$$

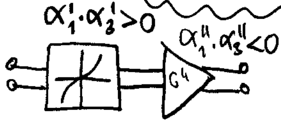
$$\boxed{P_{IP3}=\frac{1}{\frac{1}{P_{IP33}}+\frac{1}{P_{IP32}G_3}+\frac{1}{P_{IP31}G_2G_3}}}$$

Sprejemna veriga:



$$\underline{\underline{P_{IIP3}=\frac{1}{\frac{1}{P_{IIP31}}+\frac{G_1}{P_{IIP32}}+\frac{G_1G_2}{P_{IIP33}}}}}$$

Predpopačenje:

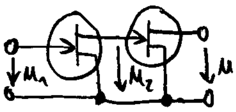


$$P_{IP3}=\frac{1}{\frac{1}{P_{IP3}''}-\frac{1}{P_{IP3}'G''}}$$

Popačenje popačenja:

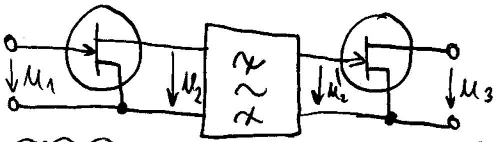
$u_2=k_1(u_1-U_{T1})^2$

$u_3=k_2(u_2-U_{T2})^2$ IMD3!

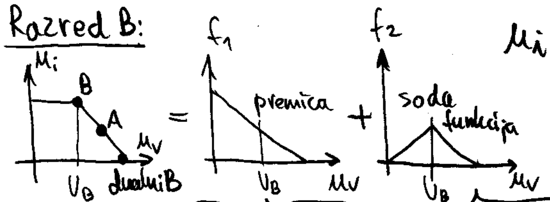


$u_3=\alpha_0+\alpha_1u_1+\alpha_2u_1^2+\boxed{\alpha_3u_1^3}+\alpha_4u_1^4$

PROTIUKREP



Razred B:

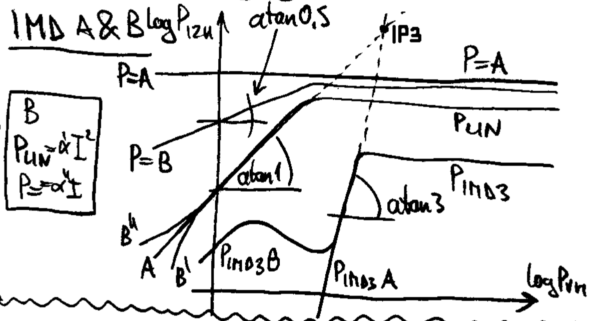


$u_i=\sum_i \alpha_i (u_v-U_B)^i$

BREZ LIHIH ČLENOV = BREZ IMD!

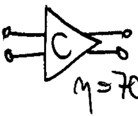
$$u_i=\overbrace{\alpha_0+\alpha_1(u_v-U_B)}+\overbrace{\alpha_2(u_v+U_B)^2+\alpha_4(u_v-U_B)^4+\alpha_6(u_v-U_B)^6}$$

IMD A&B



Konstantna ovojnica

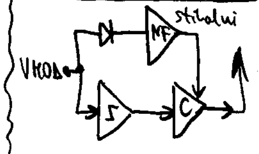
(analogni: FM, GMSK)



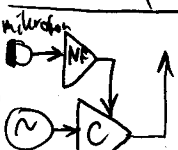
BREZ IMD

$\eta=70\%$!

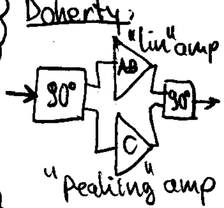
Ločeno faza/ovojnica

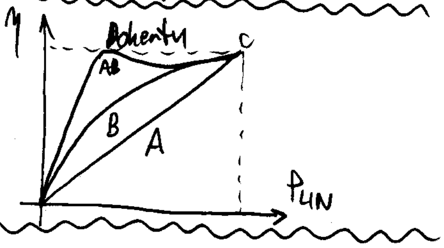


AM oddajnik

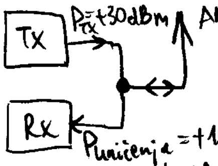


Doherty:





Ena antena RX+TX:

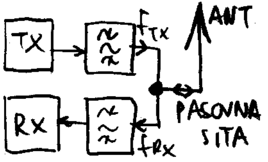


Puščenje=+10dBm

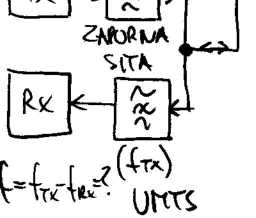
$P_{IIP3}=-10dBm$

NE GRE!

Kretnica RX/TX:



PASOVNA SITA



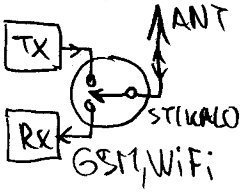
ZAPORNA SITA

$\Delta f=f_{TX}-f_{RX}=?$

Q=?

UMTS
NMT
LTE

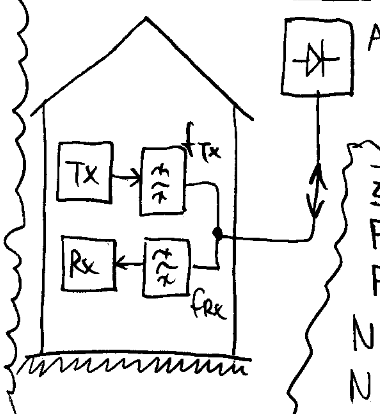
Preklop RX/TX:



STIKALO

GSM, WiFi

Pasivna IMD = PIM:



ANTENA na prostem

Cu_2O=polprevodnik ΔW=2,1eV

Zgled PIM:

FM TX1: 95MHz 1kW

FM TX2: 105MHz 1kW

NMT TX: 425MHz 10W

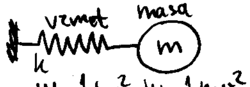
NMT RX: 415MHz -120dBm!

$$\underline{\underline{PIM=f_{NMT TX}-f_2+f_1=f_{NMT RX}}}$$

Visoko frekvenčna tehnika #9 6/12/2013

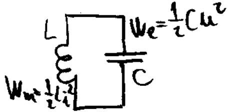
Rezonator:

mehanski:



$W_p = \frac{1}{2}kx^2$ $W_k = \frac{1}{2}mv^2$

električni:

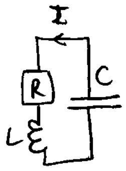


Kvaliteta:

$$Q = \omega \frac{W}{P}$$

vskladiščena

izgube

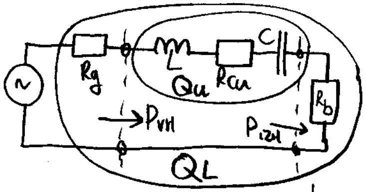


$$W = \frac{1}{2} L|I|^2$$

$$P = \frac{1}{2} R|I|^2$$

$$Q = \omega \frac{\frac{1}{2}L|I|^2}{\frac{1}{2}R|I|^2} = \frac{\omega L}{R}$$

Pasovno sito:



Neobremenjeni (UNLOADED) $Q_u = \frac{\omega L}{R_{cu}}$

Obremenjeni (LOADED) $Q_L = \frac{\omega L}{R_g + R_{cu} + R_b} \leq Q_U$

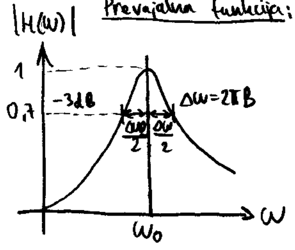
Vstavitveno slabljenje

$$a \leq 1$$

$$a = \frac{R_b}{R_{cu} + R_b}$$

Max P → $R_g = R_{cu} + R_b$

$$\boxed{a = 1 - \frac{2Q_L}{Q_u}}$$



Prevajalna funkcija:

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

$Q \gg 1 \rightarrow \frac{\omega_0}{\omega} \approx 1$ $Q = \frac{\omega_0 L}{\Sigma R} \rightarrow L = \frac{Q \Sigma R}{\omega_0}$

$$-3dB \rightarrow \Sigma R = \underbrace{\omega L - \frac{1}{\omega C}}_{X} = \frac{dX}{d\omega} \cdot \frac{\Delta\omega}{2} \approx 2L\frac{\Delta\omega}{2} = \Delta\omega L = \Delta\omega \frac{Q \Sigma R}{\omega_0} \rightarrow \boxed{\Delta\omega = \frac{\omega_0}{Q}}$$

$$\frac{dX}{d\omega} = L + \frac{1}{\omega^2 C} = L\left(1 + \frac{\omega_0^2}{\omega^2}\right)$$

Pasovna širina: $\boxed{B = \Delta f = \frac{f_0}{Q}}$

Zakasnitev: $t = \frac{\varphi}{\omega}$

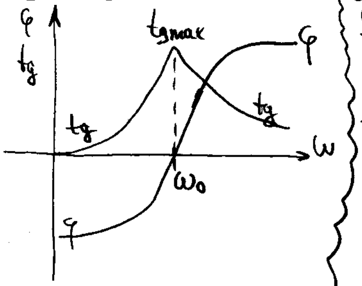
Ozkopasovno vezje

→ Skupinska zakasnitev $\boxed{t_g = \frac{d\varphi}{d\omega} = \frac{1}{1 + \left(\frac{\omega L - \frac{1}{\omega C}}{\Sigma R}\right)^2} \cdot \frac{L + \frac{1}{\omega^2 C}}{\Sigma R}}$

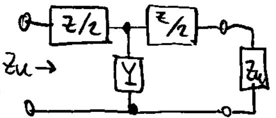
Nihajni krog:

$$\varphi = \text{arctg} \frac{\omega L - \frac{1}{\omega C}}{\Sigma R}$$

$$t_{g\,max}(\omega = \omega_0) = \frac{L + \frac{1}{\omega_0^2 C}}{\Sigma R} = \frac{2Q}{\omega_0}$$



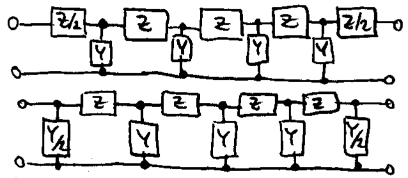
Gradnik lestvice:



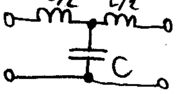
$$Z_u = Z/2 + \frac{1}{Y + \frac{1}{Z/2 + Z_u}}$$

$$\boxed{Z_u = \sqrt{\frac{Z}{Y} + \left(\frac{Z}{2}\right)^2}}$$

Lestvičasto sito:



Nizkoprepustno LPF:

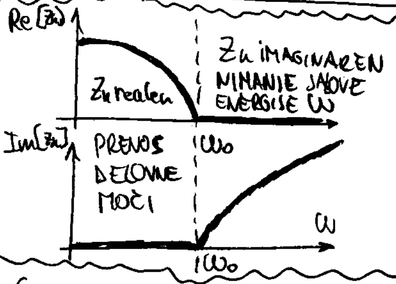


$$\boxed{Z_u = \sqrt{\frac{L}{C} - \left(\frac{\omega L}{2}\right)^2}}$$

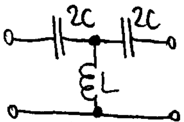
$Z = j\omega L$

$Y = j\omega C$

$$\omega_0 = \frac{2}{\sqrt{LC}}$$



Visokoprepustno HPF:

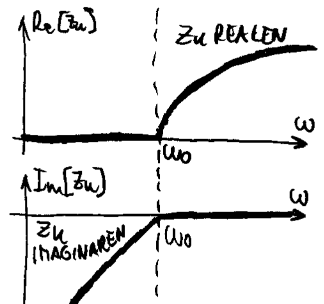


$$\boxed{Z_u = \sqrt{\frac{L}{C} - \left(\frac{1}{\omega 2C}\right)^2}}$$

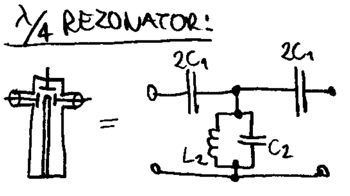
$Z = \frac{1}{j\omega C}$

$Y = \frac{1}{j\omega L}$

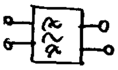
$$\omega_0 = \frac{1}{2\sqrt{LC}}$$

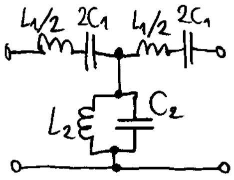


λ/4 REZONATOR:



$L_1C_1L_2C_2$ pasovno BPF:





Težava:

L_1 neizvedljiv za ozka sita

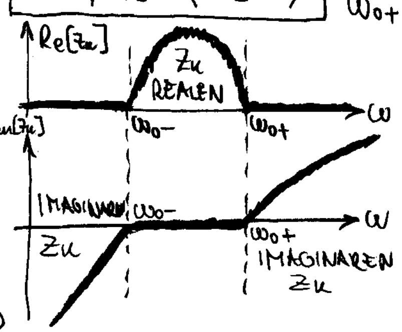
$$\boxed{Z_u = \sqrt{\frac{j\omega L_1 + \frac{1}{j\omega C_1}}{j\omega C_2 + \frac{1}{j\omega L_2}} + \left(\frac{j\omega L_1 + \frac{1}{j\omega C_1}}{2}\right)^2}}$$

IZBIRA $\omega_R = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}$

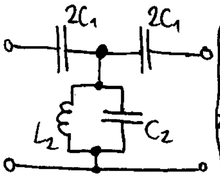
$$\boxed{Z_u = \sqrt{\frac{L_1}{C_2} - \left(\frac{\omega L_1 - \frac{1}{\omega C_1}}{2}\right)^2}}$$

ω_{0-}

ω_{0+}

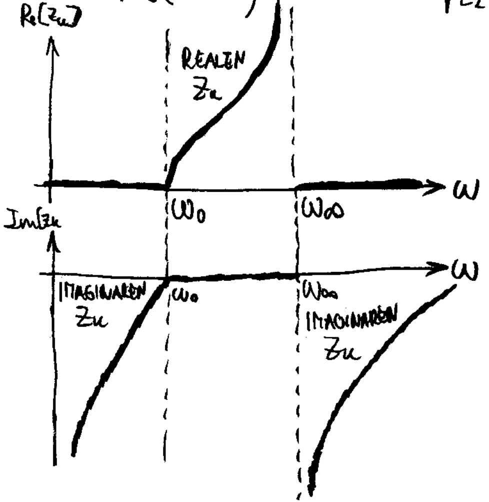


$C_1L_2C_2$ pasovno BPF:



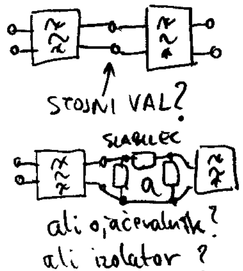
$$\boxed{Z_u = \sqrt{\frac{\frac{1}{\omega C_1}}{\frac{1}{\omega L_2} - \omega C_2} - \left(\frac{1}{\omega 2C_1}\right)^2}}$$

$$\omega_0 = \frac{1}{\sqrt{L_2(4C_1 + C_2)}} \qquad \omega_\infty = \frac{1}{\sqrt{L_2C_2}}$$



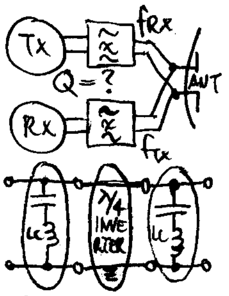
Visokofrekvenčna tehnika #10 13/12/2013

Zaporedna vezava sit

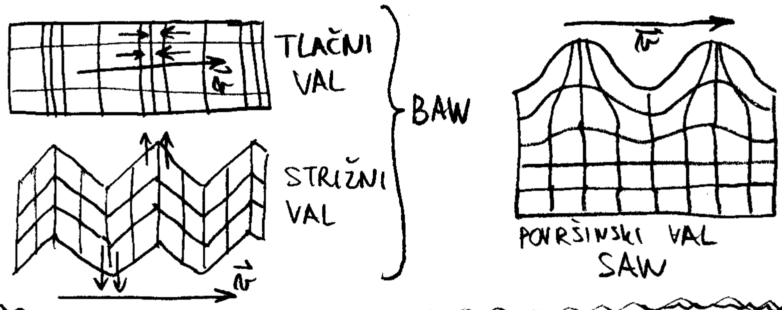


ali ojačevalnik?
ali izolator?

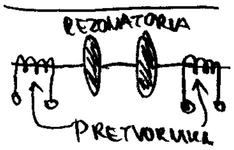
Antenska kretnica



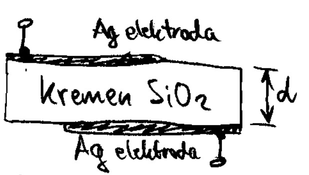
Mehanska valovanja v trdni snovi:



Mehansko sito:



Piezoelektrik: rezonator + pretvornik



$$d = m\frac{\Lambda}{2}$$

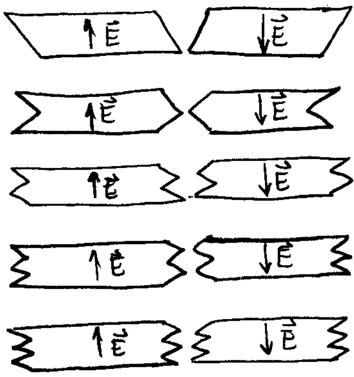
$$\Lambda = \frac{v}{f}$$

$v = 2km/s — 5km/s$

kristal SiO_2 AT rez → $v = 3.32km/s$

$m = 1, 2, 3, 4, 5, 6 \dots$ CELO ŠTEVILO

Overtoni:



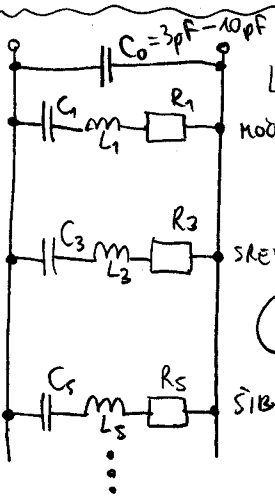
m=1 OSNOVNA REZONANCA f_1

m=2 NI SKLOPA z $\vec{E}$!

m=3 TRETJI OVERTON f_3

m=4 NI SKLOPA z $\vec{E}$!

m=5 PETI OVERTON f_5



Nadomestno vezje:

$L_1 \approx L_3 \approx L_5 \approx 3mH - 10mH$

MOČEN SKLOP

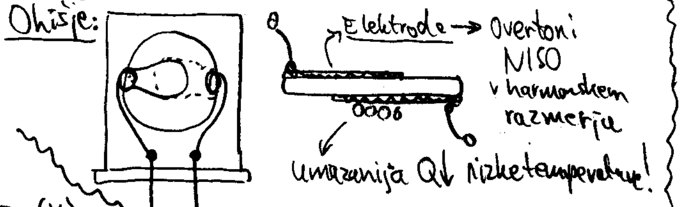
$R_1 \approx 20\Omega - 50\Omega$

SREDNJI SKLOP

$$\boxed{Q = \frac{\omega L_i}{R_i} = 10^4 - 10^5 \,!}$$

ŠIBEK SKLOP

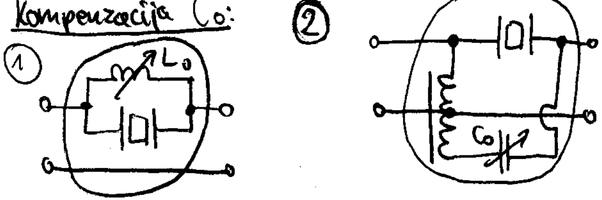
Ohišje:

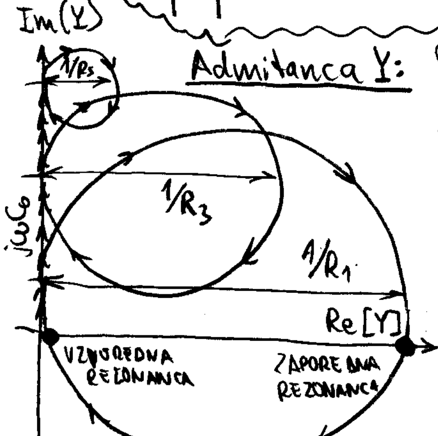


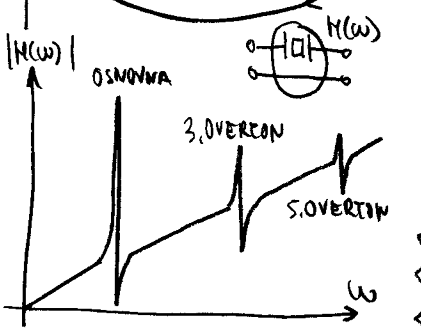
Elektrode → Overtoni NISO v harmonskem razmerju

umazanija Q↓ nizke temperature!

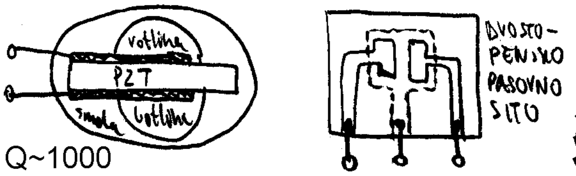
Kompenzacija C_0:







Piezokeramika: $BaTiO_3$, $PbZr_xTi_{1-x}O_3$ = PZT

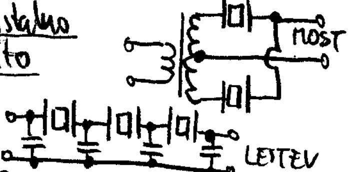


Q~1000

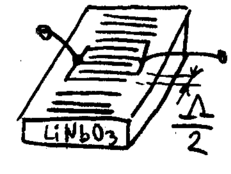
Integracija FBAR: ZnO, AlN

d ~ 1μm → f ~ 2GHz Q~1000

Kristalno sito

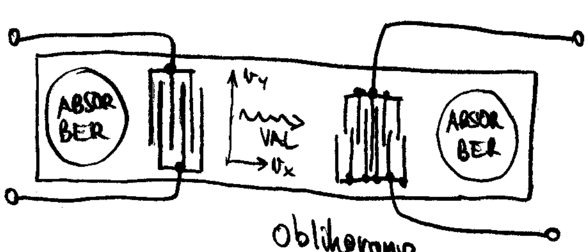


SAW rezonator:



30MHz < f < 3GHz

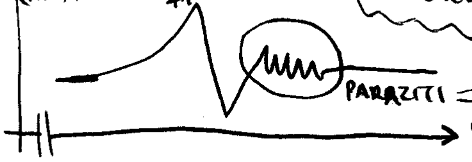
SAW sito:



oblikovane elektrode → FIR sito

Parazitne rezonance:

SiO_2

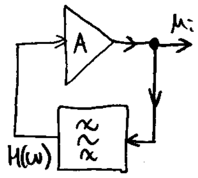


→ NETOČNO BRUŠENJE

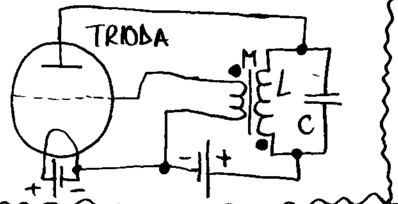
→ ELEKTRODE?

Visoko frekvenčna tehnika #11 20/12/2013

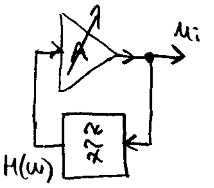
Oscilator:

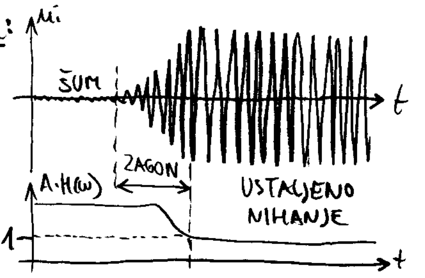


Alexander Meissner 1912:

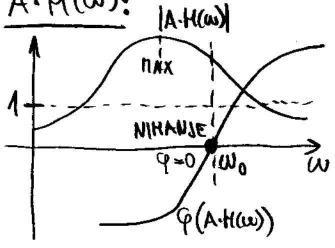


Zagon oscilatorja:

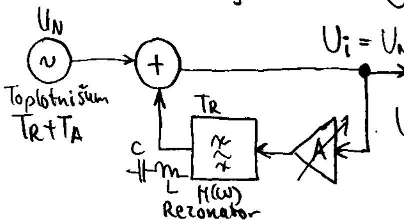




A·H(ω):



Šum oscilatorja:



$$U_i = U_N + U_i A H(\omega)$$

$$U_i = \frac{U_N}{1 - A H(\omega)}$$

Ustaljeno nihanje → $A H(\omega_0) = 1$

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

$$\omega = \omega_0 + \Delta\omega \; ; \; \Delta\omega \ll \omega_0$$

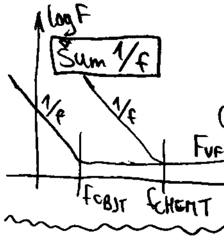
$$\frac{j\omega L + \frac{1}{j\omega C}}{\Sigma R} \approx 2j \frac{\Delta\omega L}{\Sigma R} = 2jQ_L \frac{\Delta\omega}{\omega_0}$$

$$U_i \approx \frac{U_N}{1 - \frac{1}{1 + 2jQ_L \frac{\Delta\omega}{\omega_0}}} = U_N\left(1 + \frac{1}{2jQ_L}\frac{\omega_0}{\Delta\omega}\right) = U_N\left(1 + \frac{1}{2jQ_L}\frac{f_0}{\Delta f}\right)$$

$$P = \alpha |U|^2$$

$$P_i = P_N \left[1 + \left(\frac{f_0}{2Q_L \Delta f}\right)^2\right]$$

$$P_N = B k_B (T_R + T_A) = B k_B T_0 F$$



$$F = F_{VF}\left(1 + \frac{f_c}{f}\right)$$

BJT, HBT → f_c = 1kHz — 10kHz

GaAsFET, HEMT → f_c = 1MHz — 10MHz

$\boxed{\text{MEŠANJE NAVZGOR V NELINEARNOSTI A!}}$

Integrirani šum:

$$\sigma_\varphi = \sqrt{2\int_{f_a}^{f_b} L(\Delta f)\, d\Delta f}$$

RESIDUAL ØM NOISE [rd]

$$\sigma_f = \sqrt{2\int_{f_a}^{f_b} \Delta f^2 L(\Delta f)\, d\Delta f}$$

RESIDUAL FM NOISE [Hz]

Normirani fazni šum L(Δf):

David B. Leeson 1966

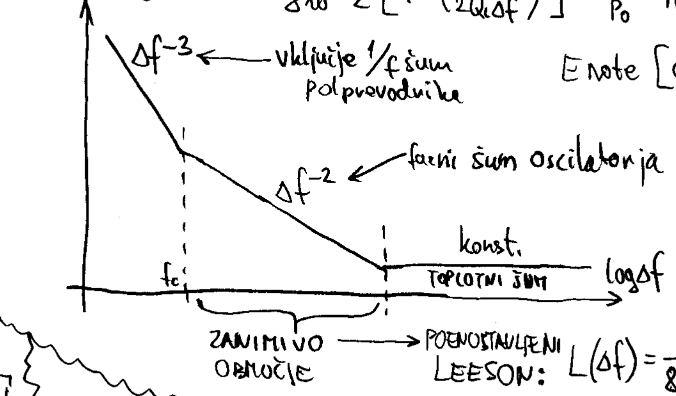
$$L(\Delta f) = \frac{P_i/2}{B P_0} = \frac{1}{2}\left[1 + \left(\frac{f_0}{2Q_L \Delta f}\right)^2\right] \cdot \frac{k_B T_0}{P_0} F_{VF}\left(1 + \frac{f_c}{|\Delta f|}\right) \; [\mathrm{rd}^2/\mathrm{Hz}]$$

$\boxed{P_0 \equiv \text{izhodna sinusna moč @}\omega_0}$

$$P_{\text{FAZNI ŠUM}} = \frac{1}{2} P_{\text{celotni šum}} !$$

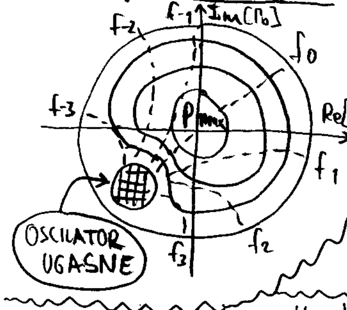
$$L(\Delta f)_{dB} = 10 \log_{10} \frac{1}{2}\left[1 + \left(\frac{f_0}{2Q_L \Delta f}\right)^2\right] \frac{k_B T_0}{P_0} F_{VF}\left(1 + \frac{f_c}{|\Delta f|}\right) \cdot 1\mathrm{Hz}$$

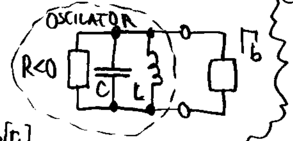
Enote [dBc/Hz]



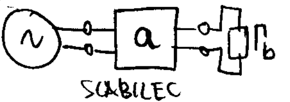
→ POENOSTAVLJENI LEESON: $L(\Delta f) = \frac{f_0^2 k_B T_0 F}{8 Q_L^2 \Delta f^2 P_0}$

Rieke-jev diagram (Γ_b):

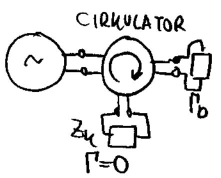


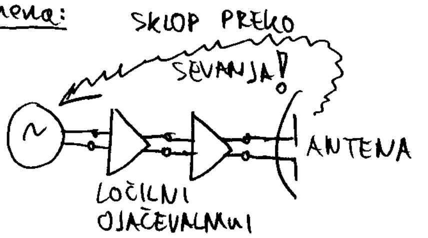


Protiukrep → ločitev bremena:

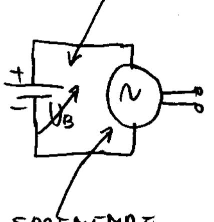


$\Gamma_b' = a^2 \Gamma_b$ →



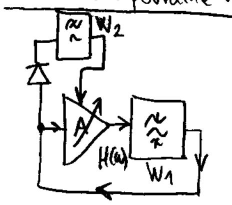


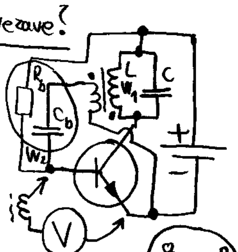
MOTNJE NAPAJANJA?

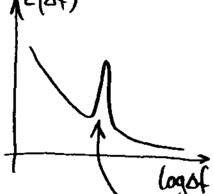


SPREMEMBE TEMPERATURE?

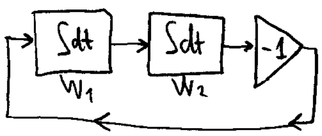
Stabilnost povratne vezave?

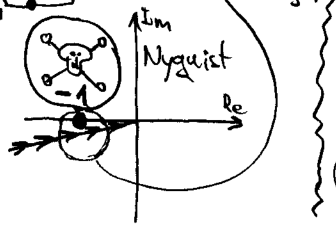






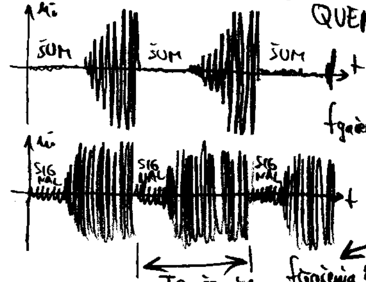
Povratna vezava U_{BE}=





Super-regenerativni RX: Armstrong 1922

QUENCHING



$$f_{gašenja} = \frac{1}{T_{gašenja}}$$

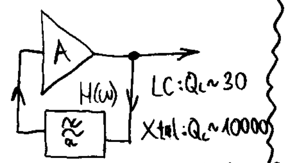
$Q_L \approx 30$

$$f_{gašenja} \approx \frac{f_0}{1000}$$

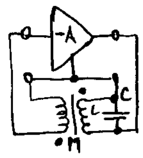
$$G = 20\log\frac{U_i}{U_{signal}} = 20\log\frac{10\mathrm{V}}{1\mu\mathrm{V}} = 140\mathrm{dB} + \text{AM demod!}$$

Visokofrekvenčna tehnika # 12 6/1/2014

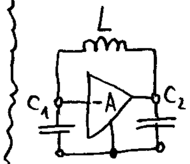
Ponovitev: OSCILATOR



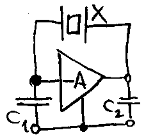
Meissner:

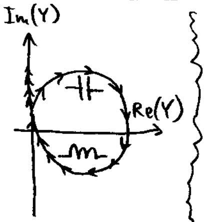


Colpitts:

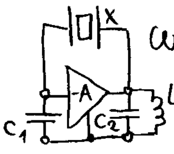


Pierce:



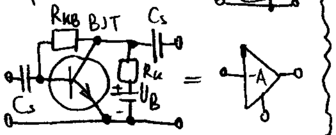


3. overton:

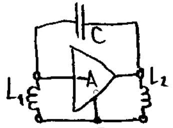


$$\omega_1 < \frac{1}{\sqrt{LC_2}} < \omega_3$$

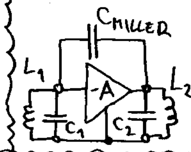
Ojačevalnik A:



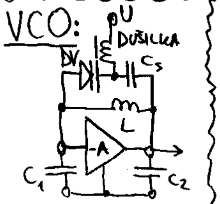
Hartley:



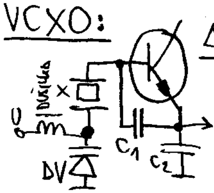
Huth-kühn:



VCO:



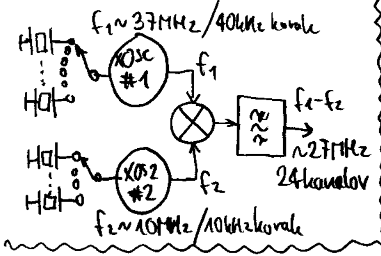
VCXO:



$$\frac{\Delta f}{f_1} < 0.1\%$$

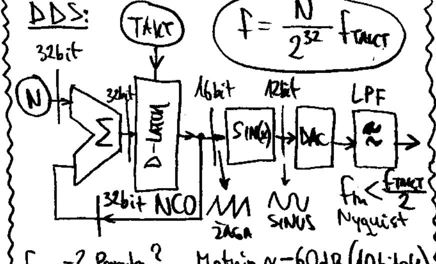
$$\frac{\Delta f}{f_3} < 0.01\%$$

Analogni sintetizator:



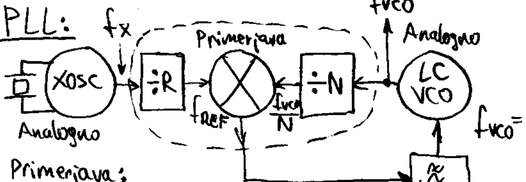
DDS:

$$f = \frac{N}{2^{32}} f_{TAKT}$$



f_{TAKT}? Poraba? Motnje ~ −60dB (10bitef)

PLL:

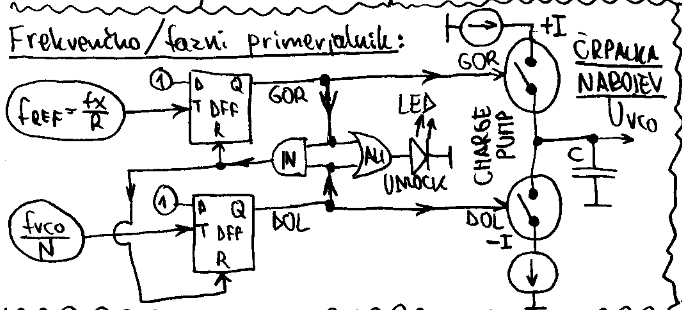


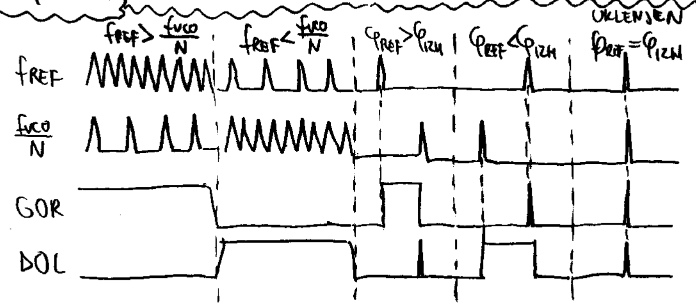
$$f_{vco} = \frac{N}{R} f_x$$

Primerjava:

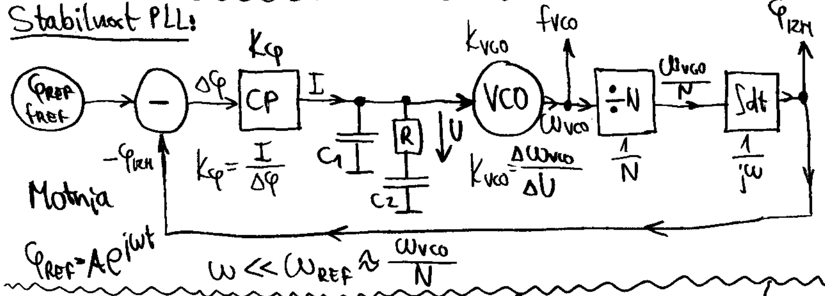
samo f → nedefiniran φ
samo φ → začetna uklenitev? } → Primerjava f + φ

Frekvenčno/fazni primerjalnik:





Stabilnost PLL:



$$K_\varphi = \frac{I}{\Delta\varphi} \qquad K_{VCO} = \frac{\Delta\omega_{VCO}}{\Delta U}$$

$$\varphi_{REF} = Ae^{j\omega t}$$

$$\omega \ll \omega_{REF} \approx \frac{\omega_{VCO}}{N}$$

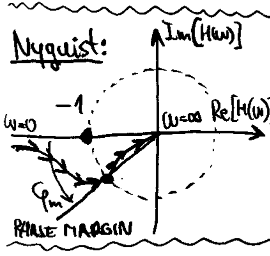
$$H(\omega) = K_\varphi \cdot \frac{1}{j\omega C_1 + \frac{1}{R + \frac{1}{j\omega C_2}}} \cdot K_{VCO} \cdot \frac{1}{N} \cdot \frac{1}{j\omega}$$

$$H(\omega) = \frac{-K_\varphi K_{VCO}}{\omega^2 N(C_1+C_2)} \cdot \frac{1 + j\omega RC_2}{1 + j\omega R\frac{C_1C_2}{C_1+C_2}}$$

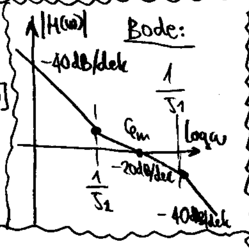
NIČLA

POL

Nyquist:



Bode:



$$\tau_1 = R\frac{C_1C_2}{C_1+C_2} < \tau_2 = RC_2$$

$$\varphi_m = \text{arctg}\,\frac{\omega(\tau_2-\tau_1)}{1+\omega^2\tau_1\tau_2}$$

$$\frac{d\varphi_m}{d\omega} = 0 \rightarrow \omega_m = \frac{1}{\sqrt{\tau_1\tau_2}}$$

$$\tau_2 = m\tau_1$$

$$1 = |H(\omega_m)| = \frac{K_\varphi K_{VCO}}{\omega_m^2 N C_1 \sqrt{m}} \rightarrow \omega_m = \sqrt{\frac{K_\varphi K_{VCO}}{NC_1\sqrt{m}}}$$

$$\varphi_m = \text{arctg}\,\frac{m-1}{2\sqrt{m}} \qquad C_1 = \frac{K_\varphi K_{VCO}}{\omega_m^2 N\sqrt{m}} \qquad R = \frac{\sqrt{m}}{\omega_m C_2}$$

$$C_2 = C_1(m-1)$$

Načrtovanje PLL:

$m = 1 \rightarrow C_2 = 0, \varphi_m = 0$ NESTABILNO!

$m = 3 \rightarrow C_2 = 2C_1$ HITRO

$m = 10 \rightarrow$ DOBER KOMPROMIS ($\varphi_m \sim 60°$)

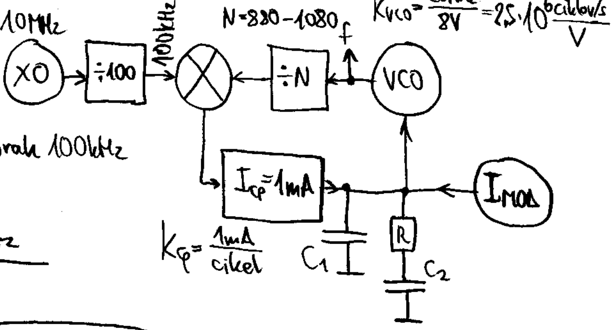
$m = 30 \rightarrow$ STABILNO A POČASNO

$m = \infty \rightarrow$ NEIZVEDLJIVO

Ⓐ IZBIRA C_1 (MOTNJE ω_{REF}) $\longrightarrow \omega_m$

Ⓑ IZBIRA $\omega_m \approx 2\pi B \longrightarrow C_1$

Zgled: FM oddajnik



$$K_{VCO} = \frac{20MHz}{8V} = 2{,}5 \cdot 10^6 \frac{ciklov/s}{V}$$

f = 88MHz − 108MHz / korak 100kHz

N = 880 − 1080

f_{MOD} = 300Hz − 4kHz

$\omega_m \ll 2\pi f_{modMIN}$

IZBEREM $\omega_m = 600 rd/s \approx \frac{1}{3} 2\pi\ 300Hz$

IZBEREM m = 10, N ~ 1000

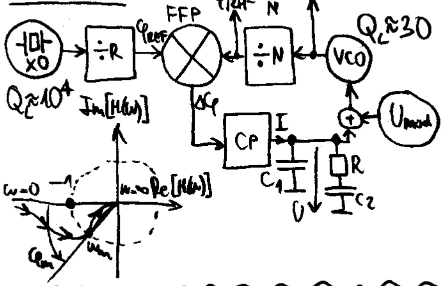
$$C_1 = \frac{K_\varphi K_{VCO}}{\omega_m^2 N\sqrt{m}} = \frac{10^{-3} A/cikel \cdot 2{,}5 \cdot 10^6 ciklov/Vs}{(600 rd/s)^2 \cdot 1000 \cdot \sqrt{10}} = \underline{\underline{2.2\mu F}}$$

$$C_2 = C_1(m-1) = \underline{\underline{20\mu F}}$$

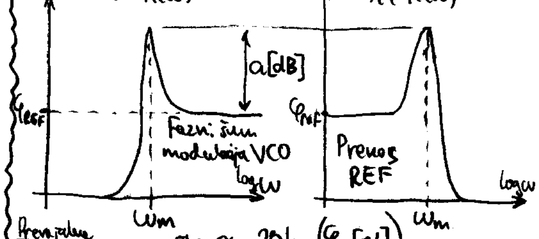
$$R = \frac{\sqrt{m}}{\omega_m C_2} = \underline{\underline{267\Omega}}$$

Visokofrekvenčna tehnika #13 10/1/2014

Ponovitev:

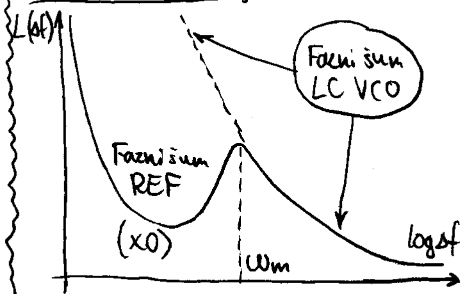


$\Delta\varphi = \frac{\varphi_{REF}}{1+H(\omega)}$ $\varphi_{IZH} = \frac{\varphi_{REF} H(\omega)}{1+H(\omega)}$



Prenosne funkcije: $a_{dB} \approx -20\log(\varphi_m[rd])$

Fazni šum PLL-ja:



Območje FFP: $|\Delta\varphi| < 2\pi$

(mešalnik $|\Delta\varphi| < \pi/2$)

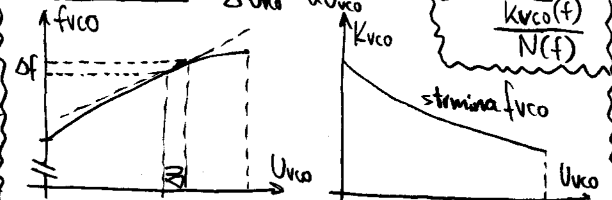
sicer preskok faze!!!

$|\Delta\varphi_{VCO}| < 2\pi N$ Zaled $N=1000$, $f_{mod}=300Hz$

$|\Delta f_{VCO}| < 2\pi N f_{mod} \approx$ 2MHz >> 75kHz

UKV FM koleb ±75kHz

Določanje $K_{VCO} = \frac{\Delta f_{VCO}}{\Delta U_{VCO}} = \frac{df_{VCO}}{dU_{VCO}}$



Pomembno: $\frac{K_{VCO}(f)}{N(f)}$

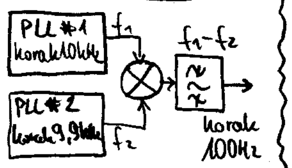
PLL z majhnim korakom → počasen!

Korak = $f_{REF} = \frac{f_{XO}}{R}$

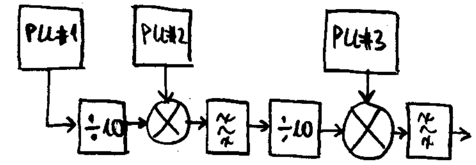
$\omega_M \approx 2\pi B \ll 2\pi f_{REF}$

Majhen korak → visok L(Δf) VCO!

Odštevanje dveh PLL:

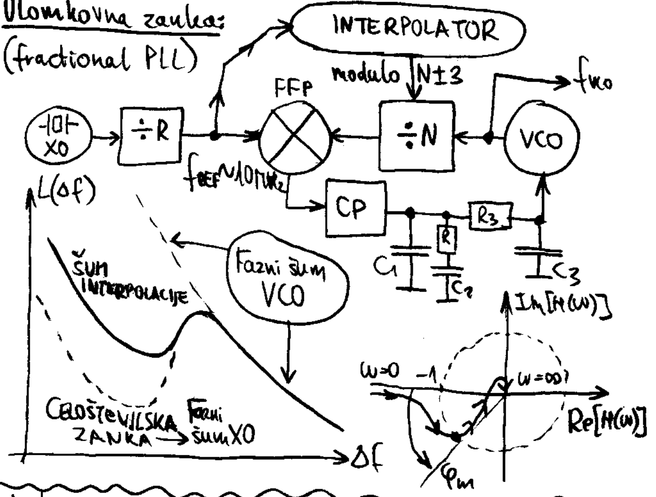


Veriga PLL:

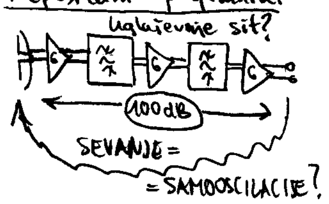


Ulomkovna zanka:

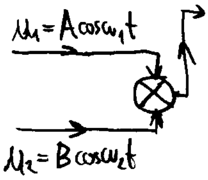
(fractional PLL)



Neposredni sprejemnik:



Mešalnik (množilnik)



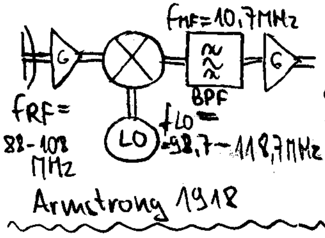
$u_1 = A\cos\omega_1 t$

$u_2 = B\cos\omega_2 t$

$u_3 = \alpha AB\cos\omega_1 t\cos\omega_2 t$

$u_3 = \frac{\alpha AB}{2}\left[\cos(\omega_1+\omega_2)t + \cos(\omega_1-\omega_2)t\right]$

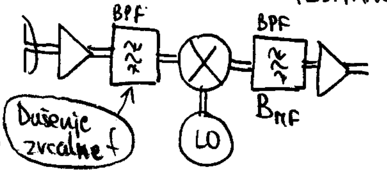
Heterodinski sprejemnik:



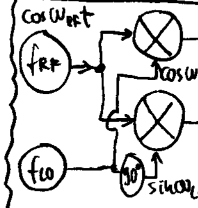
Armstrong 1918

Zrcalni odziv: $f_{MF} = f_{ZRCALNI} - f_{LO}$

$f_{ZRCALNI}$ = 109,4MHz − 129,4MHz



Kvadraturni mešalnik:



$\cos\omega_{RF}t\cos\omega_{LO}t = \frac{1}{2}\left[\cos(\omega_{RF}+\omega_{LO})t + \cos(\omega_{RF}-\omega_{LO}t)\right]$

$\cos\omega_{RF}t\sin\omega_{LO}t = \frac{1}{2}\left[\sin(\omega_{RF}+\omega_{LO})t - \sin(\omega_{RF}-\omega_{LO})t\right]$

Homodinski sprejemnik:

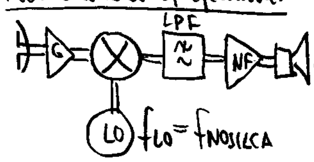
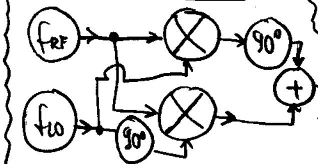


IMAGE-REJECT MIXER

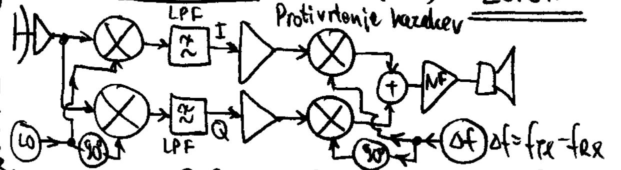


SAMO $f_{RF} + f_{LO}$!

$f_{RF} - f_{LO}$ slabljen 20-20...40dB

Ničelna medfrekvenca: Weaver (1956) → ZeroIF

Protivrtenje kazalcev



Nelinearnot → mešanje:

$i = I_s\left(e^{\frac{u}{25mV}} - 1\right) = \alpha_0 + \alpha_1 u + \alpha_2 u^2 + \alpha_3 u^3 + ..$

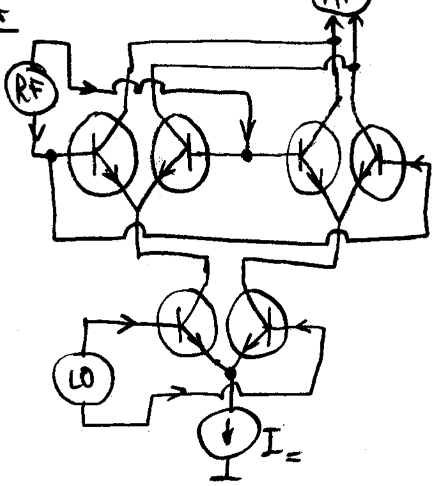
$\alpha_2 u^2 = \alpha_2\left(u_{RF}^2 + 2u_{RF}u_{LO} + u_{LO}^2\right)$

Fotodioda: $I_e = \alpha E_0^2$

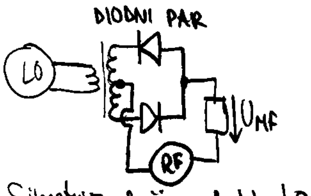
$I_e = (I/P)P_0 = (I/P)A\frac{|E_0|^2}{2Z_0}$

Gilbert cell:

(DBM)

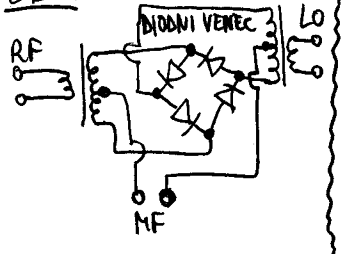


Balančni mešalnik: (BM)



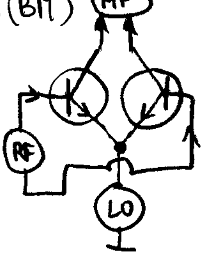
Simetrija duši produkte LO

DBM:



Diferencialni par:

(BM)



Visokofrekvenčna tehnika #14 17/1/2014

Laminati:

FR-2 papir + fenolnasmola (pertinaks)

FR-4 steklena vlakna + epoksi (vitroplast)

$tg\,\delta \approx 0.02$ $Q \approx 50$

$\varepsilon_r = 4.3 - 5{,}3$ (upada 1Hz → 10GHz)

PTFE + vlakna $tg\,\delta \approx 0{,}001$

$\varepsilon_r = 2{,}0 - 2{,}7$ (vlakna ↑)

PTFE + keramika

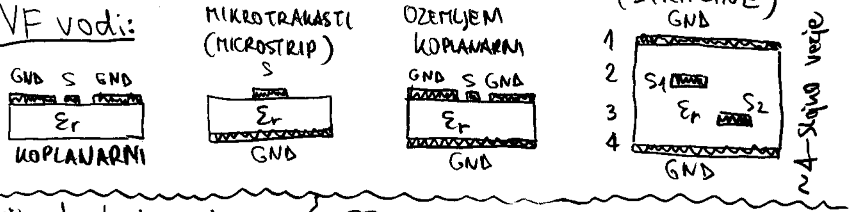
$\varepsilon_r = 6{,}0$ ali $10{,}0$ $tg\,\delta \approx 0{,}002$

Ogljikovodiki + keramika (R4000)

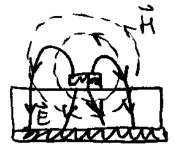
$\varepsilon_r = 3{,}0 - 3{,}5$ $tg\,\delta \approx 0{,}002$

združljivi s prepregom FR-4

VF vodi:

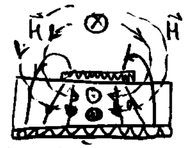


Mikrotrakasti rodovi:

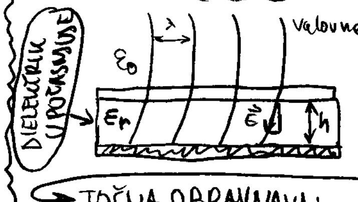


~TEM

OSNOVNI ROD → SKORAJ TEM



PRVI VIŠJI ROD ~TE1



$\vec{E}$ in $\vec{H}$ imata vzdolžno komponento

→ TOČNA OBRAVNAVA:

① HIBRIDNI RODOVI!

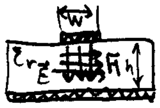
② NAPETOST U NE OBSTAJA!

③ KARAKTERISTIČNA Z_k NE OBSTAJA!

NF približek $h \ll \lambda$: ~TEM, $E_z \approx 0$, $H_z \approx 0$

možna definicija U, I, Z_k

NF približek brez stresanja:



$C/\ell \approx \frac{w}{h}\varepsilon_0\varepsilon_r$

$L/\ell \approx \frac{h}{w}\mu_0$

$Z_k \approx \frac{h}{w}\frac{Z_0}{\sqrt{\varepsilon_r}}$

NEUPORABNO!

Zgled $\varepsilon_r = 4{,}5$, $Z_k = 50\Omega$ → $\frac{w}{h} = 3{,}5$

NF približek Wheeler:

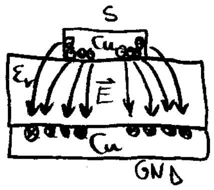
enačbe/grafi

Zgled $\varepsilon_r = 4{,}5$

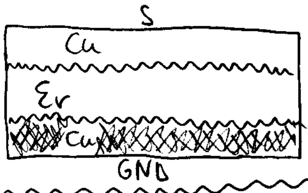
$Z_k = 50\Omega$

$\frac{w}{h} = 1{,}84$

Izriv toka na rob:



Hrapavost bakra:



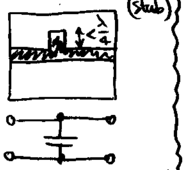
FR-4 → navidezni $\gamma_{Cu} \sim 1{,}5 \cdot 10^6$ S/m

Mikrovalovni laminati

① valjani Cu γ↑

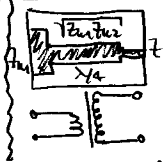
② elektrolitski Cu γ↓

Kapacitivni štrcelj: (stub)

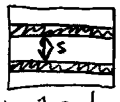


Induktivni štrcelj:

λ/4 trafo:

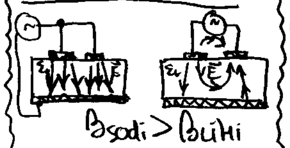


Sklop:



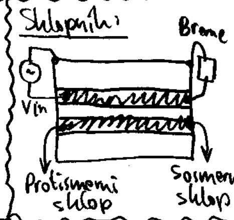
majhen, ko velja s > 3h

Sodi in lihi rod:

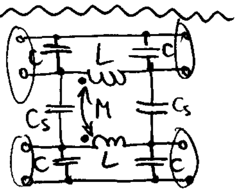


$\beta_{sodi} > \beta_{lihi}$

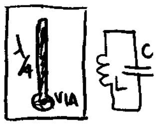
Sklopniki:



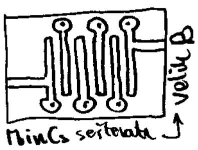
$\varepsilon_r \neq 1$



λ/4 rezonator:

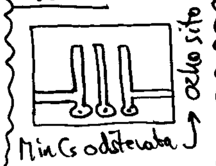


Interdigitalno sito:



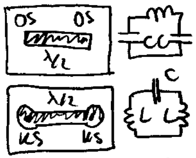
MinCs seštevata ↑

Glavnik:

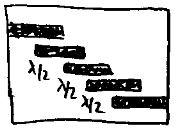


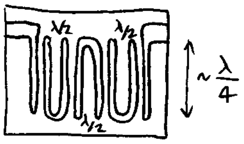
MinCs odštevata ↑

λ/2 rezonator

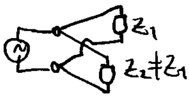


Pasovno sito iz λ/2:

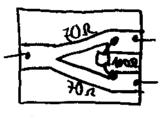




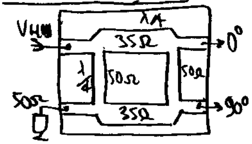
Neenako deljenje?



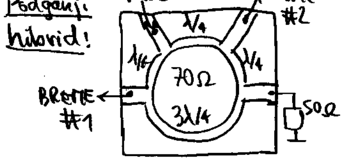
Wilkinsonov hibrid:



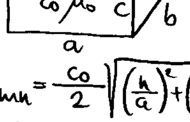
Kvadraturni hibrid:



Podganji hibrid!

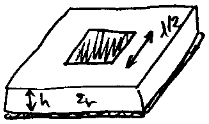


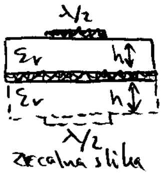
Votlinski rezonator:

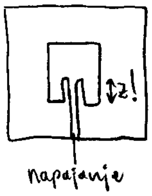


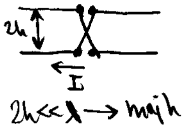
$$f_{lmn} = \frac{c_0}{2}\sqrt{\left(\frac{l}{a}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{n}{c}\right)^2}$$

Krpica (Patch) antena:



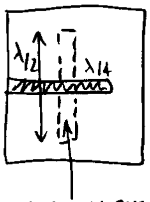






$2h \ll \lambda$ → majhen R_s, η

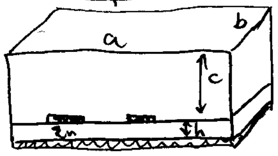
Reža (slot):

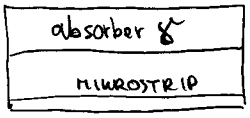


IZREZ V GND

visok R_s, η

Rezonance ohišja:





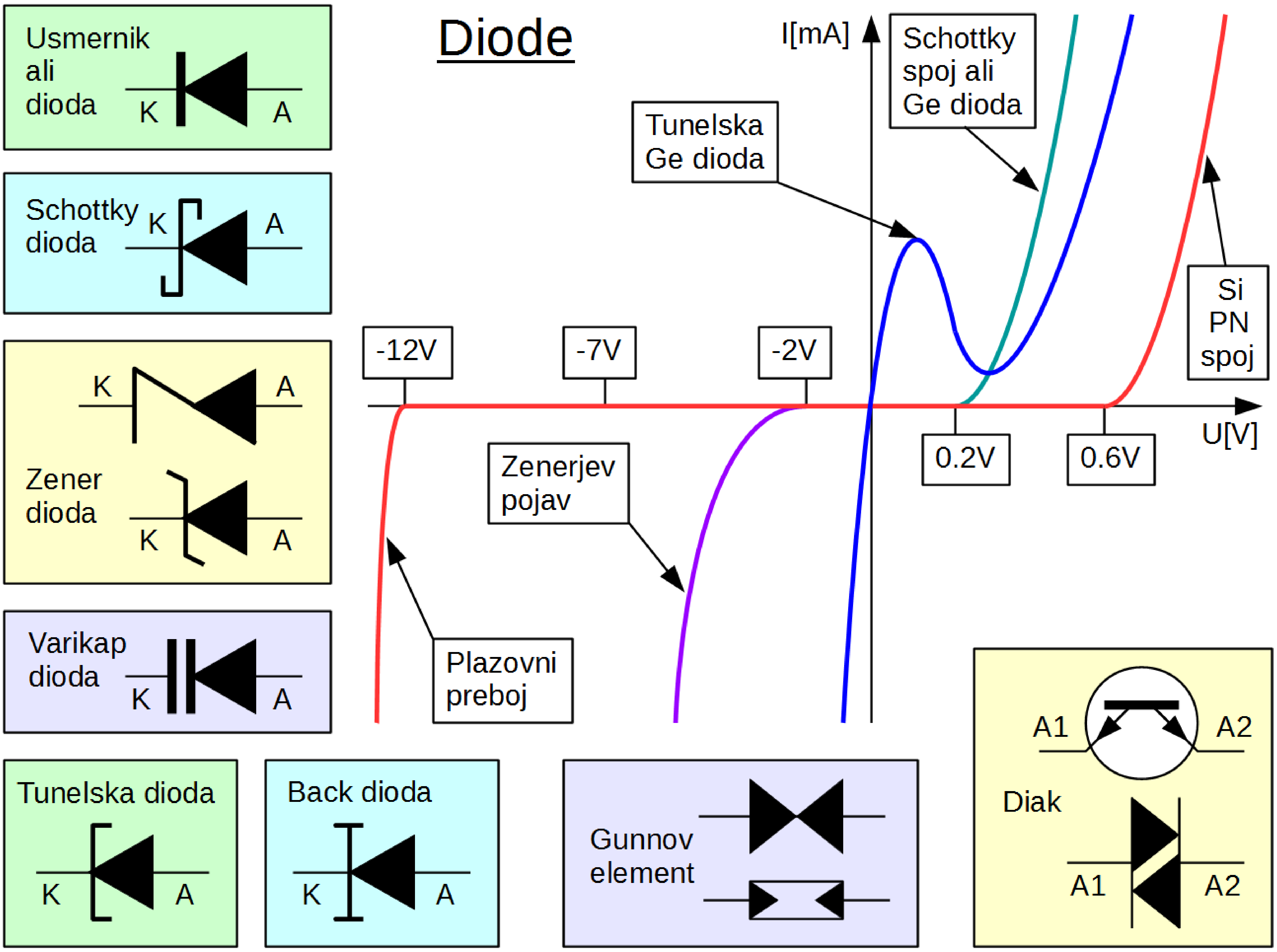
absorber: → prevodna pena

→ guma z delci Fe

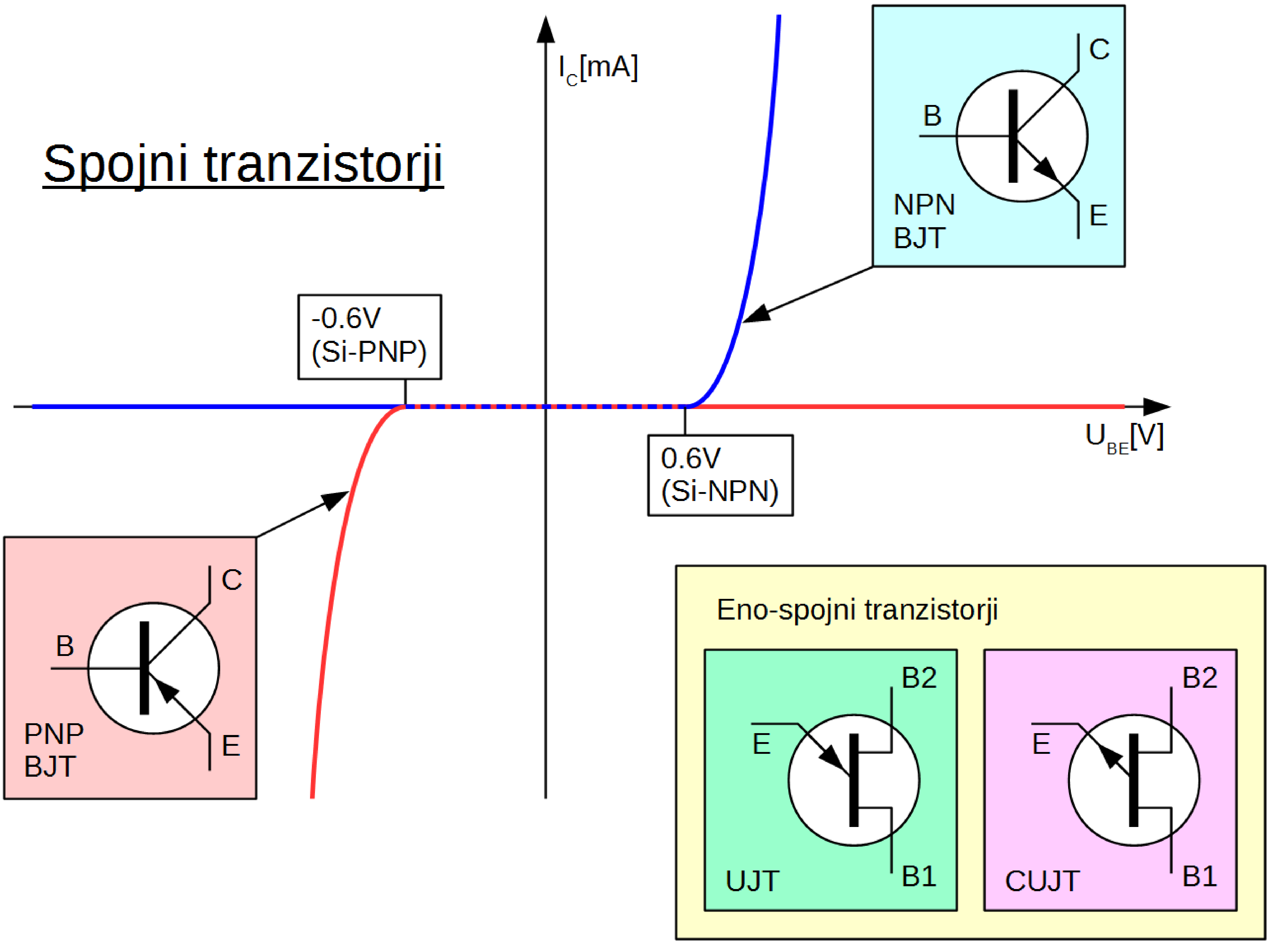
Osnovne električne lastnosti polprevodnikov

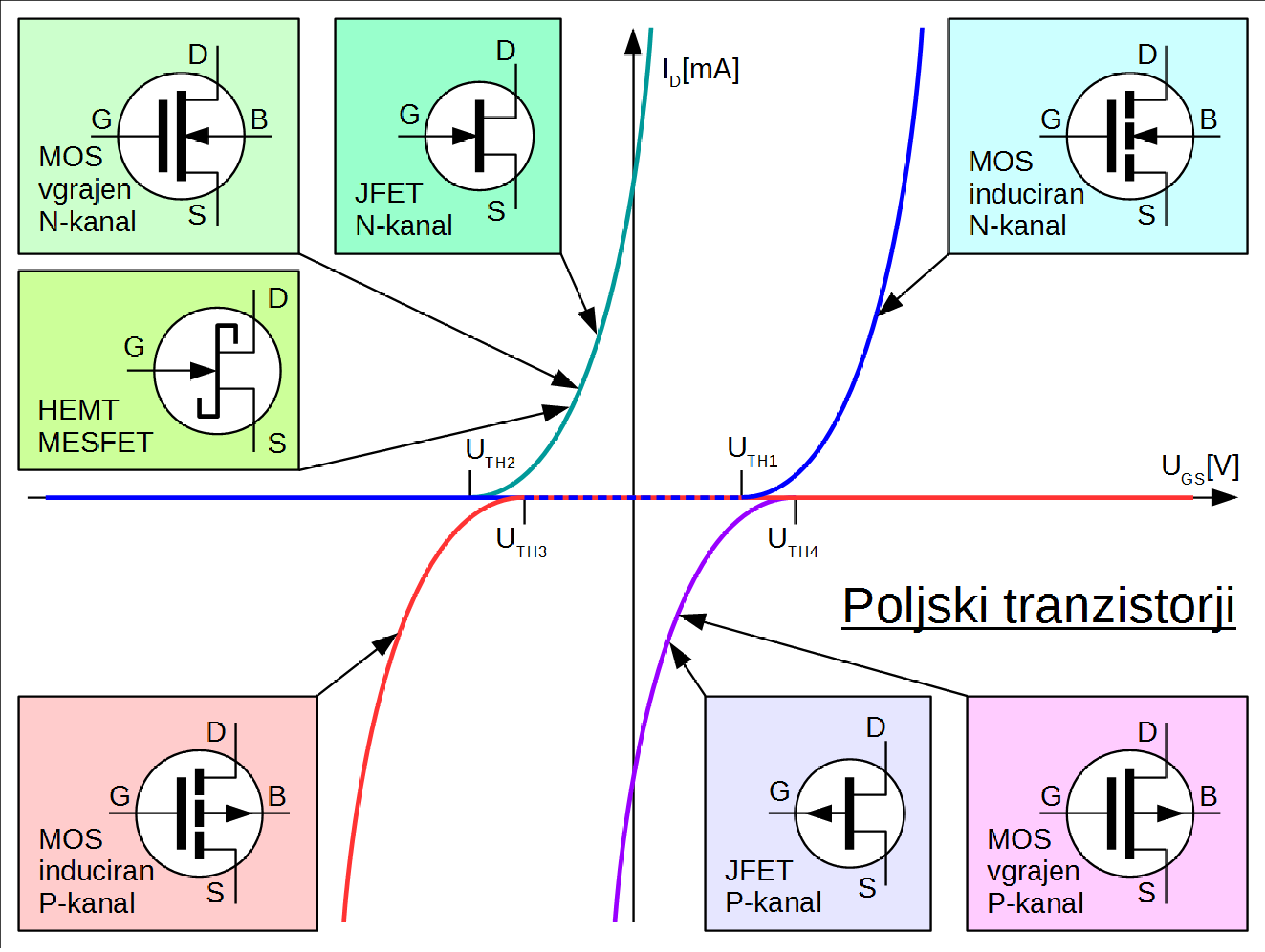
Polprevodnik	Prepovedan energijski pas (bandgap) ΔW [eV]	Prebojna trdnost E_{MAX} [V/cm]	Mobilnost elektronov μ_n [cm^2/Vs]	Mobilnost vrzeli μ_p [cm^2/Vs]
PbS	0.37	(preboj<2V)	600	200
Se	1.95	(preboj<25V)	0.005	0.14
PbSe	0.27		900	700
PbTe	0.32		1700	930
Cu_2O	2.137	(preboj<8V)	0.2	0.1
Si	1.11	$3•10^5$	1400	450
Ge	0.67	10^5	3900	1900
$Si_{1-x}Ge_x$	0.67-1.11	$3•10^5$		
SiO_2	9	10^6-10^7		
Si_3N_4	5.4	$3•10^6$		
C (diamant)	5.5	10^6-10^7	2200	1800
3C-SiC	2.36	10^6	800	320
4H-SiC	3.23	$3•10^6$-$5•10^6$	900	120
6H-SiC	3.05	$3•10^6$-$5•10^6$	400	90
GaAs	1.43	$4•10^5$	5000	400
AlAs	2.16	$6•10^5$	1200	420
$Ga_{1-x}Al_xAs$	1.43-2.16	$4•10^5$-$6•10^5$		
InP	1.344	$5•10^5$	5400	200
GaP	2.26	10^6	250	150
GaSb	0.726	50000	3000	1000
InAs	0.354	40000	40000	400
InSb	0.17	1000	77000	850
GaN	3.4	$5•10^6$	1800	30
AlN	6.28	$1.2•10^6$-$1.8•10^6$	300	14
InN	0.65		3200	
BN	5.4	$3•10^6$-$6•10^6$	200	500
CdS	2.42		400	
CdSe	1.74		650	
CdTe	1.44		1100	100
$Hg_{1-x}Cd_xTe$	0-1.5			

Diode

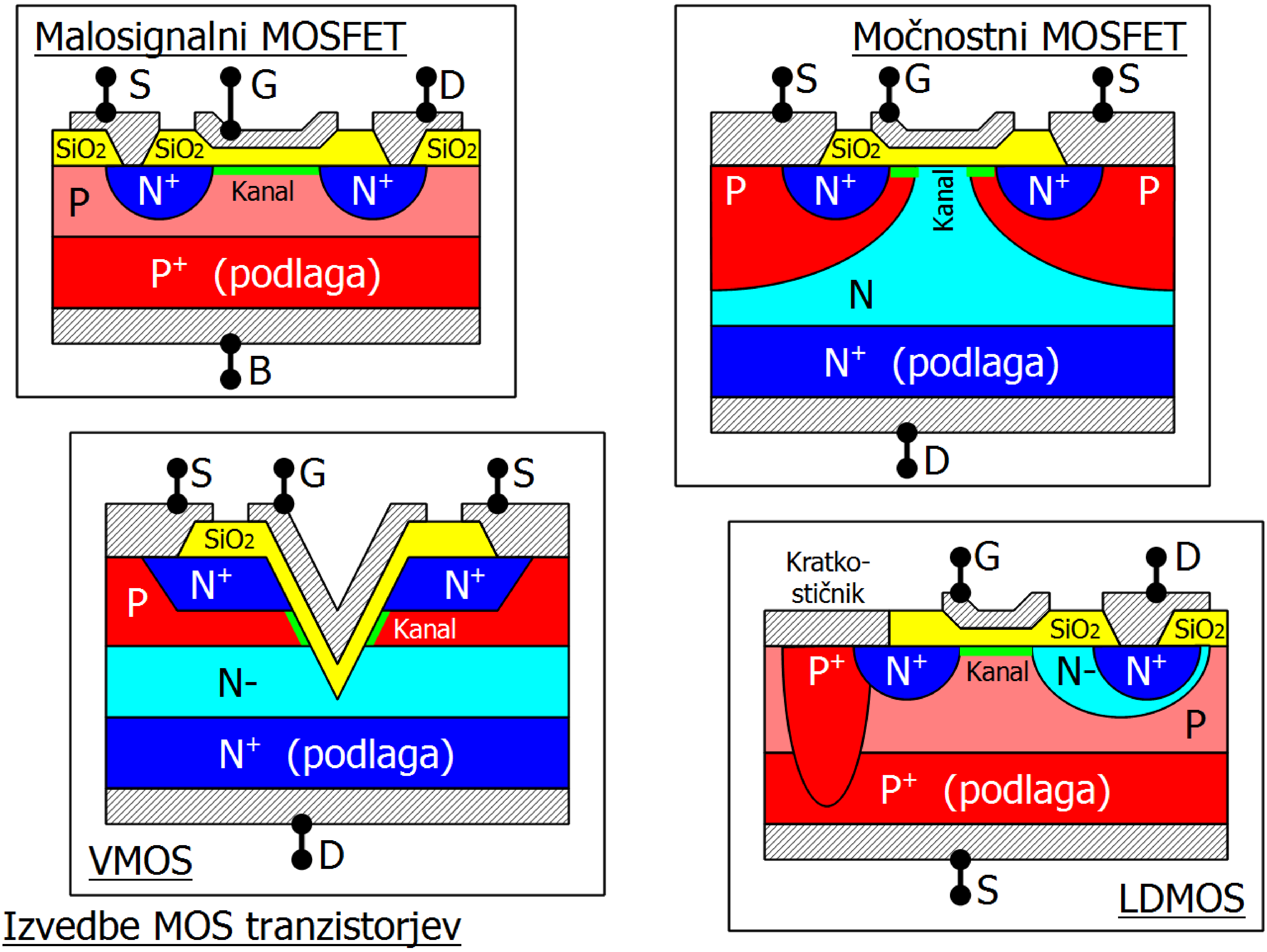


Spojni tranzistorji



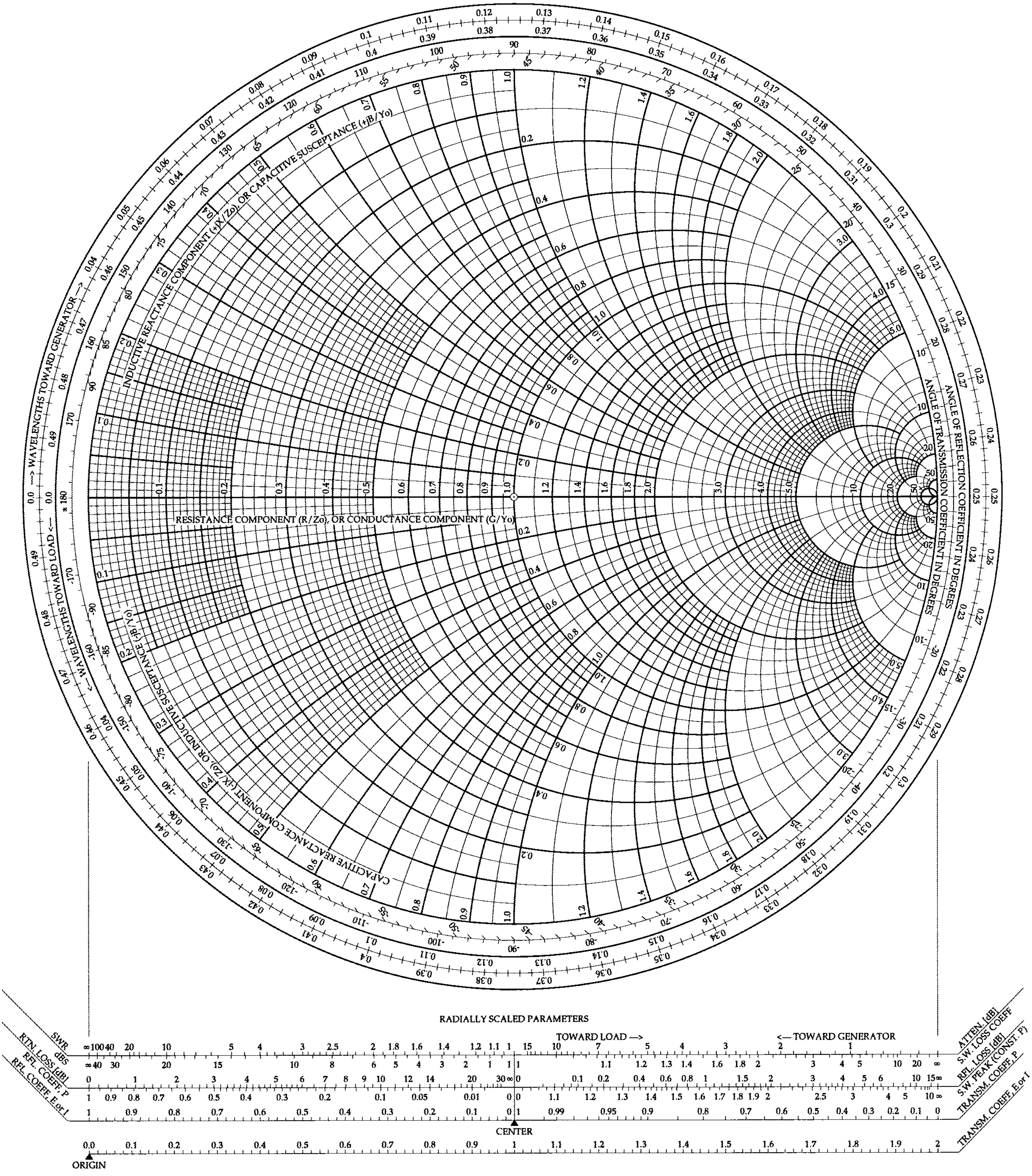


Poljski tranzistorji

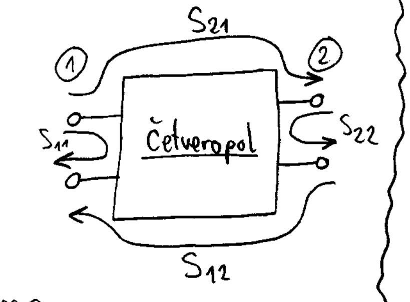


Izvedbe MOS tranzistorjev

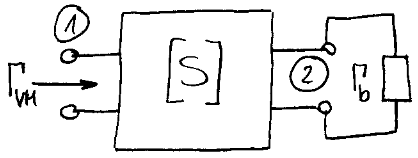
Smith-ov diagram:
impedanca/admitanca v merilu odbojnosti



S-parametri:



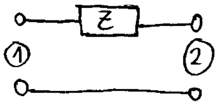
Obremenjen četveropol:



$$\Gamma_{VH} = S_{11} + S_{21}S_{12}\left(\Gamma_b + S_{22}\Gamma_b^2 + S_{22}^2\Gamma_b^3 + \dots\right)$$

$$\Gamma_{VH} = S_{11} + \frac{S_{21}S_{12}\Gamma_b}{1 - S_{22}\Gamma_b}$$

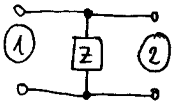
Zaporedni Z:



$$S_{11} = S_{22} = \frac{Z}{Z + 2Z_k}$$

$$S_{21} = S_{12} = \frac{2Z_k}{Z + 2Z_k}$$

Vzporedni Z:



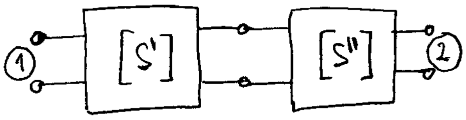
$$S_{11} = S_{22} = \frac{Z \| Z_k - Z_k}{Z \| Z_k + Z_k} = \frac{-Z_k}{2Z + Z_k}$$

$$S_{21} = S_{12} = \frac{2Z \| Z_k}{Z \| Z_k + Z_k} = \frac{2Z}{2Z + Z_k}$$

Verižna četveropola:

$$S_{11} = S'_{11} + \frac{S'_{21}S'_{12}S''_{11}}{1 - S'_{22}S''_{11}}$$

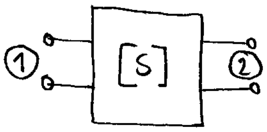
$$S_{12} = \frac{S''_{12}\,S'_{12}}{1 - S'_{22}\,S''_{11}}$$



$$S_{21} = \frac{S'_{21}S''_{21}}{1 - S''_{11}S'_{22}}$$

$$S_{22} = S''_{22} + \frac{S''_{12}S''_{21}S'_{22}}{1 - S'_{22}S''_{11}}$$

Rollett-ova stabilnost:



$$\boxed{\begin{aligned} K &= \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} \\ \Delta &= S_{11}S_{22} - S_{12}S_{21} \end{aligned}}$$

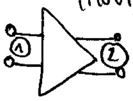
Brezpogojna stabilnost:

$$K > 1 \quad \text{in} \quad |\Delta| < 1$$

$$\left(|S_{11}| < 1 \qquad |S_{22}| < 1\right)$$

Ojačanje:

(moči)



Maximum Available Gain:

$(K > 1)$ RAZPOLOŽLJIVO

$$MAG = \left(K - \sqrt{K^2 - 1}\right)\frac{|S_{21}|}{|S_{12}|}$$

Maximum Stable Gain:

$(K \leq 1)$ STABILNO

$$MSG = \frac{|S_{21}|}{|S_{12}|}$$

Insertion Gain:

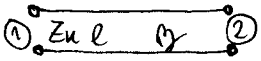
VSTAVITVENO

$$G = |S_{21}|^2$$

Brezizgabni vod:

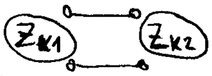
$$S_{11} = S_{22} = 0$$

$$S_{21} = S_{12} = e^{-j\beta l}$$



Skok Zk

$$S_{11} = \frac{Z_{k2} - Z_{k1}}{Z_{k2} + Z_{k1}} \qquad S_{22} = \frac{Z_{k1} - Z_{k2}}{Z_{k1} + Z_{k2}}$$



$$S_{21} = S_{12} = \sqrt{1 - S_{11}^2}$$

Idealni transformator

$$S_{11} = \frac{1 - N^2}{1 + N^2} \qquad S_{22} = \frac{N^2 - 1}{N^2 + 1}$$

$$S_{21} = S_{12} = \frac{2N}{1 + N^2}$$

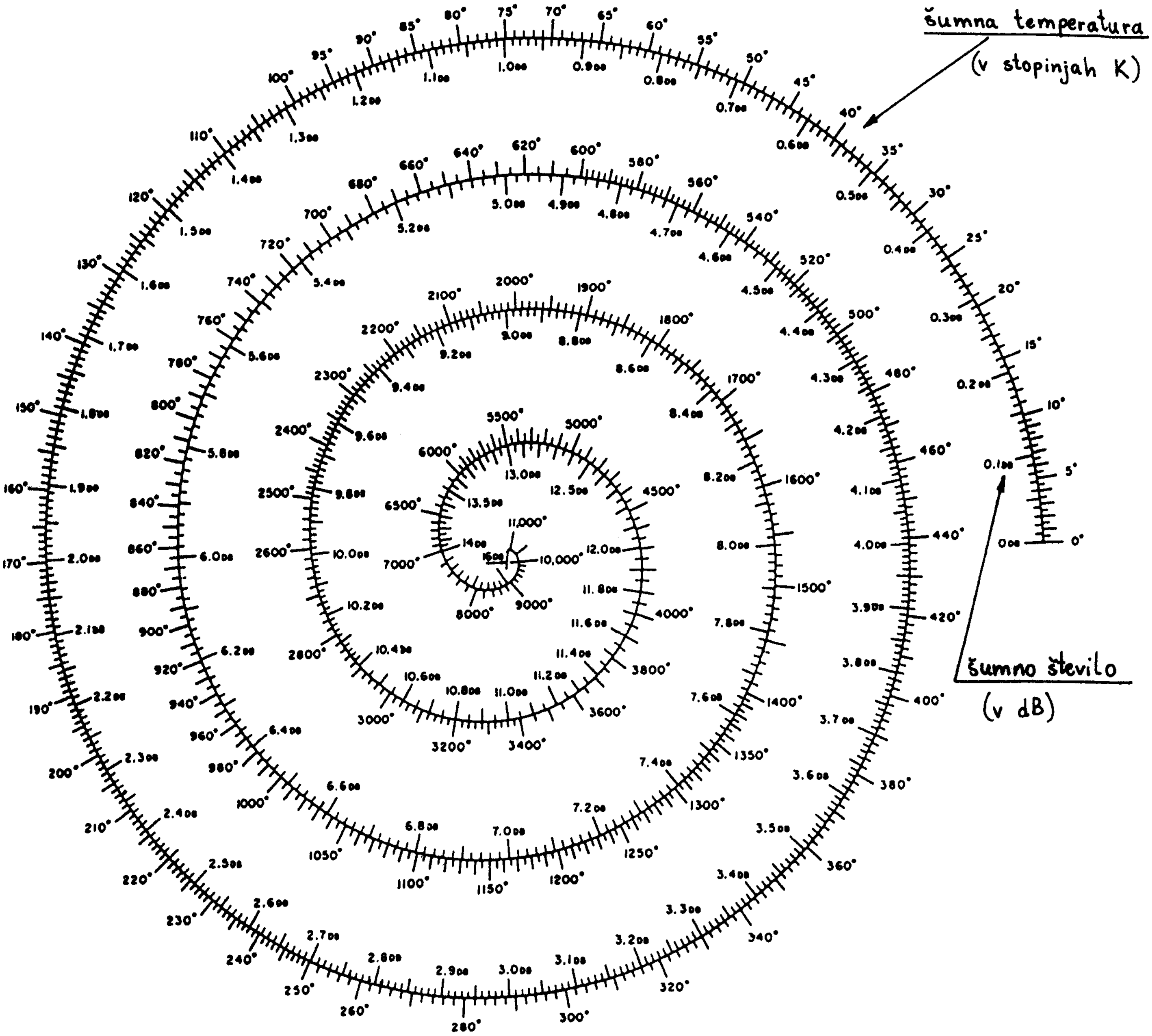
	S	z	y	h	$ABCD$
S	$\begin{matrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{matrix}$	$S_{11} = \frac{(z'_{11} - 1)(z'_{22} + 1) - z'_{12} z'_{21}}{\Delta_1}$ $S_{12} = \frac{2z'_{12}}{\Delta_1}$ $S_{21} = \frac{2z'_{21}}{\Delta_1}$ $S_{22} = \frac{(z'_{11} + 1)(z'_{22} - 1) - z'_{12} z'_{21}}{\Delta_1}$	$S_{11} = \frac{(1 - y'_{11})(1 + y'_{22}) + y'_{12} y'_{21}}{\Delta_2}$ $S_{12} = \frac{-2y'_{12}}{\Delta_2}$ $S_{21} = \frac{-2y'_{21}}{\Delta_2}$ $S_{22} = \frac{(1 + y'_{11})(1 - y'_{22}) + y'_{12} y'_{21}}{\Delta_2}$	$S_{11} = \frac{(h'_{11} - 1)(h'_{22} + 1) - h'_{12} h'_{21}}{\Delta_3}$ $S_{12} = \frac{2h'_{12}}{\Delta_3}$ $S_{21} = \frac{-2h'_{21}}{\Delta_3}$ $S_{22} = \frac{(1 + h'_{11})(1 - h'_{22}) + h'_{12} h'_{21}}{\Delta_3}$	$\begin{matrix} \frac{A' + B' - C' - D'}{\Delta_4} & \frac{2(A'D' - B'C')}{\Delta_4} \\ \frac{2}{\Delta_4} & \frac{-A' + B' - C' + D'}{\Delta_4} \end{matrix}$
z	$z'_{11} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{\Delta_5}$ $z'_{12} = \frac{2S_{12}}{\Delta_5}$ $z'_{21} = \frac{2S_{21}}{\Delta_5}$ $z'_{22} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{\Delta_5}$	$\begin{matrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{matrix}$	$\begin{matrix} \frac{y_{22}}{\lvert y\rvert} & \frac{-y_{12}}{\lvert y\rvert} \\ \frac{-y_{21}}{\lvert y\rvert} & \frac{y_{11}}{\lvert y\rvert} \end{matrix}$	$\begin{matrix} \frac{\lvert h\rvert}{h_{22}} & \frac{h_{12}}{h_{22}} \\ \frac{-h_{21}}{h_{22}} & \frac{1}{h_{22}} \end{matrix}$	$\begin{matrix} \frac{A}{C} & \frac{\Delta_8}{C} \\ \frac{1}{C} & \frac{D}{C} \end{matrix}$
y	$y'_{11} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{\Delta_6}$ $y'_{12} = \frac{-2S_{12}}{\Delta_6}$ $y'_{21} = \frac{-2S_{21}}{\Delta_6}$ $y'_{22} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{\Delta_6}$	$\begin{matrix} \frac{z_{22}}{\lvert z\rvert} & \frac{-z_{12}}{\lvert z\rvert} \\ \frac{-z_{21}}{\lvert z\rvert} & \frac{z_{11}}{\lvert z\rvert} \end{matrix}$	$\begin{matrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{matrix}$	$\begin{matrix} \frac{1}{h_{11}} & \frac{-h_{12}}{h_{11}} \\ \frac{h_{21}}{h_{11}} & \frac{\lvert h\rvert}{h_{11}} \end{matrix}$	$\begin{matrix} \frac{D}{B} & \frac{-\Delta_8}{B} \\ \frac{-1}{B} & \frac{A}{B} \end{matrix}$
h	$h'_{11} = \frac{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}{\Delta_7}$ $h'_{12} = \frac{2S_{12}}{\Delta_7}$ $h'_{21} = \frac{-2S_{21}}{\Delta_7}$ $h'_{22} = \frac{(1 - S_{22})(1 - S_{11}) - S_{12} S_{21}}{\Delta_7}$	$\begin{matrix} \frac{\lvert z\rvert}{z_{22}} & \frac{z_{12}}{z_{22}} \\ \frac{-z_{21}}{z_{22}} & \frac{1}{z_{22}} \end{matrix}$	$\begin{matrix} \frac{1}{y_{11}} & \frac{-y_{12}}{y_{11}} \\ \frac{y_{21}}{y_{11}} & \frac{\lvert y\rvert}{y_{11}} \end{matrix}$	$\begin{matrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{matrix}$	$\begin{matrix} \frac{B}{D} & \frac{\Delta_8}{D} \\ \frac{-1}{D} & \frac{C}{D} \end{matrix}$
$ABCD$	$A' = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{2S_{21}}$ $B' = \frac{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}{2S_{21}}$ $C' = \frac{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}{2S_{21}}$ $D' = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{2S_{21}}$	$\begin{matrix} \frac{z_{11}}{z_{21}} & \frac{\lvert z\rvert}{z_{21}} \\ \frac{1}{z_{21}} & \frac{z_{22}}{z_{21}} \end{matrix}$	$\begin{matrix} \frac{-y_{22}}{y_{21}} & \frac{-1}{y_{21}} \\ \frac{-\lvert y\rvert}{y_{21}} & \frac{-y_{11}}{y_{21}} \end{matrix}$	$\begin{matrix} \frac{-\lvert h\rvert}{h_{21}} & \frac{-h_{11}}{h_{21}} \\ \frac{-h_{22}}{h_{21}} & \frac{-1}{h_{21}} \end{matrix}$	$\begin{matrix} A & B \\ C & D \end{matrix}$

$\Delta_1 = (z'_{11} + 1)(z'_{22} + 1) - z'_{12} z'_{21}$
$\Delta_2 = (1 + y'_{11})(1 + y'_{22}) - y'_{12} y'_{21}$
$\Delta_3 = (h'_{11} + 1)(h'_{22} + 1) - h'_{12} h'_{21}$
$\Delta_4 = A' + B' + C' + D'$
$\Delta_5 = (1 - S_{11})(1 - S_{22}) - S_{12} S_{21}$
$\Delta_6 = (1 + S_{11})(1 + S_{22}) - S_{12} S_{21}$
$\Delta_7 = (1 - S_{11})(1 + S_{22}) + S_{12} S_{21}$
$\Delta_8 = AD - BC$

$z'_{11} = z_{11}/Z_0, \quad z'_{12} = z_{12}/Z_0, \quad z'_{21} = z_{21}/Z_0, \quad z'_{22} = z_{22}/Z_0$
$y'_{11} = y_{11}Z_0, \quad y'_{12} = y_{12}Z_0, \quad y'_{21} = y_{21}Z_0, \quad y'_{22} = y_{22}Z_0$
$h'_{11} = h_{11}/Z_0, \quad h'_{12} = h_{12}, \quad h'_{21} = h_{21}, \quad h'_{22} = h_{22}Z_0$
$A' = A, \quad B' = B/Z_0, \quad C' = CZ_0, \quad D' = D$
$|z| = z_{11}z_{22} - z_{12}z_{21}$
$|y| = y_{11}y_{22} - y_{12}y_{21}$
$|h| = h_{11}h_{22} - h_{12}h_{21}$

Z = impedančna matrika
Y = admitančna matrika
h = hibridna matrika
ABCD = verižna matrika

Pretvorbe parametrov četveropola

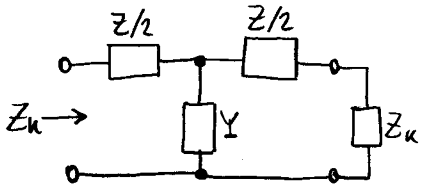


$$F[dB] = 10 \cdot \log_{10}\left(1 + \frac{T}{290\ K}\right)$$

$$T[\ K] = 290\ K \cdot \left(\ 10^{\frac{F}{10}} - 1\right)$$

<u>Povezava med šumno temperaturo in šumnim številom</u>

Frekvenčna sita: izračun Z_k odseka T



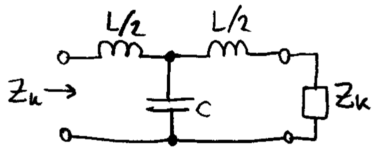
$$Z_k=\frac{Z}{2}+\cfrac{1}{Y+\cfrac{1}{\frac{Z}{2}+Z_k}}$$

$$\frac{Z}{Z_k^2-\left(\frac{Z}{2}\right)^2}=Y$$

$$\frac{1}{Z_k-\frac{Z}{2}}-\frac{1}{Z_k+\frac{Z}{2}}=Y$$

$$\boxed{Z_k=\sqrt{\frac{Z}{Y}+\left(\frac{Z}{2}\right)^2}}$$

LPF = nizkoprepustno:



$$Z=j\omega L$$

$$Y=j\omega C$$

$$\boxed{Z_k=\sqrt{\frac{L}{C}-\left(\frac{\omega L}{2}\right)^2}}$$

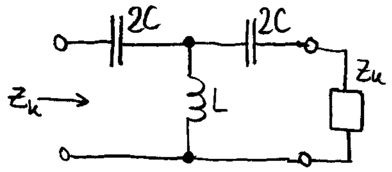
$$\omega<\omega_0\rightarrow Z_k=R$$

$$\omega>\omega_0\rightarrow Z_k=jX$$

$$\boxed{Z_k=0}\rightarrow\frac{L}{C}-\left(\frac{\omega_0 L}{2}\right)^2=0$$

$$\boxed{\omega_0=\frac{2}{\sqrt{LC}}}$$

HPF = visokoprepustno:



$$Z=\frac{1}{j\omega C}$$

$$Y=\frac{1}{j\omega L}$$

$$\boxed{Z_k=\sqrt{\frac{L}{C}-\left(\frac{1}{2\omega C}\right)^2}}$$

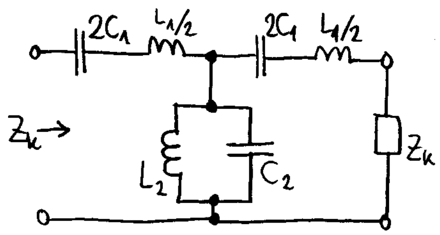
$$\omega<\omega_0\rightarrow Z_k=-jX$$

$$\omega>\omega_0\rightarrow Z_k=R$$

$$\boxed{Z_k=0}\rightarrow\frac{L}{C}-\left(\frac{1}{2\omega_0 C}\right)^2=0$$

$$\boxed{\omega_0=\frac{1}{2\sqrt{LC}}}$$

BPF = pasovno prepustno:



$$Z=\frac{1}{j\omega C_1}+j\omega L_1=j\left(\omega L_1-\frac{1}{\omega C_1}\right)$$

$$Y=\frac{1}{j\omega L_2}+j\omega C_2=j\left(\omega C_2-\frac{1}{\omega L_2}\right)$$

$$\omega<\omega_{0-}\rightarrow Z_k=-jX$$

$$\omega_{0-}<\omega<\omega_{0+}\rightarrow Z_k=R$$

$$\omega>\omega_{0+}\rightarrow Z_k=jX$$

$$\boxed{Z_k=\sqrt{\frac{\omega L_1-\frac{1}{\omega C_1}}{\omega C_2-\frac{1}{\omega L_2}}-\left(\frac{\omega L_1-\frac{1}{\omega C_1}}{2}\right)^2}}$$

$$\boxed{Z_k=0}$$

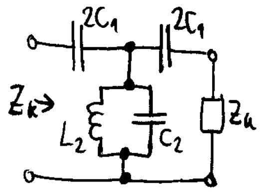
$$4=\left(\omega_0 L_1-\frac{1}{\omega_0 C_1}\right)\left(\omega_0 C_2-\frac{1}{\omega_0 L_2}\right)$$

$$\omega_0^4 L_1 C_2-\omega_0^2\left(\frac{L_1}{L_2}+\frac{C_2}{C_1}+4\right)+\frac{1}{L_2 C_1}=0$$

$$\boxed{\omega_0=\sqrt{\frac{\left(\frac{L_1}{L_2}+\frac{C_2}{C_1}+4\right)\pm\sqrt{\left(\frac{L_1}{L_2}+\frac{C_2}{C_1}+4\right)^2-4\frac{L_1C_2}{L_2C_1}}}{2L_1C_2}}}$$

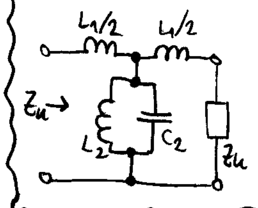
BPF (C_1,C_2,L_2)

$$L_1=0$$



BPF (C_2,L_1,L_2)

$$C_1\rightarrow\infty$$

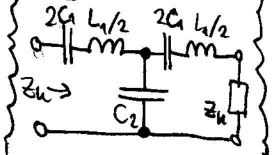


$$\boxed{Z_k=0}\rightarrow\omega_0=\frac{1}{\sqrt{L_2(4C_1+C_2)}}$$

$$\boxed{Z_k=\infty}\rightarrow\omega_\infty=\frac{1}{\sqrt{L_2C_2}}$$

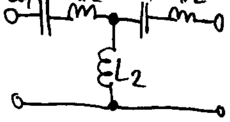
BPF (C_1,C_2,L_1)

$$L_2\rightarrow\infty$$



BPF (C_1,L_1,L_2)

$$C_2=0$$



$$\omega<\omega_0\rightarrow Z_k=-jX$$

$$\omega_0<\omega<\omega_\infty\rightarrow Z_k=R$$

$$\omega>\omega_\infty\rightarrow Z_k=-jX$$

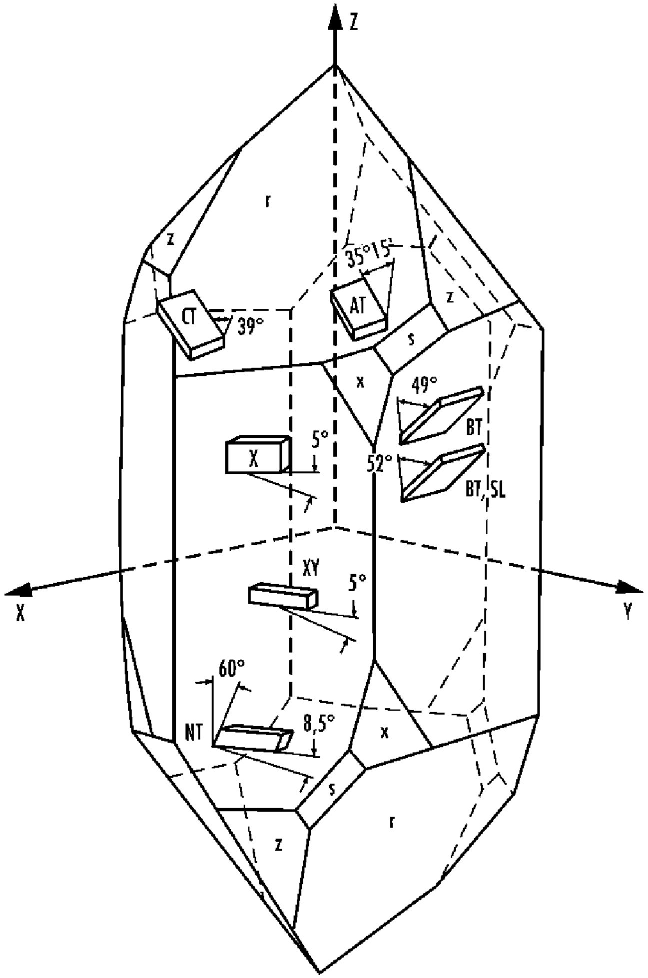
BPF $L_1C_1=L_2C_2$

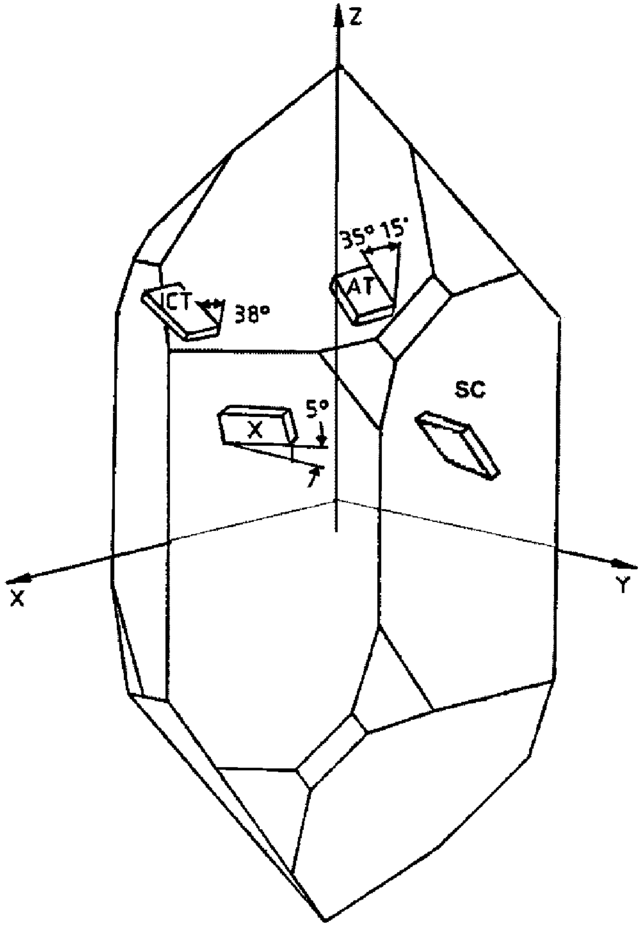
$$\frac{L_1}{L_2}=\frac{C_2}{C_1}=m$$

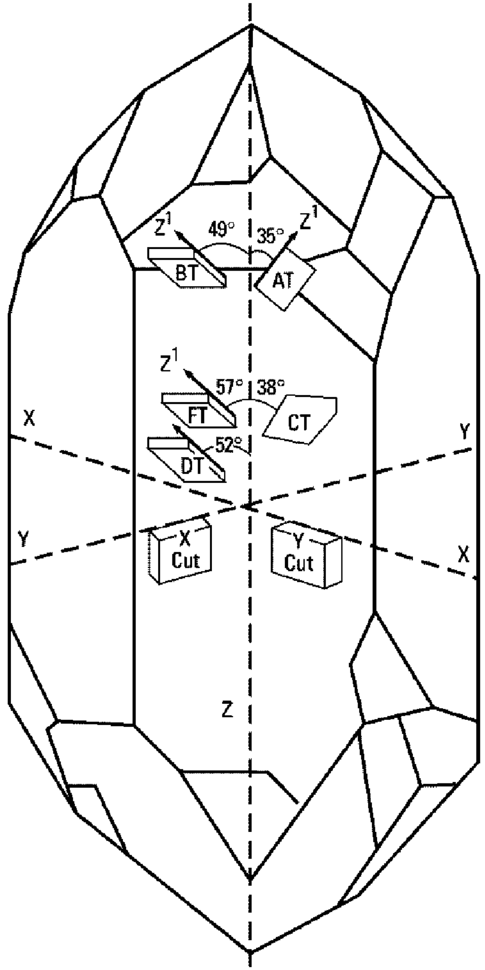
$$\frac{1}{\sqrt{L_1C_1}}=\frac{1}{\sqrt{L_2C_2}}=\omega_R$$

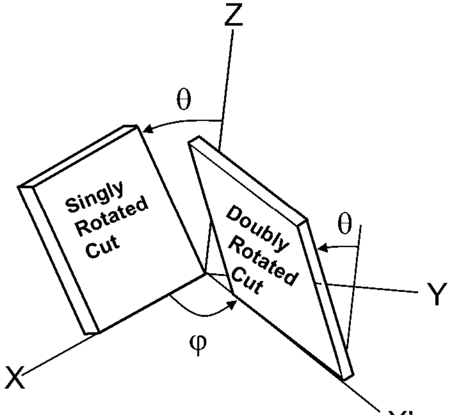
$$\omega_0=\omega_R\sqrt{\frac{m+2\pm2\sqrt{m+1}}{m}}$$

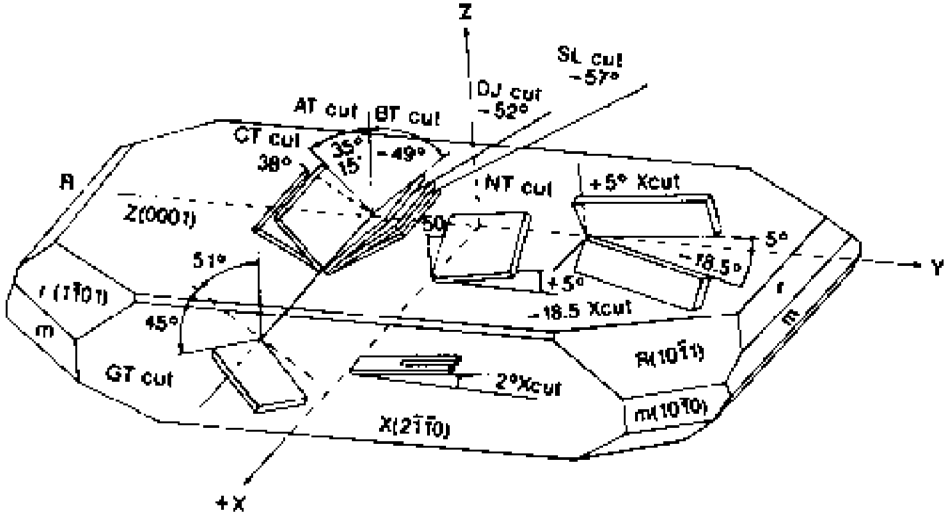
$$Z_k=\sqrt{\frac{1}{m}\left(\frac{L_1}{C_1}\right)-\left(\frac{\omega L_1-\frac{1}{\omega C_1}}{2}\right)^2}$$





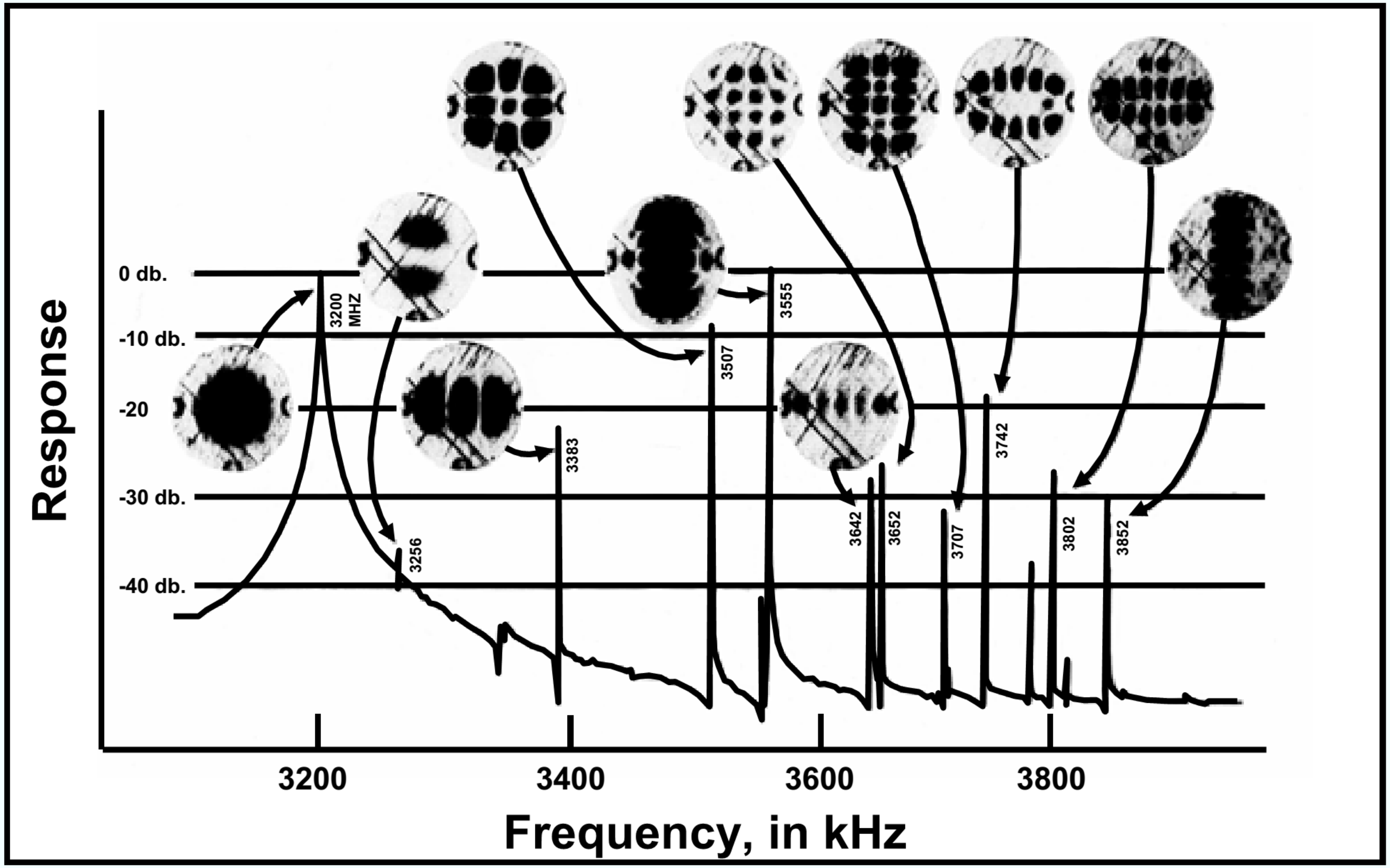






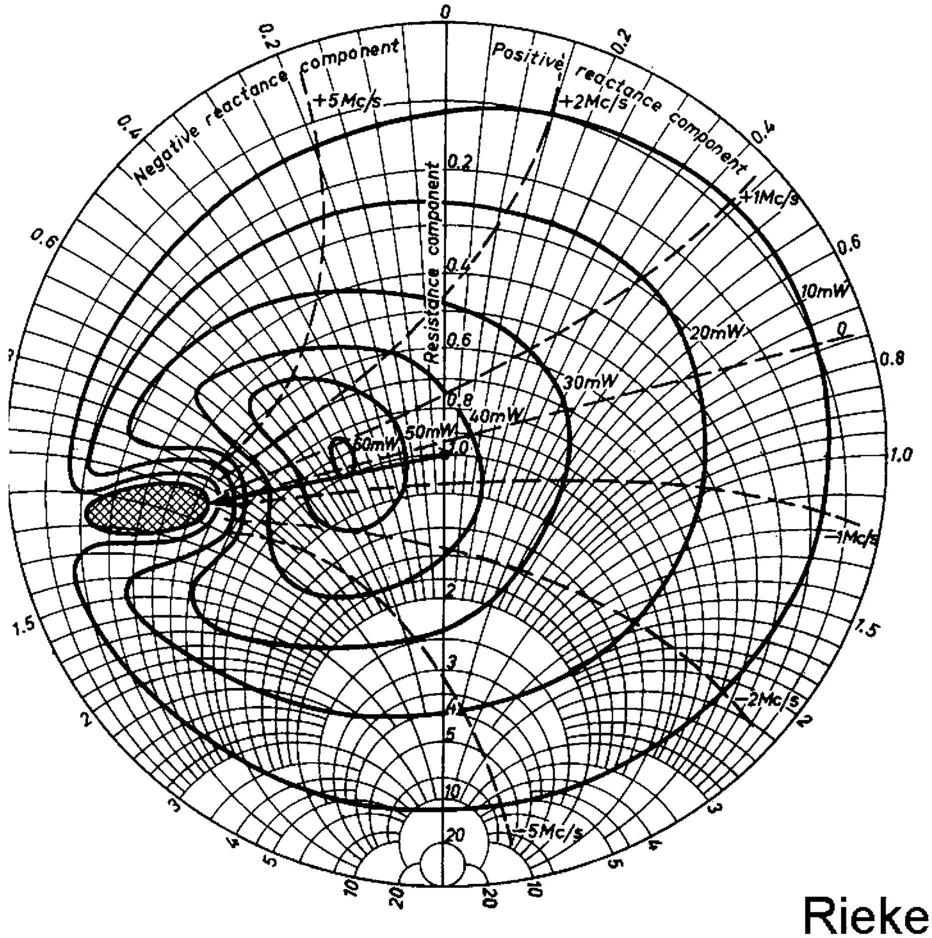
Rezine kristala kremena

Resonant Vibrations of a Quartz Plate



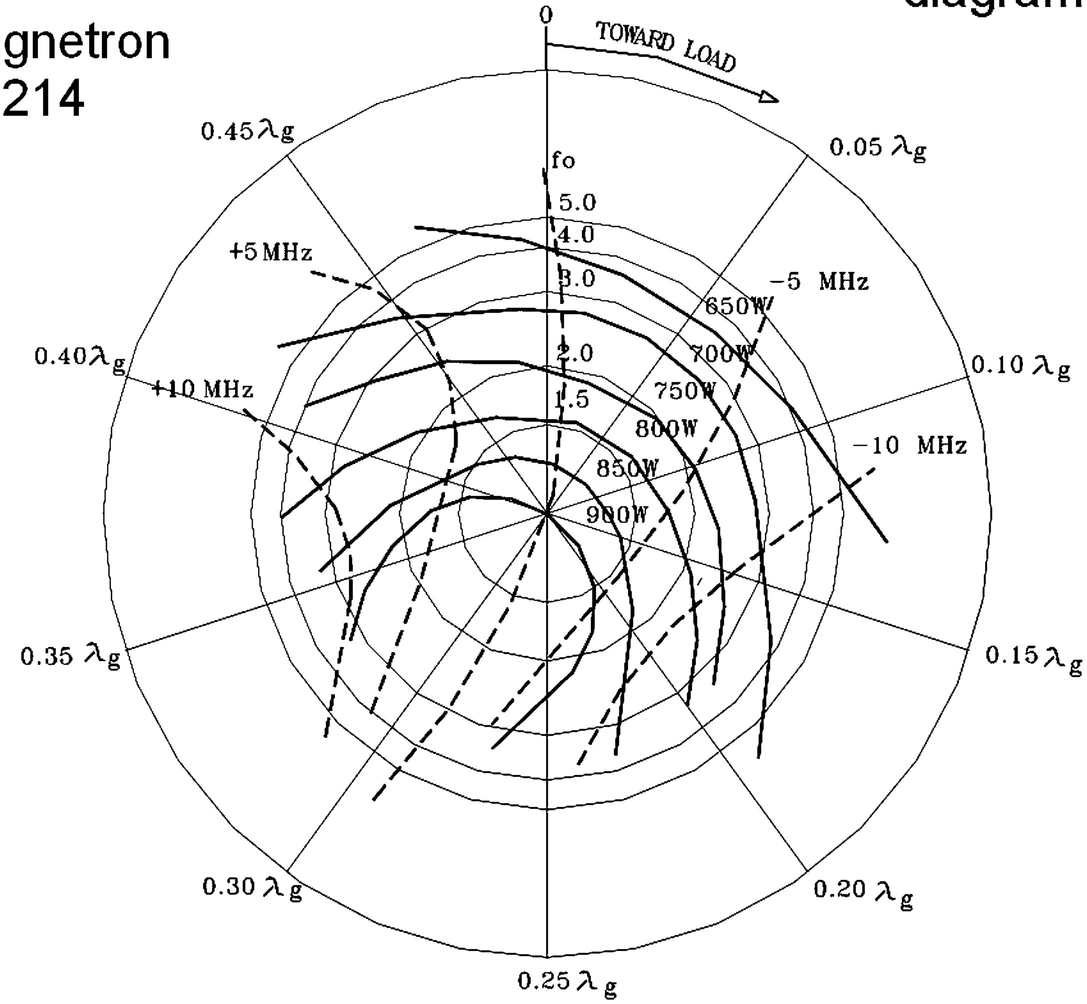
X-ray topographs (21•$\bar{0}$ plane) of various modes excited during a frequency scan of a fundamental mode, circular, AT-cut resonator. The first peak, at 3.2 MHz, is the main mode; all others are unwanted modes. Dark areas correspond to high amplitudes of displacement.

Refleksni
klistron
2K25

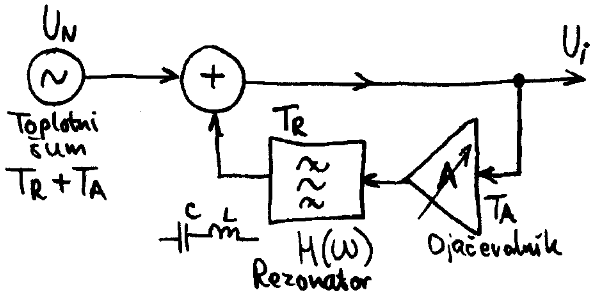


Rieke-jev
diagram

Magnetron
2M214



Fazni šum visokofrekvenčnega oscilatorja



$$U_i = U_N + U_i A H(\omega)$$

$$U_i = \frac{U_N}{1 - A H(\omega)}$$

Ustaljeno nihanje oscilatorja @ ω_0 ⟶ A nastavljen za $A H(\omega_0) = 1$

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

$\omega = \omega_0 + \Delta\omega$ (majhen odmik $\Delta\omega \ll \omega_0$)

$$j\omega L = j\omega_0 L + j\Delta\omega L$$

$$\frac{1}{j\omega C} = \frac{1}{j\omega_0(1+\frac{\Delta\omega}{\omega_0})C} \approx \frac{1}{j\omega_0 C}\left(1-\frac{\Delta\omega}{\omega_0}\right)$$

$$A H(\omega) \approx \frac{1}{1+\frac{2j\Delta\omega L}{\Sigma R}}$$

$$j\omega L + \frac{1}{j\omega C} \approx j\Delta\omega L - \frac{1}{j\omega_0 C}\,\frac{\Delta\omega}{\omega_0} = 2j\Delta\omega L$$

$$A H(\omega) \approx \frac{1}{1+2jQ_L\frac{\Delta\omega}{\omega_0}}$$

$$\frac{2j\Delta\omega L}{\Sigma R} = 2j\,\frac{\omega_0 L}{\Sigma R}\,\frac{\Delta\omega}{\omega_0} = 2j\underset{\uparrow}{Q_L}\frac{\Delta\omega}{\omega_0}$$

obremenjeni Q

$$U_i = \frac{U_N}{1-\frac{1}{1+2jQ_L\frac{\Delta\omega}{\omega_0}}} = U_N\left(1+\frac{1}{2jQ_L}\,\frac{\omega_0}{\Delta\omega}\right)$$

$$P = \alpha|U|^2$$

$$P_i = P_N\left[1+\left(\frac{1}{2Q_L}\cdot\frac{\omega_0}{\Delta\omega}\right)^2\right] = P_N\left[1+\left(\frac{1}{2Q_L}\cdot\frac{f_0}{\Delta f}\right)^2\right]$$

$$P_N = B\,k_B\,(T_R+T_A) = B\,k_B\,T_0\,F\left(1+\frac{f_c}{|\Delta f|}\right)$$

Šum 1/f:

BJT, JFET → $f_c = 1\text{kHz} - 10\text{kHz}$

MOSFET, GaAsFET, HEMT → $f_c = 1\text{MHz} - 10\text{MHz}$

$$L(\Delta f) = \underset{\uparrow}{\frac{1}{2}}\,\frac{P_i}{P_0 B} = \frac{1}{2}\left[1+\left(\frac{f_0}{2Q_L\Delta f}\right)^2\right]\frac{k_B T_0 F}{P_0}\left(1+\frac{f_c}{|\Delta f|}\right) \quad [/\text{Hz}]$$

SPEKTRALNA GOSTOTA FAZNEGA ŠUMA

brez amplitudnega šuma

Leeson-ova enačba (David B. Leeson 1966)

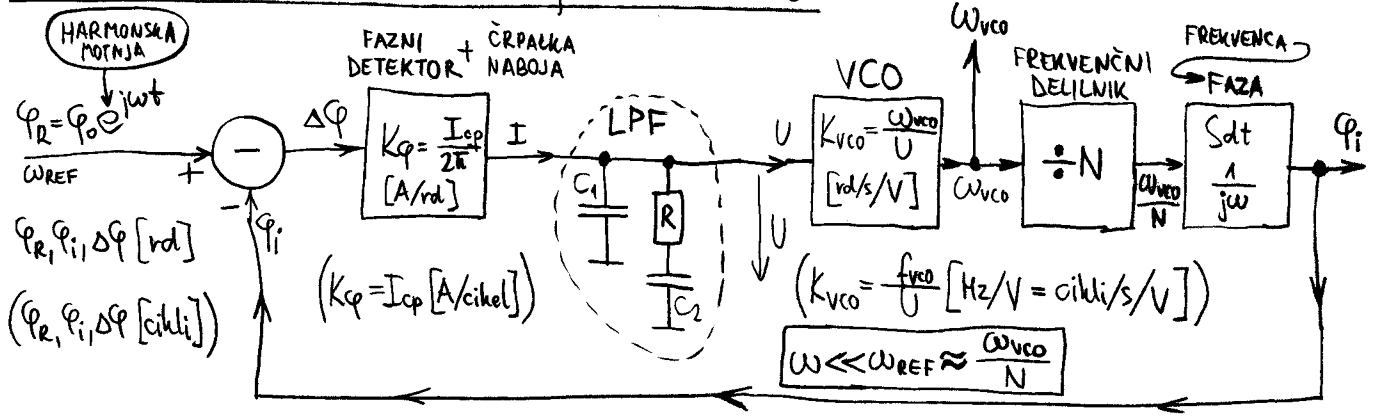
$$L(\Delta f)_{dBc} = 10\log_{10}\frac{1}{2}\left[1+\left(\frac{f_0}{2Q_L\Delta f}\right)^2\right]\frac{k_B T_0 F}{P_0}\left(1+\frac{f_c}{|\Delta f|}\right)\cdot 1\text{Hz} \quad [\text{dBc}/\text{Hz}]$$

Fazni šum: $\sigma_\varphi(f_a,f_b) = \sqrt{2\int_{f_a}^{f_b} L(\Delta f)\,d\Delta f}$ [rd] Residual PM noise

Frekvenčni šum: $\sigma_f(f_a,f_b) = \sqrt{2\int_{f_a}^{f_b} \Delta f^2 L(\Delta f)\,d\Delta f}$ [Hz] Residual FM noise

Drhtenje (jitter): $\sigma_t(f_a,f_b) = \frac{\sigma_\varphi(f_a,f_b)}{2\pi f_0} = \frac{1}{2\pi f_0}\sqrt{2\int_{f_a}^{f_b} L(\Delta f)\,d\Delta f}$ [s]

Stabilnost fazno - sklenjene zanke



$\varphi_R, \varphi_i, \Delta\varphi\ [rd]$

$(\varphi_R, \varphi_i, \Delta\varphi\ [cikli])$

$(K_\varphi = I_{cp}\ [A/cikel])$

$\left(K_{VCO} = \frac{f_{VCO}}{U}\ [Hz/V = cikli/s/V]\right)$

$$\boxed{\omega \ll \omega_{REF} \approx \frac{\omega_{VCO}}{N}}$$

$$\Delta\varphi = \varphi_R - \varphi_i = \varphi_R - \Delta\varphi H(\omega) \longrightarrow \Delta\varphi = \frac{\varphi_R}{1+H(\omega)} \quad ; \quad \varphi_i = \varphi_R \frac{H(\omega)}{1+H(\omega)}$$

$$H(\omega) = K_\varphi \cdot \frac{1}{j\omega C_1 + \frac{1}{R+\frac{1}{j\omega C_2}}} \cdot K_{VCO} \cdot \frac{1}{N} \cdot \frac{1}{j\omega} = \frac{K_\varphi K_{VCO}}{j\omega N} \cdot \frac{j\omega R C_2 + 1}{-\omega^2 R C_1 C_2 + j\omega(C_1+C_2)}$$

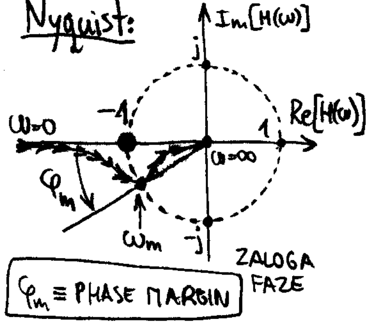
SKLADNE MERSKE ENOTE

$$\boxed{H(\omega) = -\frac{K_\varphi K_{VCO}}{\omega^2 (C_1+C_2) N} \cdot \frac{1+j\omega R C_2}{1+j\omega R \frac{C_1 C_2}{C_1+C_2}} = -\frac{K_\varphi K_{VCO}}{\omega^2 (C_1+C_2) N} \cdot \frac{1+j\omega\tau_2}{1+j\omega\tau_1}}$$

$\tau_2 = R C_2$

$\tau_1 = R \frac{C_1 C_2}{C_1+C_2}$

Nyquist:



$\boxed{\varphi_m \equiv \text{PHASE MARGIN}}$

$$\varphi_m = \mathrm{arctg} \frac{\omega_m(\tau_2 - \tau_1)}{1+\omega_m^2 \tau_1 \tau_2} \qquad 0 = \frac{d}{d\omega_m}\left(\frac{\omega_m(\tau_2-\tau_1)}{1+\omega_m^2\tau_1\tau_2}\right) = \frac{(\tau_2-\tau_1)(1-\omega_m^2\tau_1\tau_2)}{(1+\omega_m^2\tau_1\tau_2)^2}$$

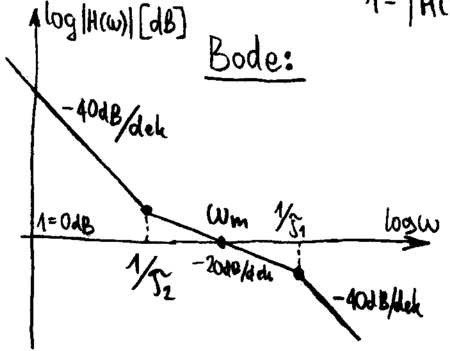
$$\boxed{\varphi_m = \mathrm{arctg} \frac{m-1}{2\sqrt{m}}} \qquad \omega_m = \frac{1}{\sqrt{\tau_2\tau_1}} = \frac{1}{\tau_1\sqrt{m}} \qquad \tau_2 = m\,\tau_1$$

$$1 = |H(\omega_m)| = \frac{K_\varphi K_{VCO}}{\omega_m^2 N C_1 m} \cdot \sqrt{\frac{1+m}{1+\frac{1}{m}}} = \frac{K_\varphi K_{VCO}}{\omega_m^2 N C_1 \sqrt{m}}$$

$$\boxed{C_2 = (m-1) C_1}$$

$$\boxed{C_1 = \frac{K_\varphi K_{VCO}}{\omega_m^2 N \sqrt{m}}}$$

Bode:

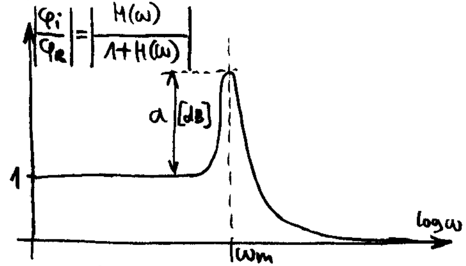


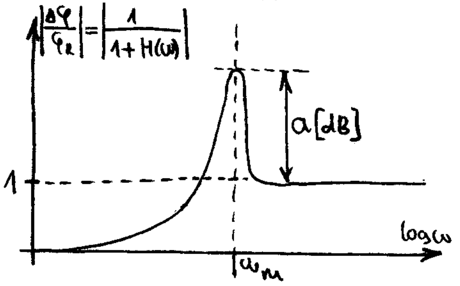
m	C_2/C_1	$\varphi_m[°]$	$a[dB] \approx -20\log\varphi_m[rd]$
1	0	0°	∞dB
1.1	0.1	2.7°	26.4dB
1.2	0.2	5.2°	20.8dB
1.5	0.5	11.5°	13.9dB
2	1	19.5°	9.4dB
3	2	30.0°	5.6dB
5	4	41.8°	2.7dB
10	9	54.9°	0.4dB
20	19	64.8°	—
50	49	73.9°	—
100	99	78.6°	—
200	199	81.9°	—

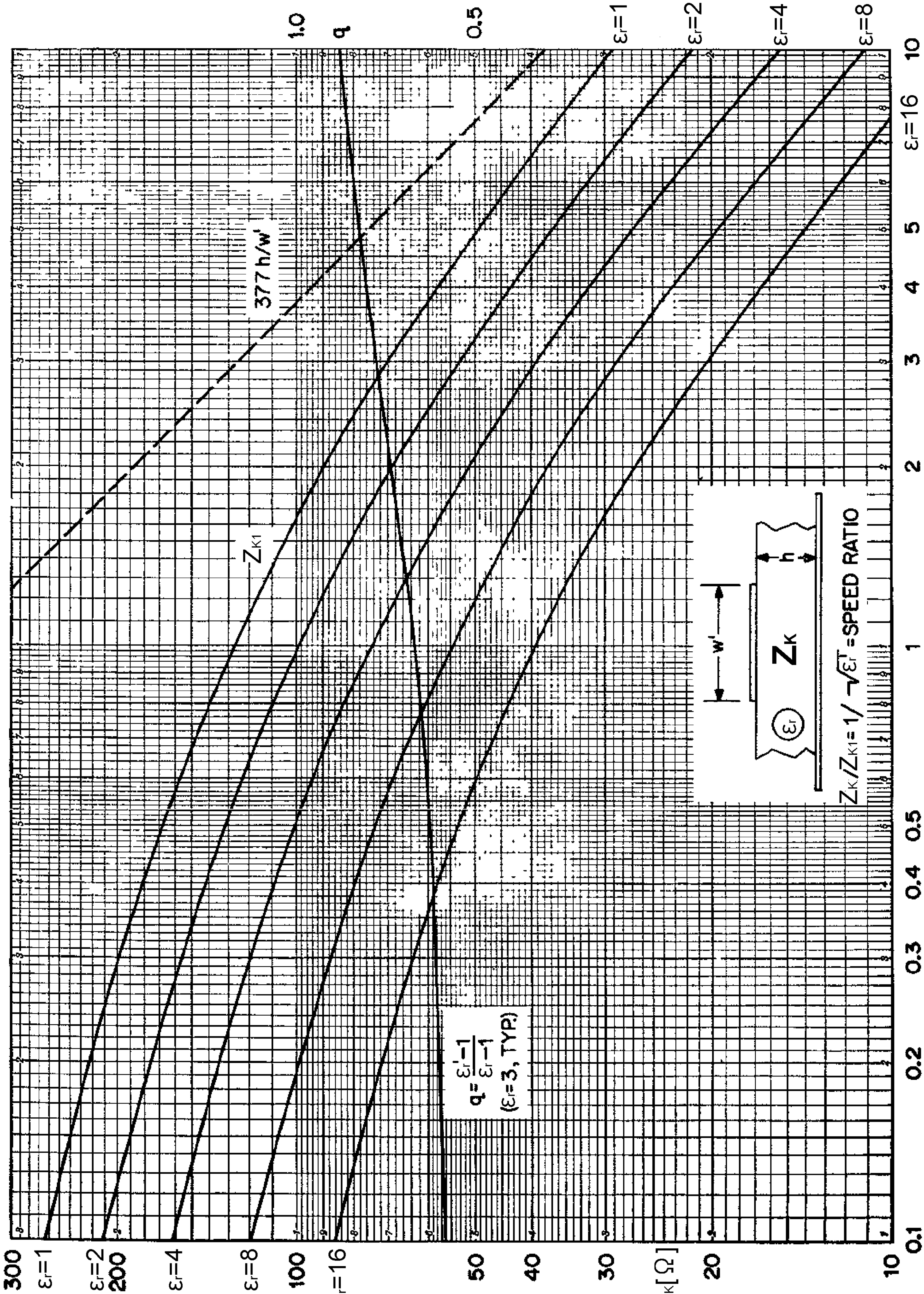
$$\boxed{R = \frac{\sqrt{m}}{\omega_m C_2}}$$

$$\boxed{\omega_m = \sqrt{\frac{K_\varphi K_{VCO}}{N C_1 \sqrt{m}}}}$$

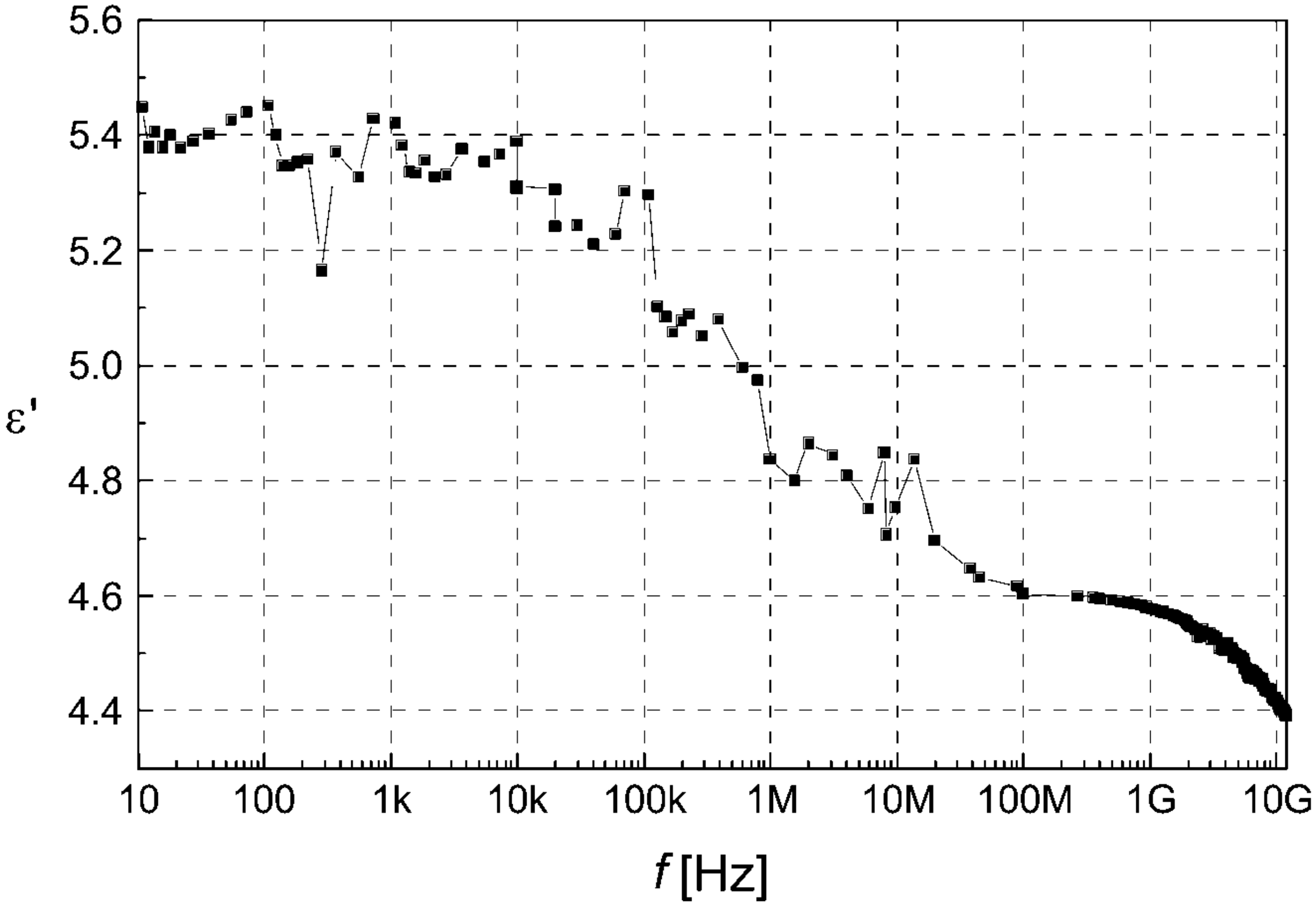
$$B_{ZANKE} \approx \frac{\omega_m}{2\pi}$$



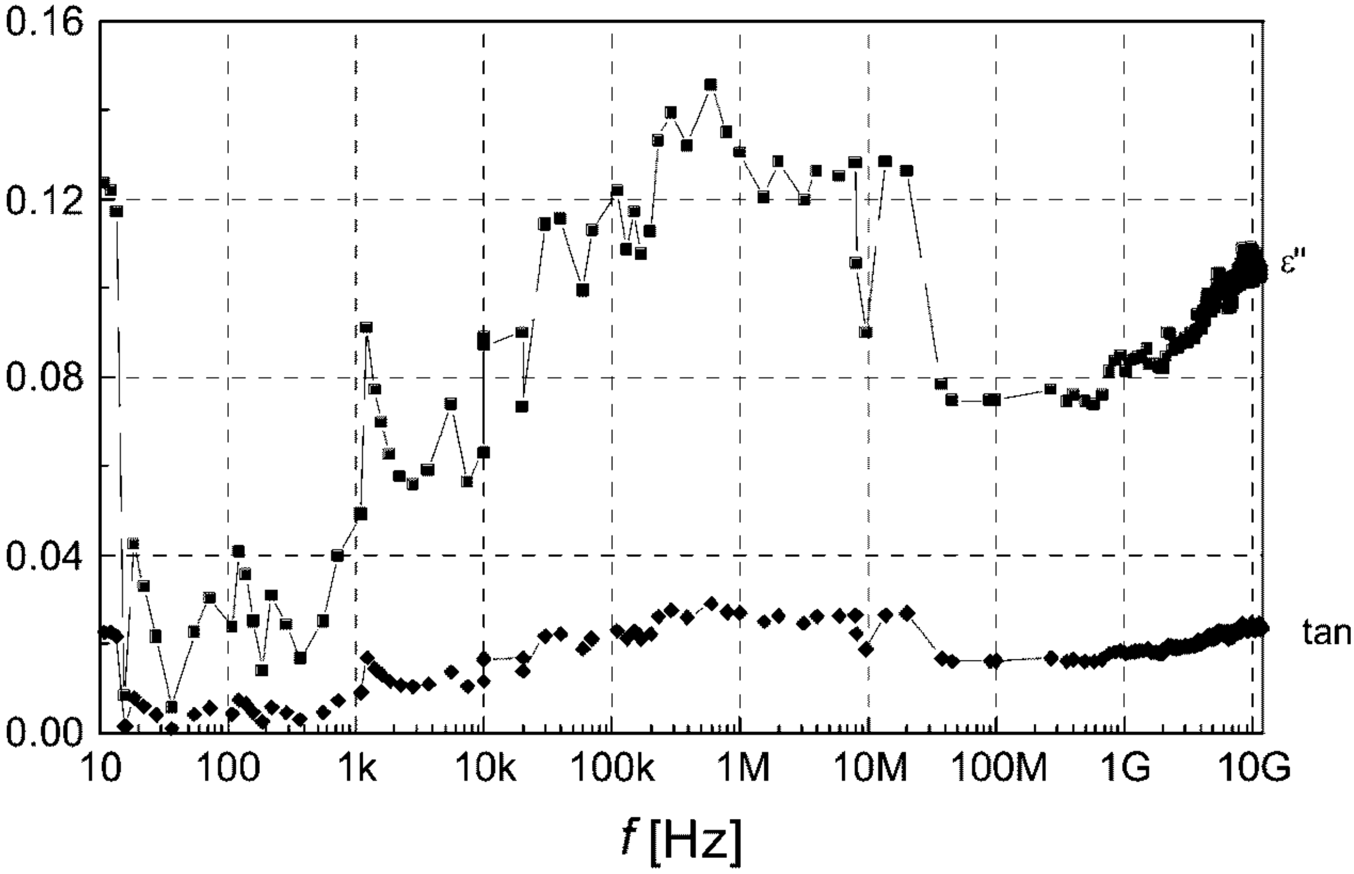




Karakteristična impedanca mikrotrakastega voda (TEM približek Wheeler 1977)



Izmerjena relativna dielektričnost vitroplasta



Izmerjene dielektrične izgube vitroplasta