

23. Seminar Radijske Komunikacije

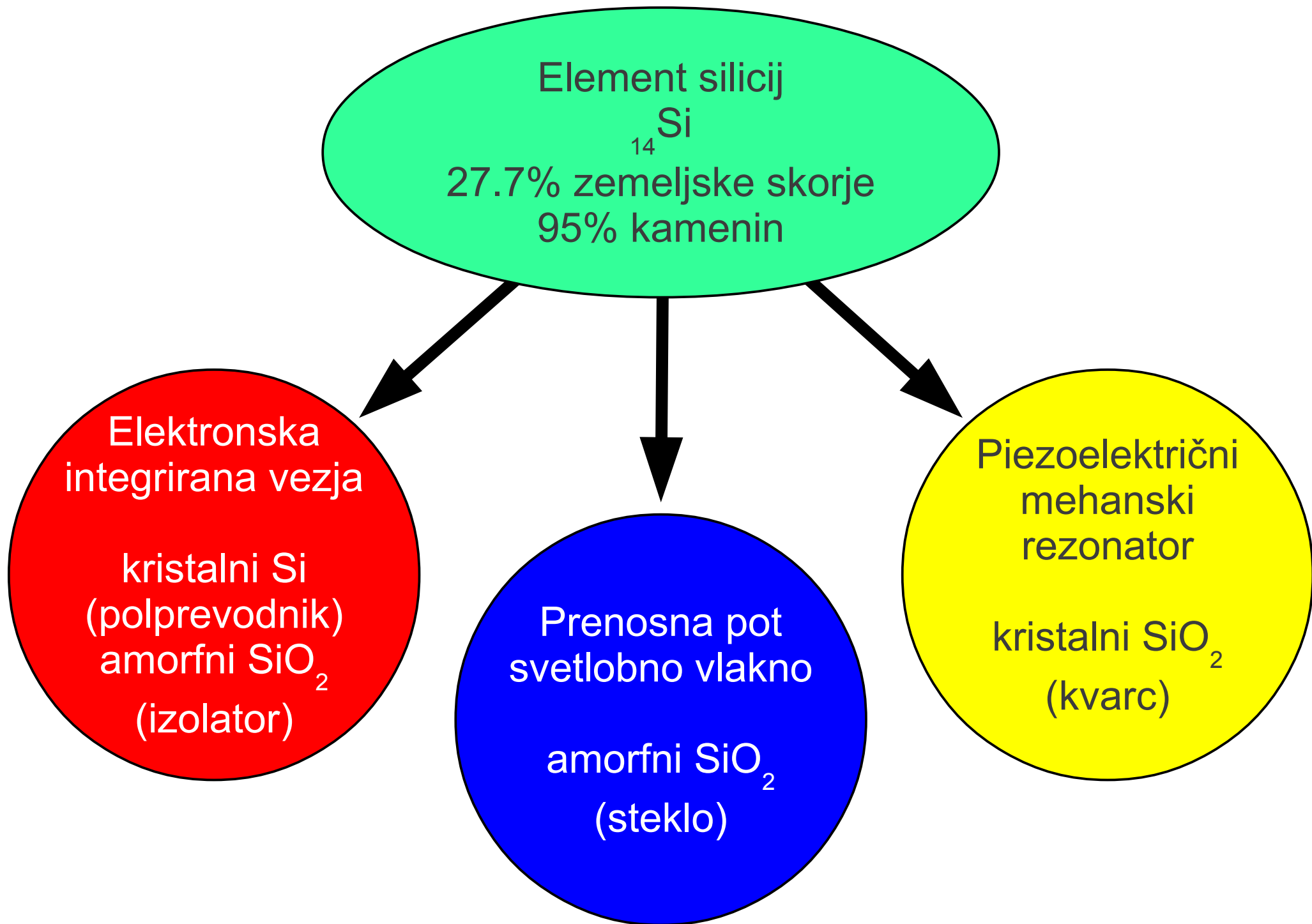
Piezoelektrični rezonatorji v radijski tehniki

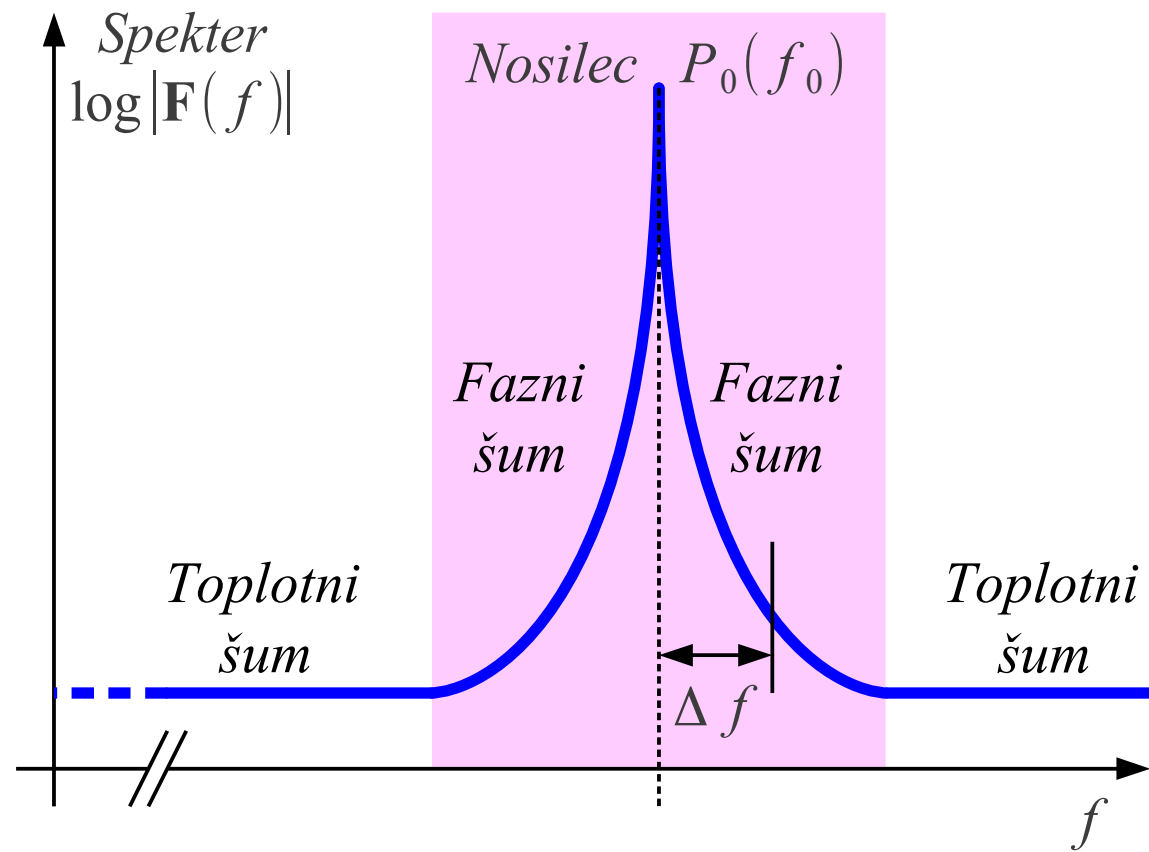
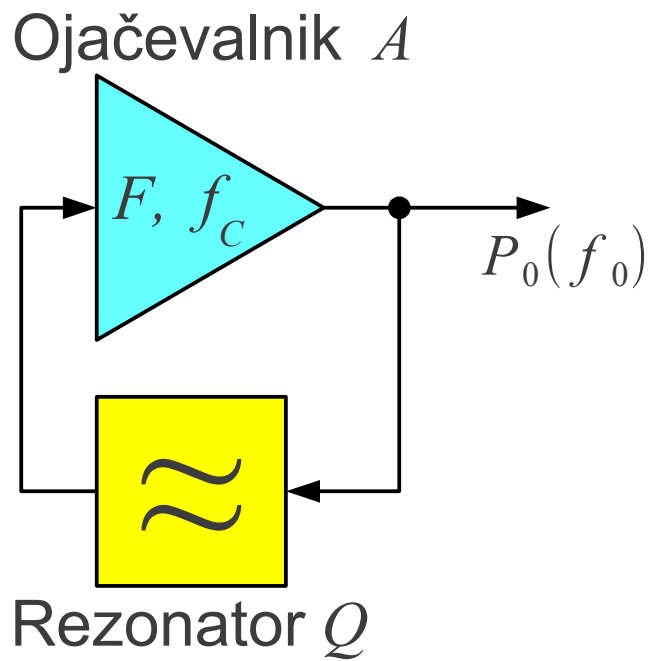
Matjaž Vidmar

LSO, FE, Ljubljana, 31.1.–2.2.2018

Seznam prosojnic predavanja: Piezoelektrični rezonatorji v radijski tehniki

- 1 – Vloge silicija v telekomunikacijah
- 2 – Fazni šum oscilatorja
- 3 – Omejitve faznega šuma
- 4 – Zgodovina kvarca v elektroniki
- 5 – Mehanska valovanja
- 6 – Piezoelektrične naprave
- 7 – Naravni kremenov kristal
- 8 – Zgodovinski kremenov rezonator FT243
- 9 – Umetni kremenov kristal
- 10 – Rezine kremenovega kristala
- 11 – Določanje kristalnih osi z žarki X
- 12 – Rodovi nihanja rezin kremena
- 13 – Rezine AT
- 14 – Strižni rodovi nihanja rezine AT
- 15 – Električno nadomestno vezje rezine AT
- 16 – Admitanca rezine AT
- 17 – Röntgenska slika prečnih rodov rezine AT
- 18 – Neharmonski prečni rodovi rezine AT
- 19 – Temperaturna odvisnost frekvence od kota reza AT
- 20 – Oblika preseka rezine AT
- 21 – Vpliv debeline kovinskih elektrod na površini rezine
- 22 – Vgradnja rezine AT v ohišje
- 23 – Ohišja piezoelektričnih rezonatorjev
- 24 – Kristalni oscilatorji
- 25 – Histereza lepenja umazanije v oscilatorju
- 26 – Nastavljivi kristalni oscilatorji
- 27 – Kristalna pasovna sita
- 28 – Naročilo rezonatorja
- 29 – Piezokeramika
- 30 – Tehnologije FBAR
- 31 – FBAR pasovna sita
- 32 – SAW pasovno sito FIR
- 33 – SAW pasovno sito za 36MHz
- 34 – SAW rezonator





Leesonova enačba: spektralna gostota faznega šuma

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

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

$T_0 \approx 290 \text{ K} \equiv$ temperatura vezja

$F \equiv$ šumno število ojačevalnika

$f_c \equiv$ mejna frekvenca šuma $1/f$

$Q_L \equiv$ obremenjeni Q rezonatorja

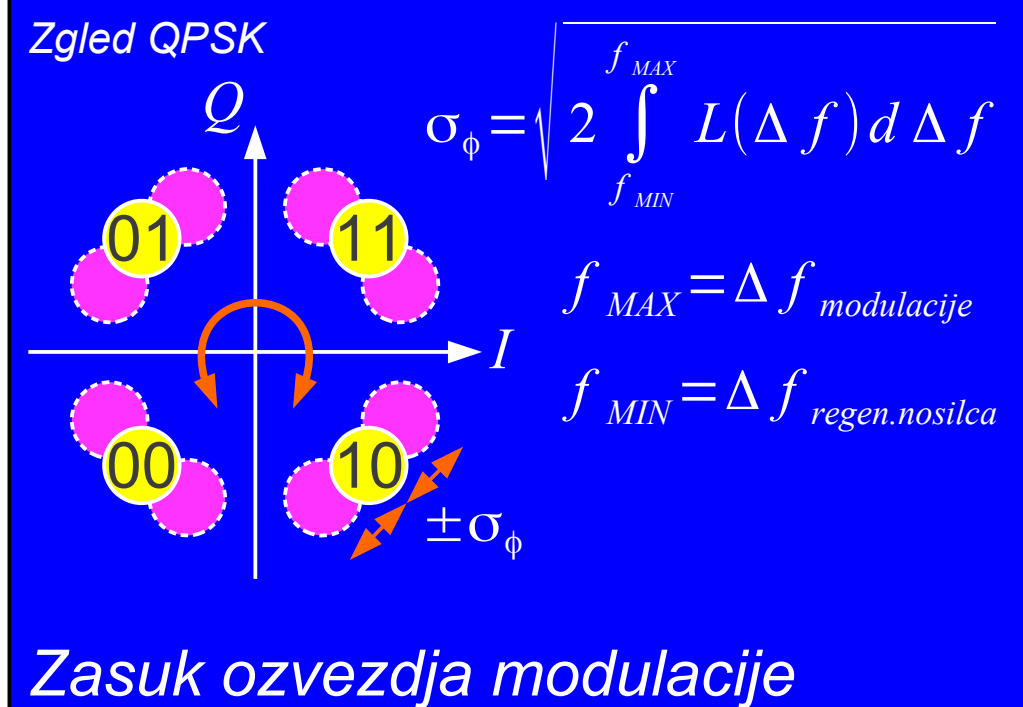
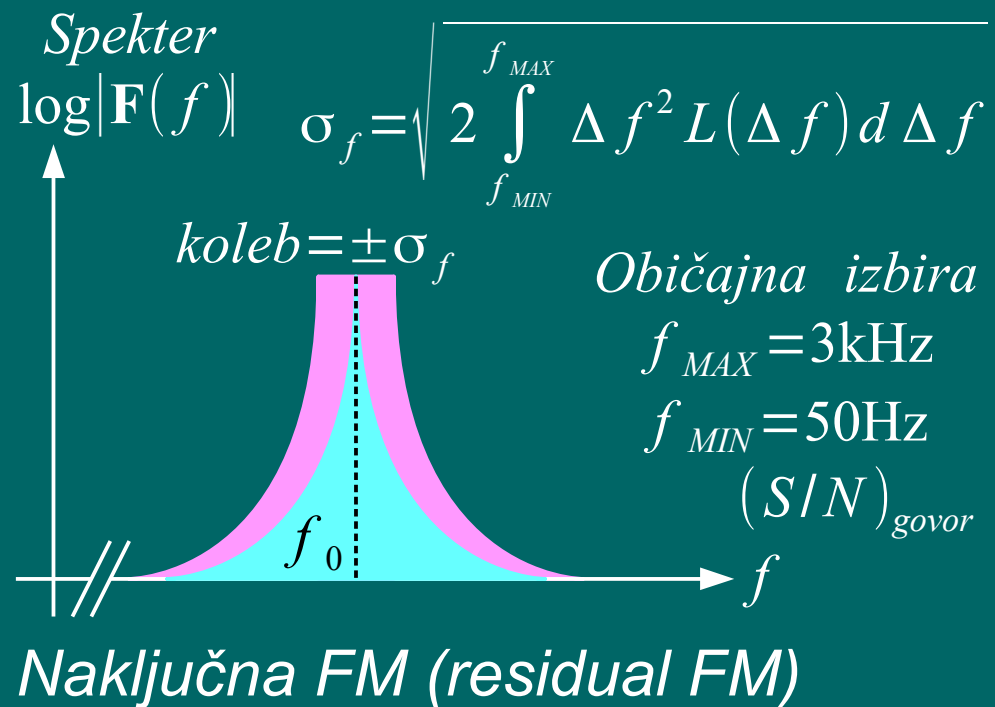
$Q_L \approx 30$ (LC nihajni krog)

$Q_L \approx 1000$ (električna votlina)

$Q_L \approx 30000$ (kremenov kristal)

2 – Fazni šum oscilatorja

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



Analogne radijske zveze:

$$Q_L \approx 30 \dots 1000$$

SSB (A3j brez nosilca) $\rightarrow f_0 < 30\text{MHz}$

FM (govor $B=15\text{kHz}$) $\rightarrow f_0 < 1\text{GHz}$

FM (slika $B=30\text{MHz}$) $\rightarrow f_0 < 30\text{GHz}$

Številске radijske zveze:

$$Q_L \approx 1000 \dots 30000$$

Gost OFDM ($N > 1000$) $\rightarrow f_0 < 1\text{GHz}$

Redek OFDM ($N < 100$) $\rightarrow f_0 < 10\text{GHz}$

Preprost QPSK $\rightarrow f_0 < 100\text{GHz}$

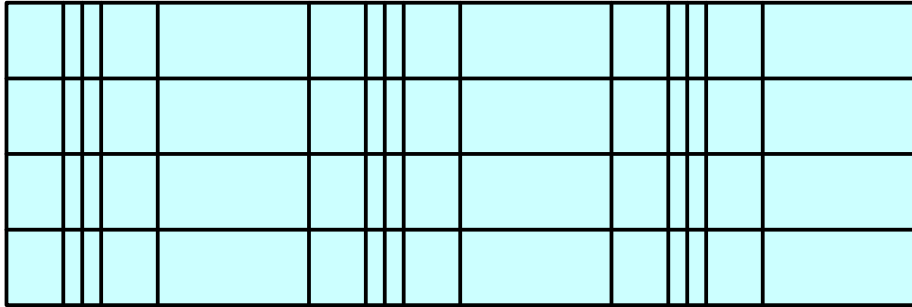
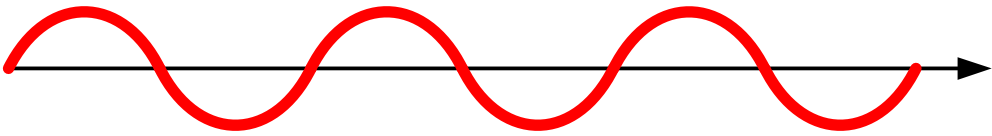
3 – Omejitve faznega šuma

- 1880 – Jacques in Pierre Curie odkrijeta piezoelektrični pojav
- 1905 – G. Spezia hidrotermalna rast kremenovih kristalov v laboratoriju
- 1917 – Prva uporaba piezoelektričnega pojava v sonarju
- 1918 – Prva uporaba piezoelektričnega kristala v oscilatorju
- 1926 – Prvi radiodifuzni oddajnik s kremenovim kristalom
- 1927 – Odkrit prvi temperaturno-kompenzirani rez kristala kremenena
- 1927 – Prva ura s kremenovim kristalom
- 1934 – Razvit prvi praktični temperaturno-kompenzirani AT rez
- 1949 – Razvit obrobljeni visoko stabilni AT rez z visokim Q
- 1956 – Dosegljivi prvi umetno izdelani kremenovi kristali
- 1956 – Opisan prvi TCXO
- 1972 – Kremenov kristal v obliki glasbenih vilic za ročne ure
- 1974 – Napovedan SC rez in preverjen 1976

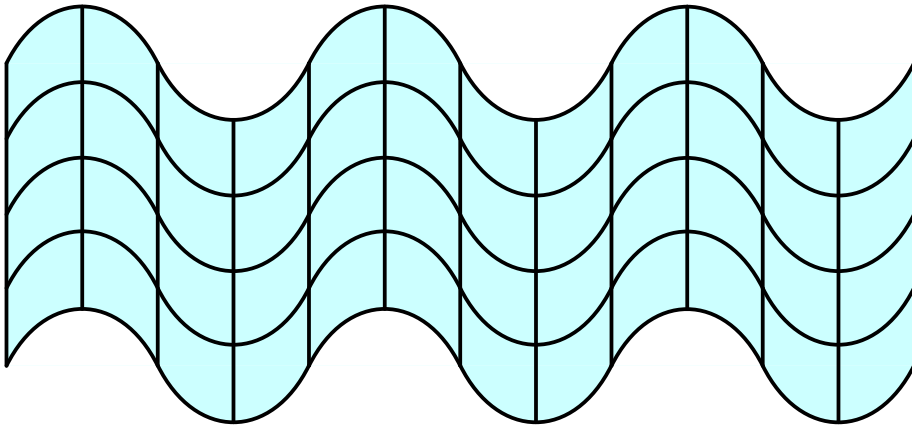
4 – Zgodovina kvarca v elektroniki

5 – Mehanska valovanja

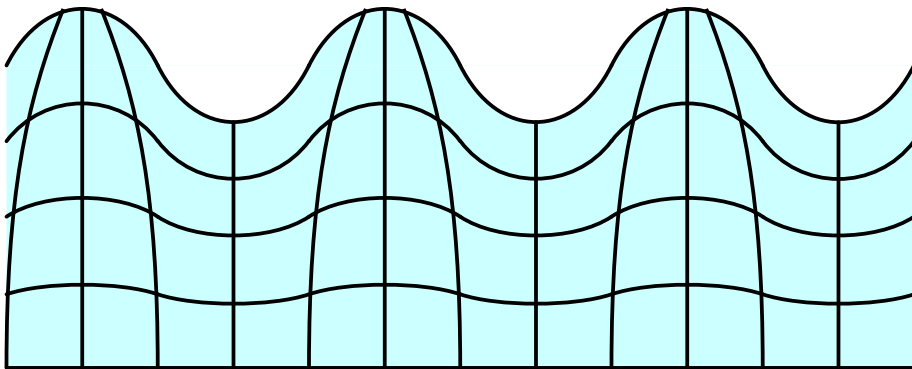
$v \approx 2\text{km/s} \dots 12\text{km/s}$ (*trdne snovi*)





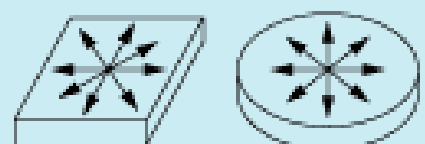
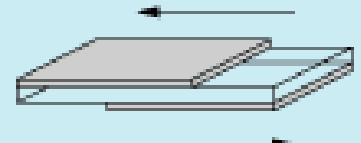
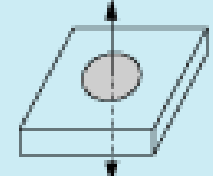
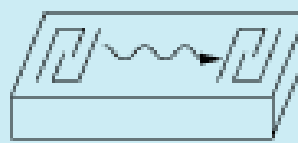
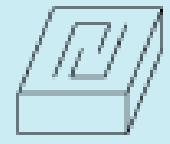
Tlačni val "P" (primary/pressure wave) plini, tekočine, trdne snovi ("BAW" bulk acoustic wave)



Strižni val "S" (secondary/shear wave) samo trdne snovi ("BAW" bulk acoustic wave)



Površinski val "SAW" (surface acoustic wave) površina trdne snovi

Vibrating mode	Frequency [Hz]								Application
	1k	10k	100k	1M	10M	100M	1G		
	Flextural mode								Piezoelectric buzzer
	Length mode								kHz Ceramic filter kHz Ceramic resonator
	Area expansion mode								kHz Ceramic resonator
	Thickness shear mode								MHz Ceramic filter
	Thickness expansion mode								MHz Ceramic resonator
	Surface Acoustic Wave								SAW filter SAW resonator
	BGS Wave/SH Wave								HF trap HF Ceramic resonator HF Ceramic filter

←→ Vibration Modes

$v \approx 3\text{km/s} \dots 12\text{km/s}$

Tališče
1670°C

$T < 573^\circ\text{C}$
 α -kvarc
desnosučni
in levosučni

$T > 573^\circ\text{C}$
 β -kvarc

Mehanski
 $Q > 10^6$

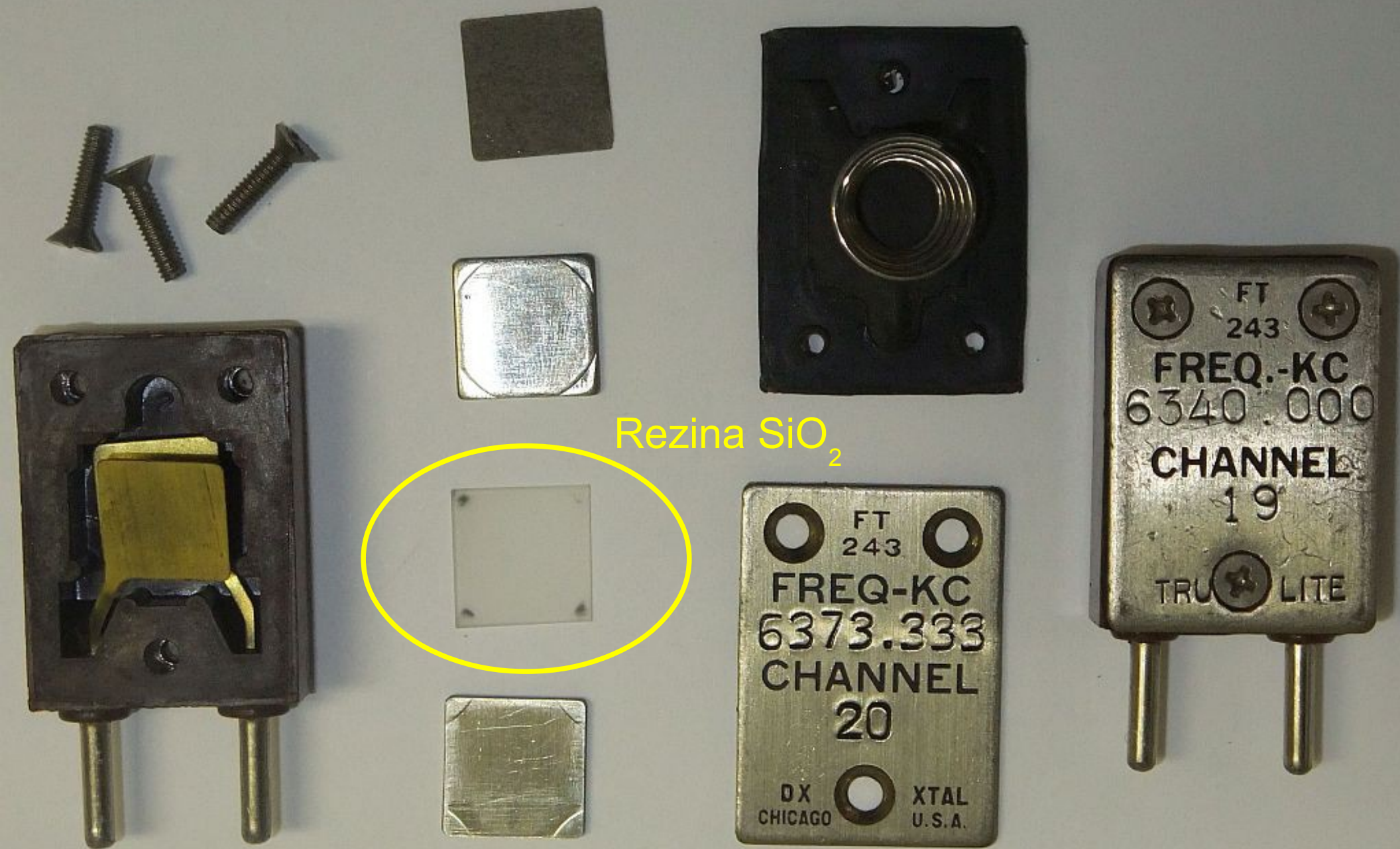
Piezoelektrik



Hidrotermalna rast v $\text{H}_2\text{O} + \text{NaCl}$ (tisoči let) $p \approx 1000\text{bar}$

Nečistoče? Vključki? Prisotnost obeh kristalnih oblik? Nahajališča?

7 – Naravni kremenov kristal



[8 – Zgodovinski kremenov rezonator FT243](#)

Hidrotermalna rast

$$v_{\text{rast}}(z) \approx 3 \cdot v_{\text{rast}}(x)$$

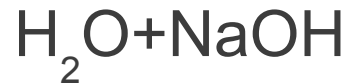
desnosučni α -kvarc



$p \approx 700\text{--}1000\text{bar}$

$T \approx 345^\circ\text{C}$ $\Delta T \approx 10^\circ\text{C}$

$$v_{\text{rast}}(z) \approx 0.4\text{mm/dan}$$

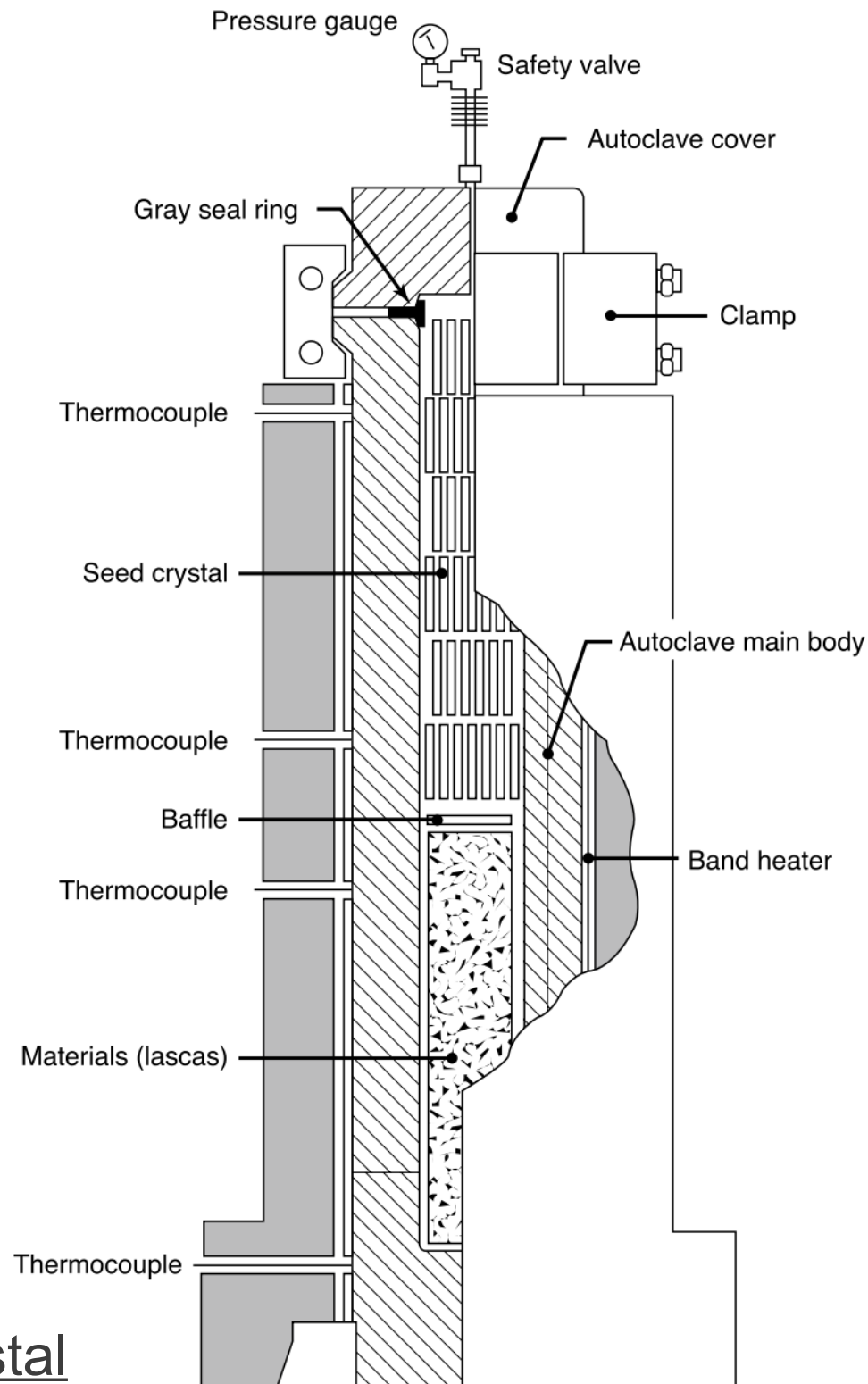


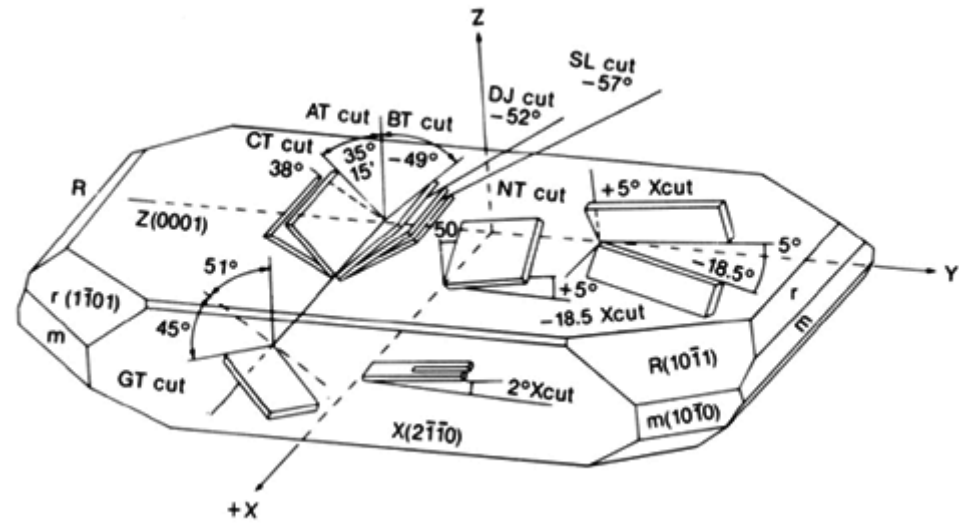
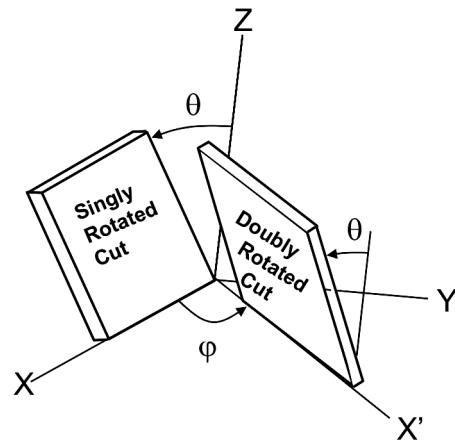
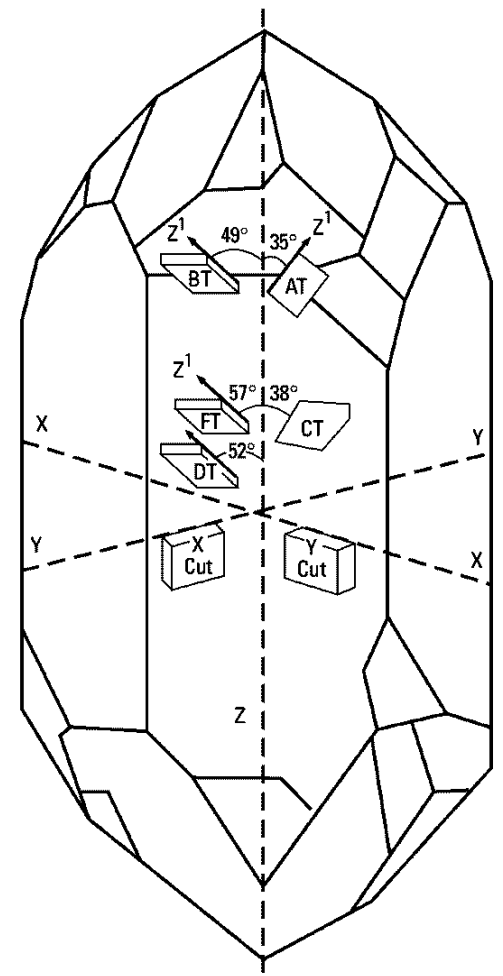
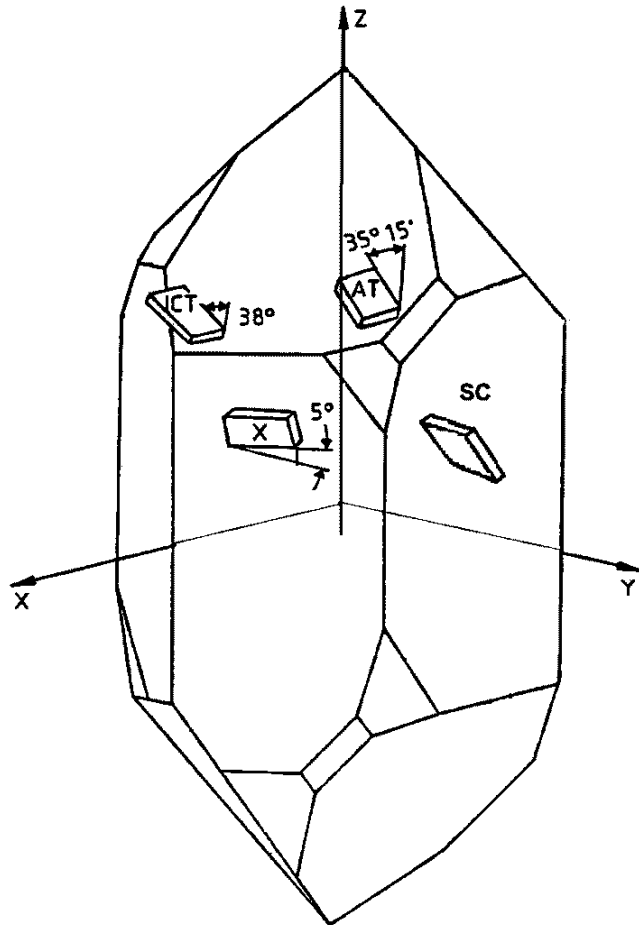
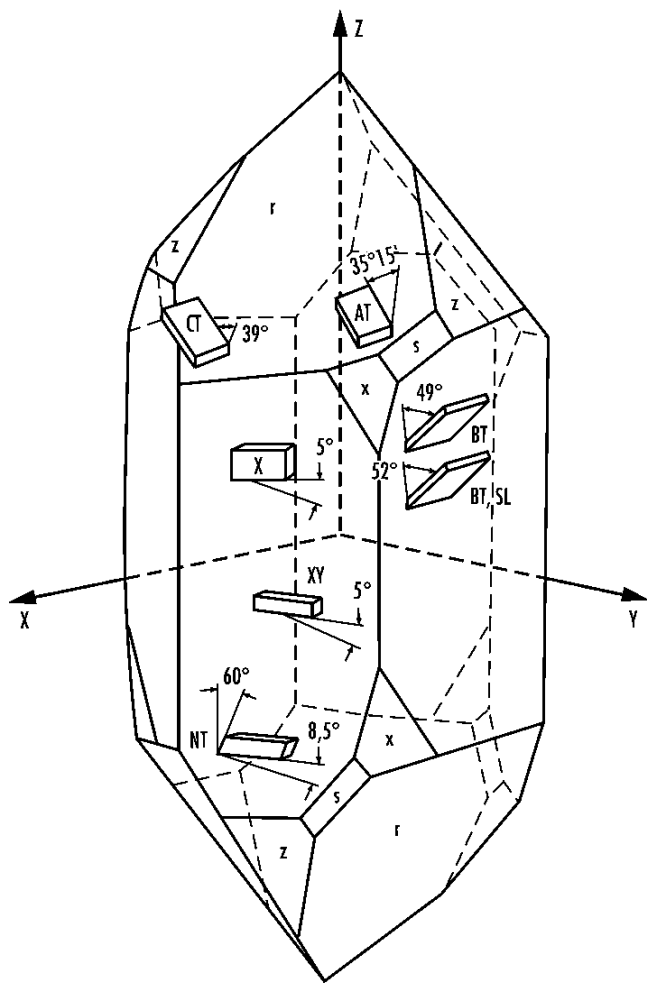
$p \approx 1000\text{--}1500\text{bar}$

$T \approx 380^\circ\text{C}$ $\Delta T \approx 25^\circ\text{C}$

$$v_{\text{rast}}(z) \approx 1\text{mm/dan}$$

9 – Umetni kremenov kristal





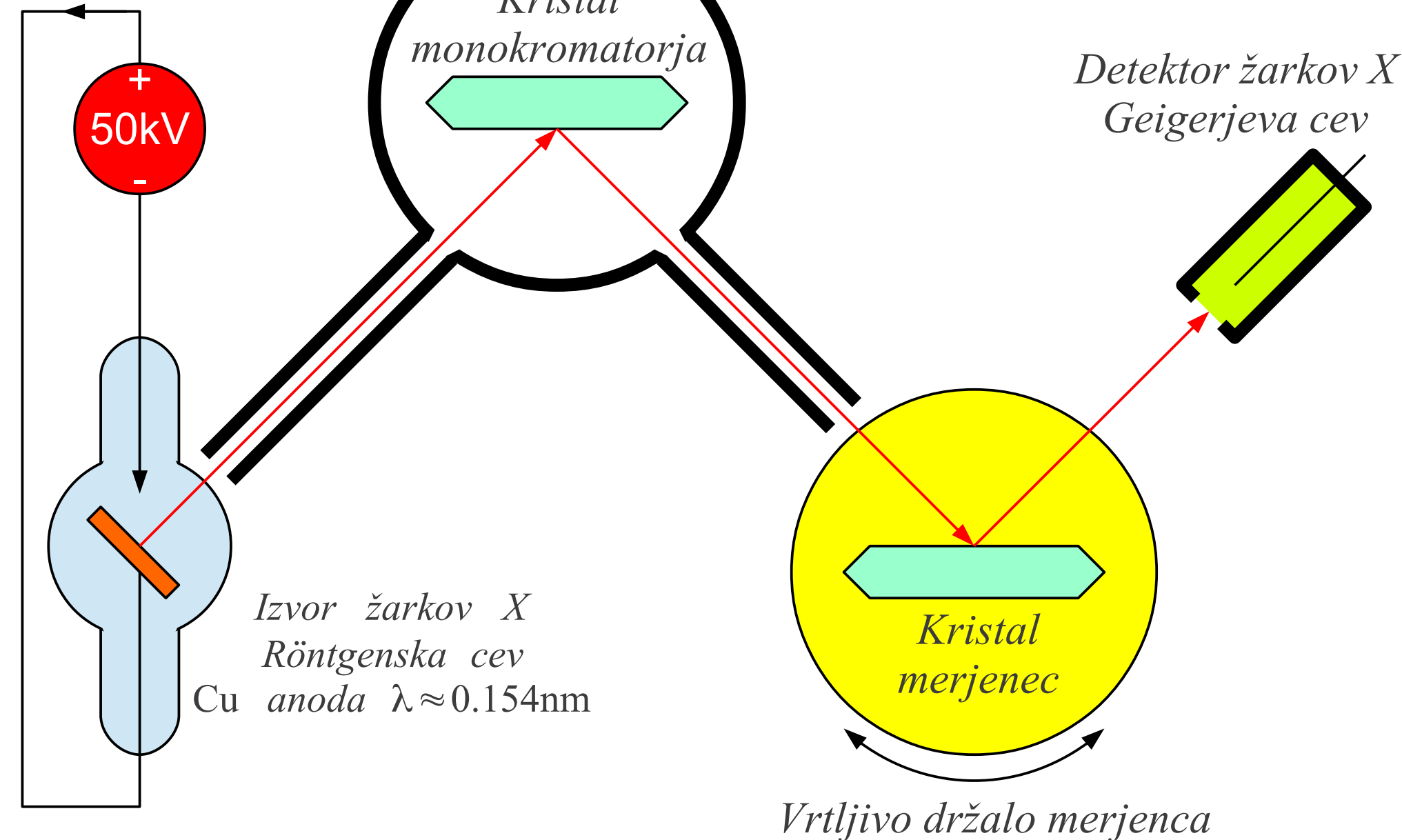
10 – Rezi kremenovega kristala

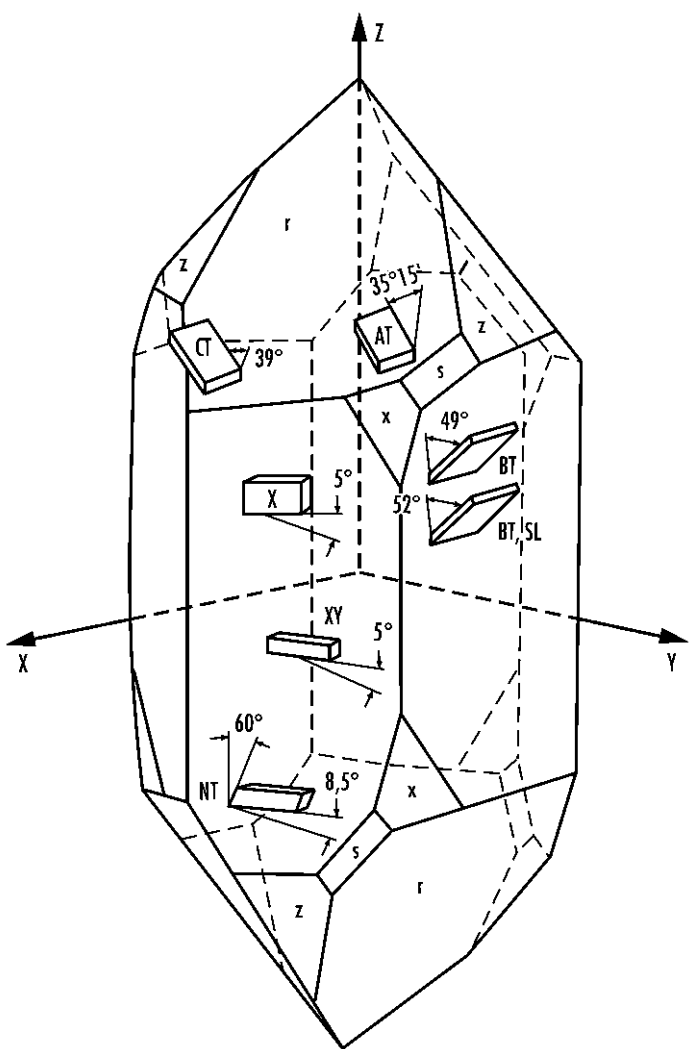
Pb oklop za žarke X

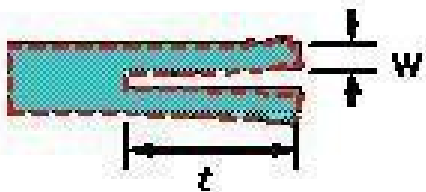
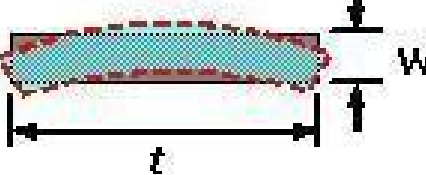
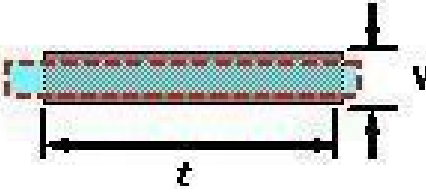
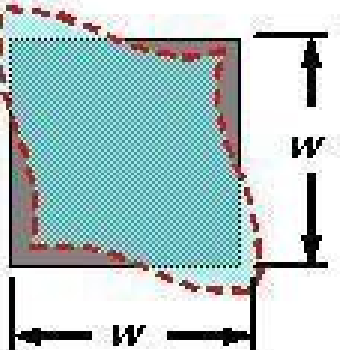
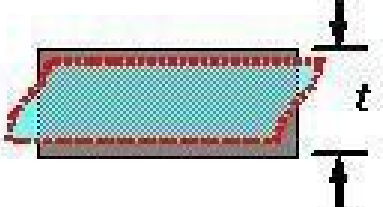
$I \approx 10\text{mA}$

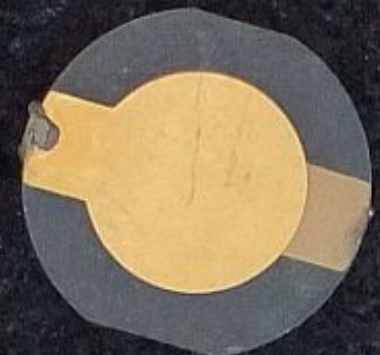
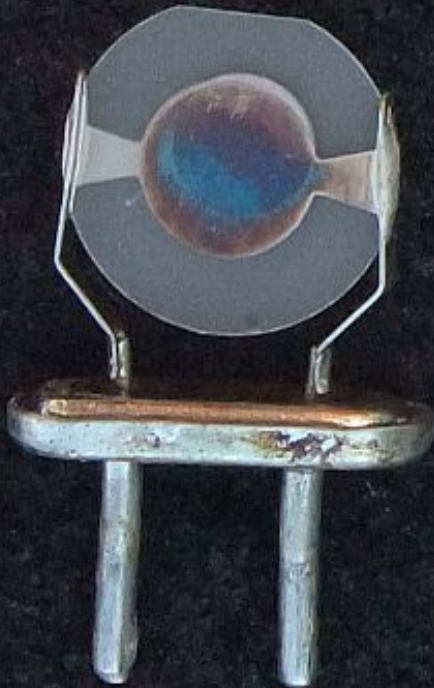
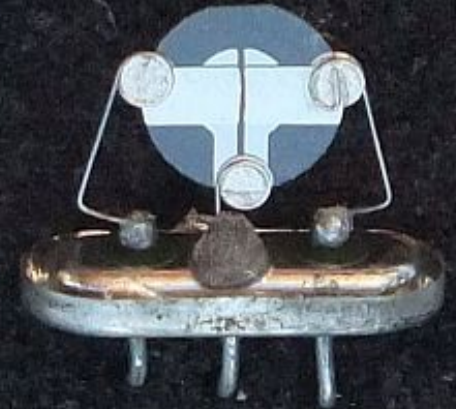
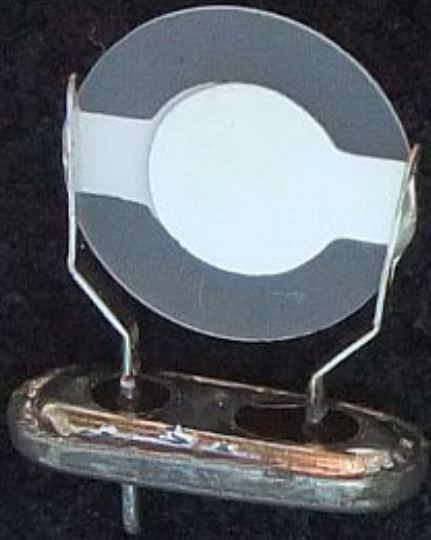
*Kristal
monokromatorja*

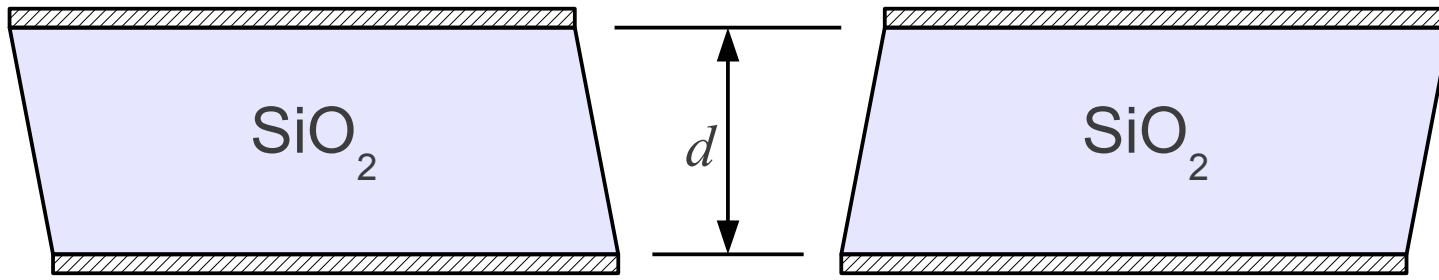
*Detektor žarkov X
Geigerjeva cev*



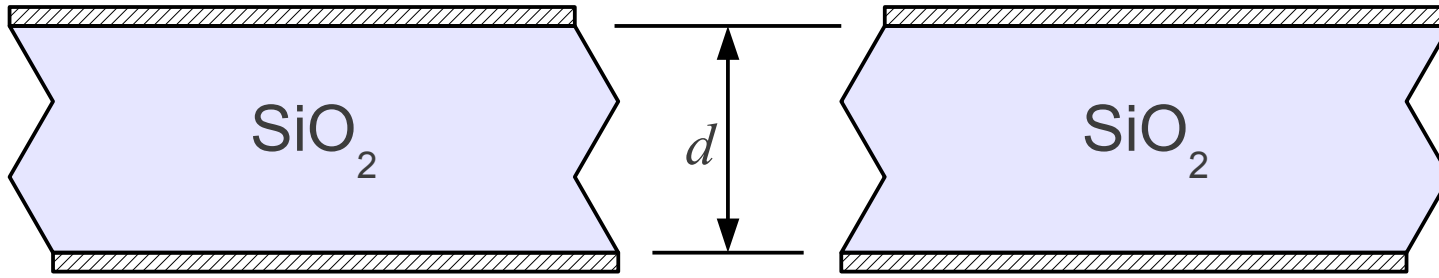


Vibration Mode		Orientation Angle
Tuning Fork		+ 2° X
Flexure		XY NT
Extension		+ 5° X - 18.5° X
Face Shear		DT CT SL
Thickness Shear		AT Fundamental AT 3 rd Overtone AT 5 th Overtone BT Fundamental

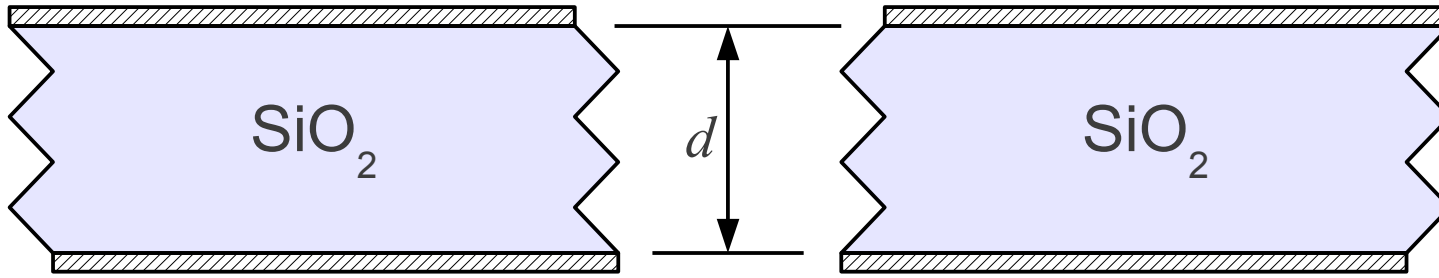




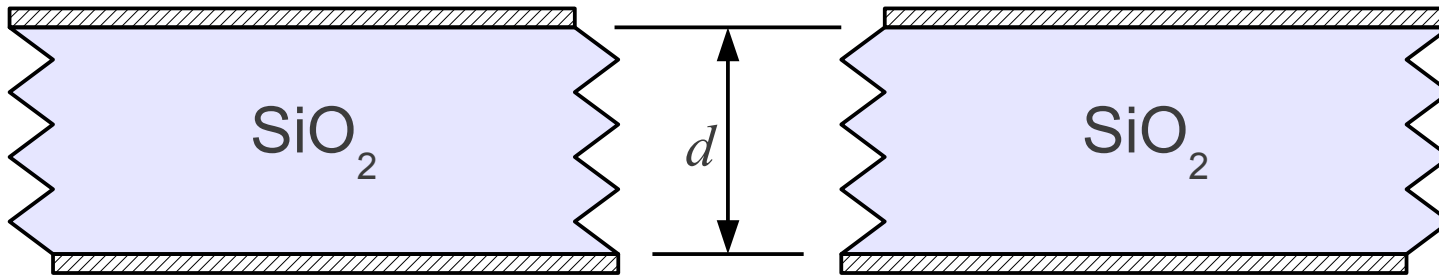
Osnovna rezonanca
 $f_1 \approx v/2d$



Tretji overton $\sim 3f_1$

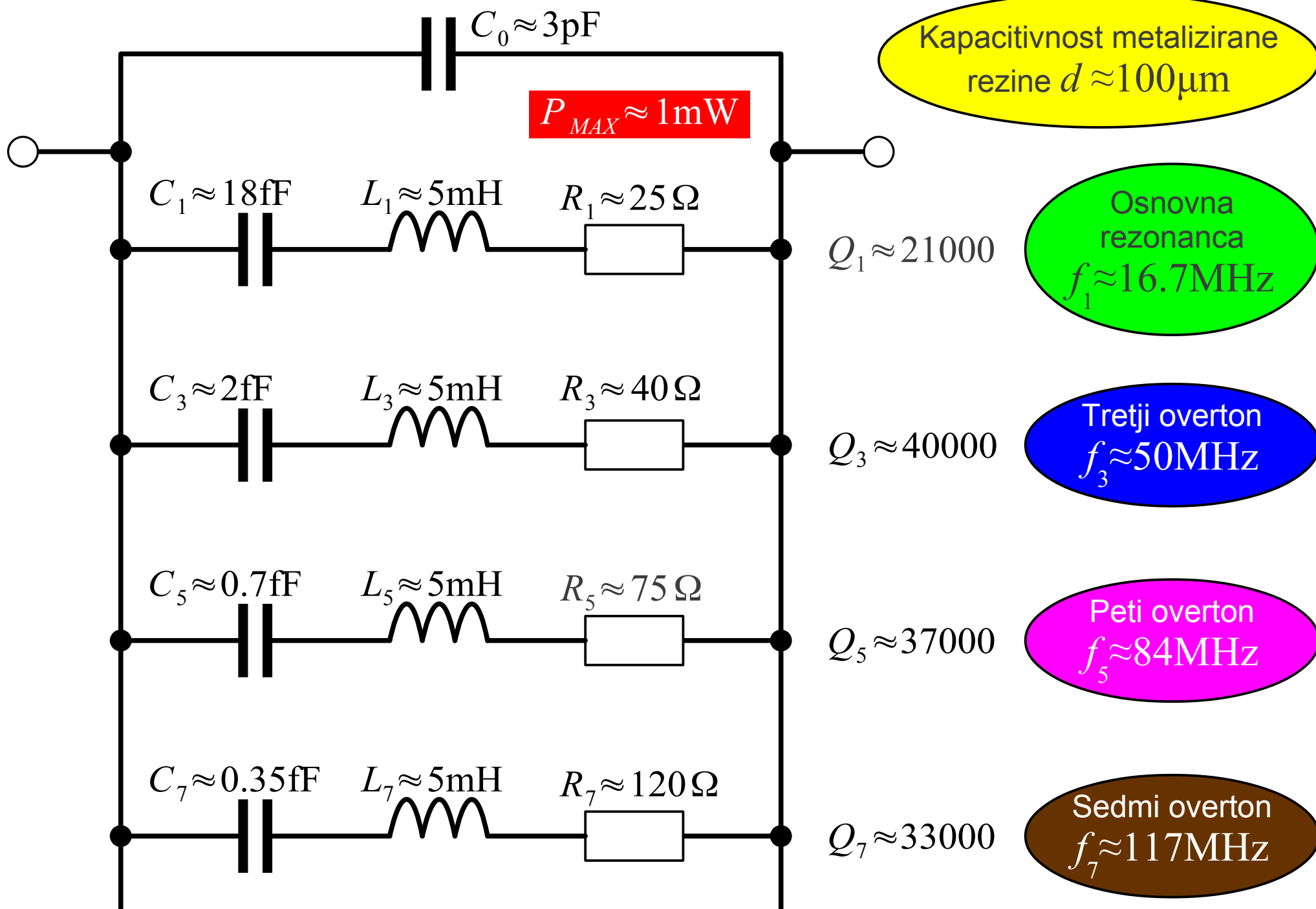


Peti overton $\sim 5f_1$



Sedmi overton $\sim 7f_1$

$v \approx 3.32\text{km/s}$



$B = \text{Im}[Y]$

$Y(f) = G + jB$

$j\omega C_0$

$1/R_7$

$1/R_5$

Sedmi
overtone f_7

$1/R_3$

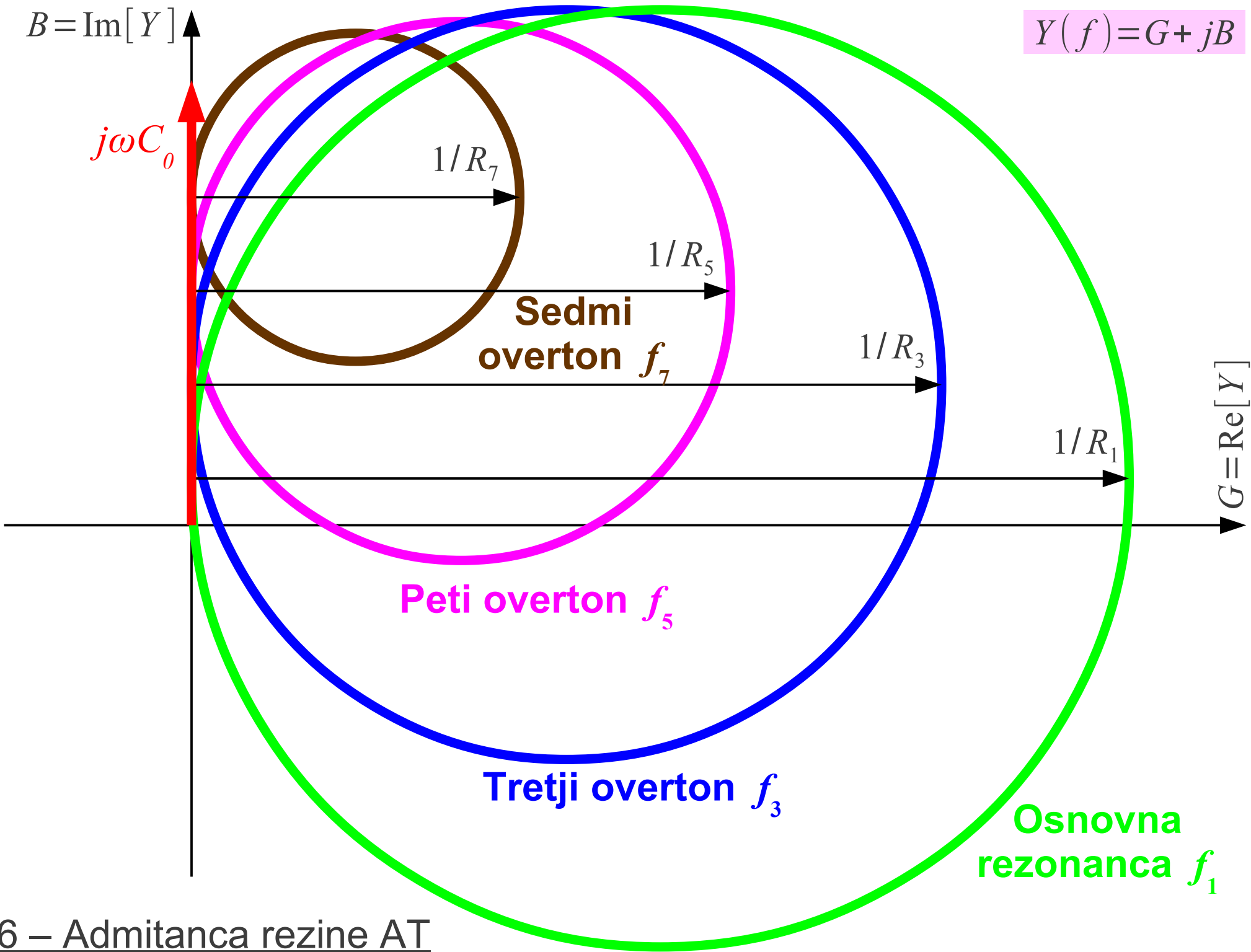
$1/R_1$

$G = \text{Re}[Y]$

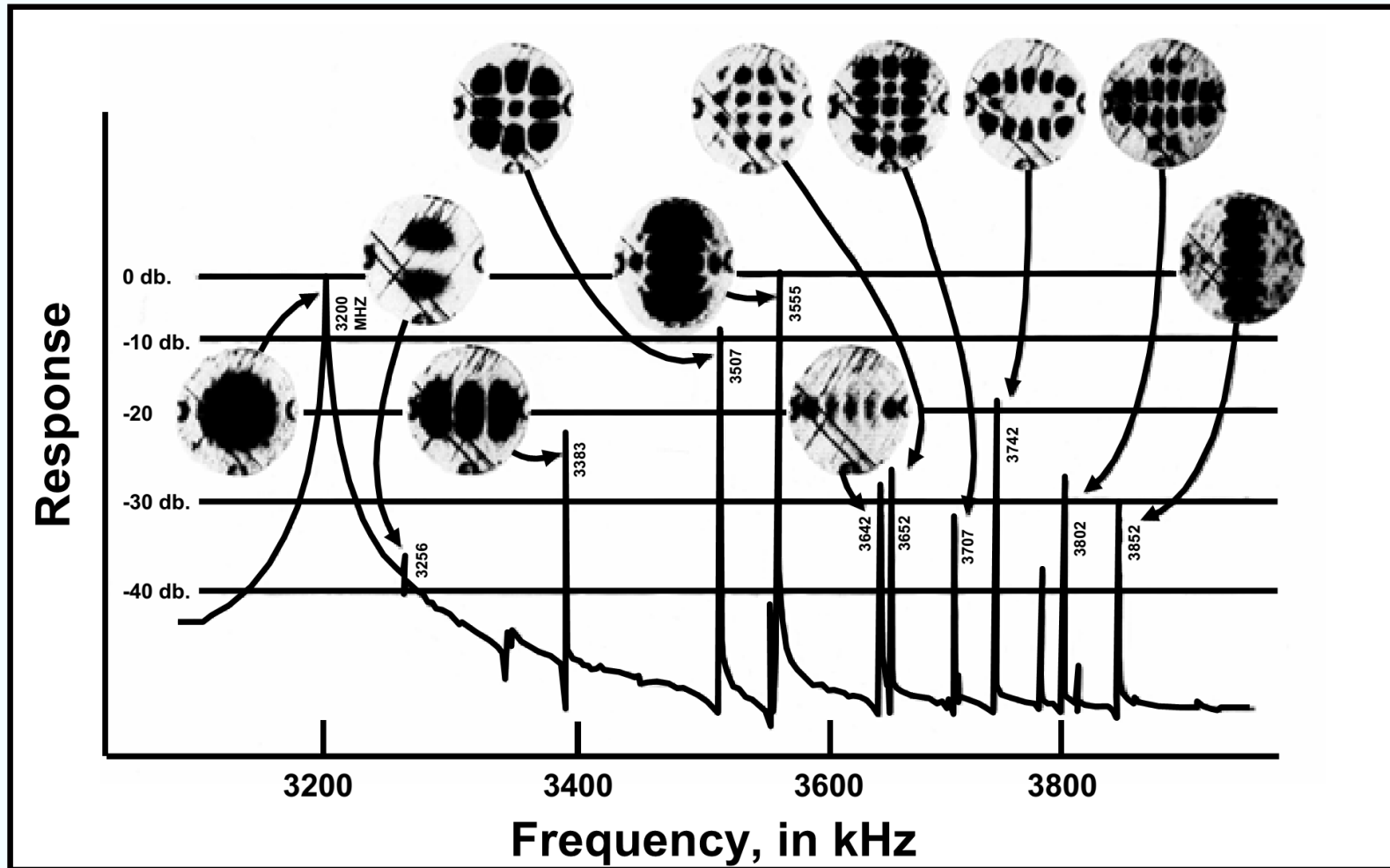
Peti overtone f_5

Tretji overtone f_3

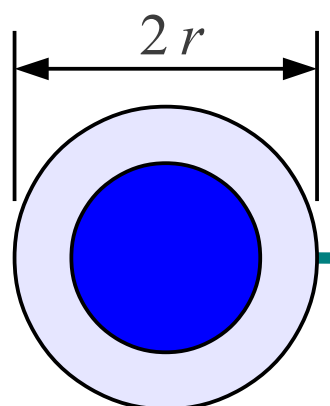
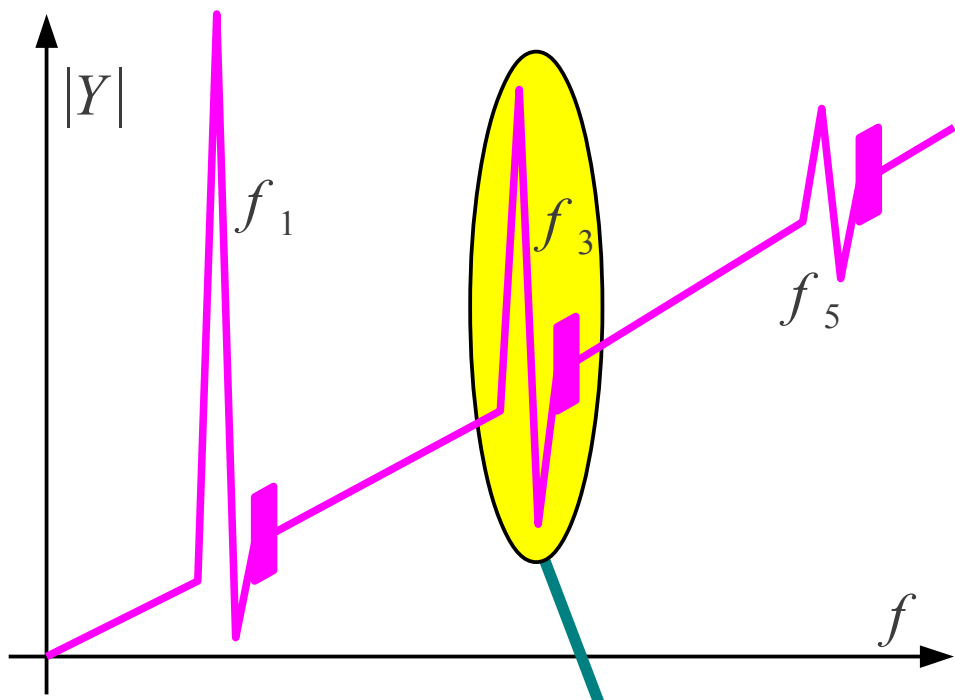
Osnovna
rezonanca f_1



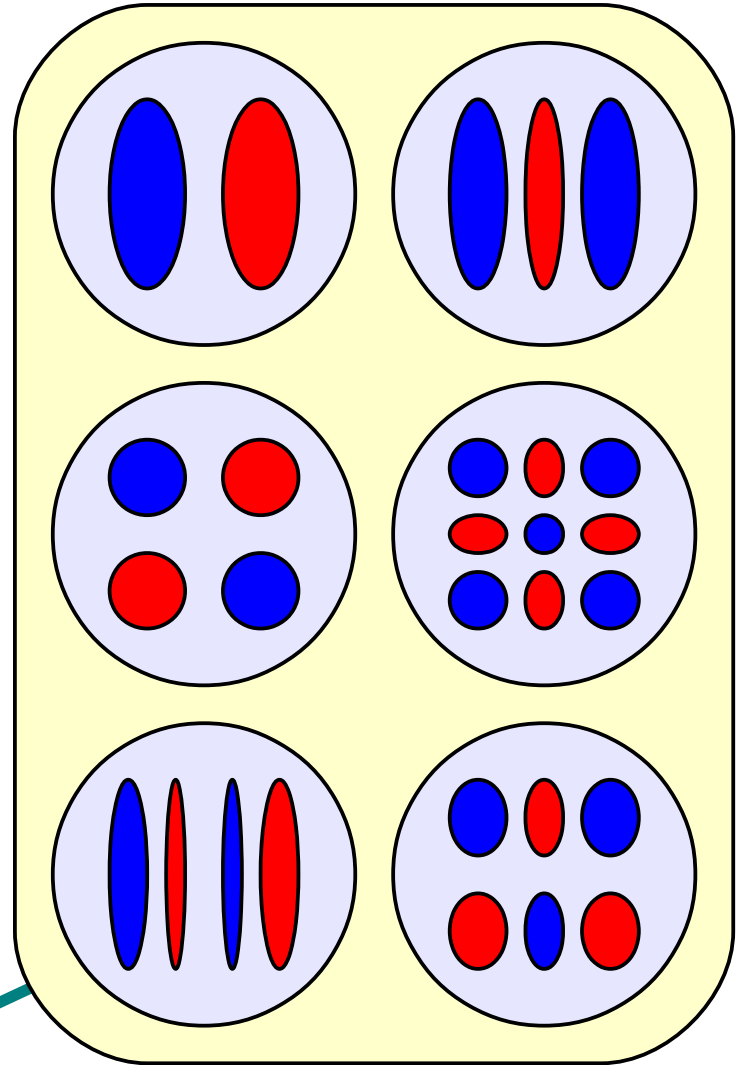
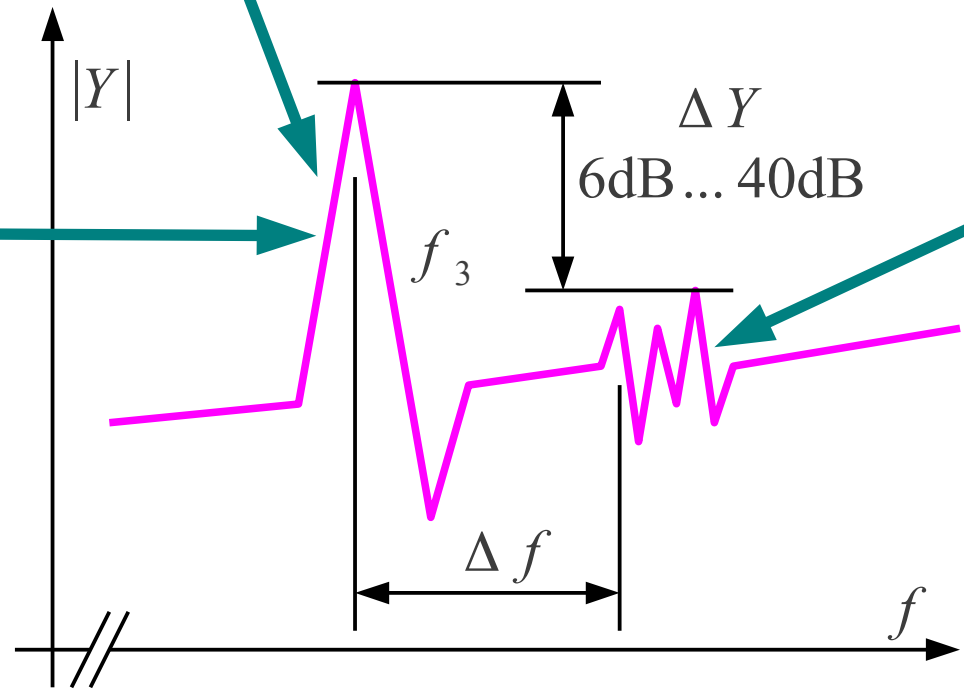
Resonant Vibrations of a Quartz Plate



X-ray topographs ($21\cdot\bar{0}$ 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.



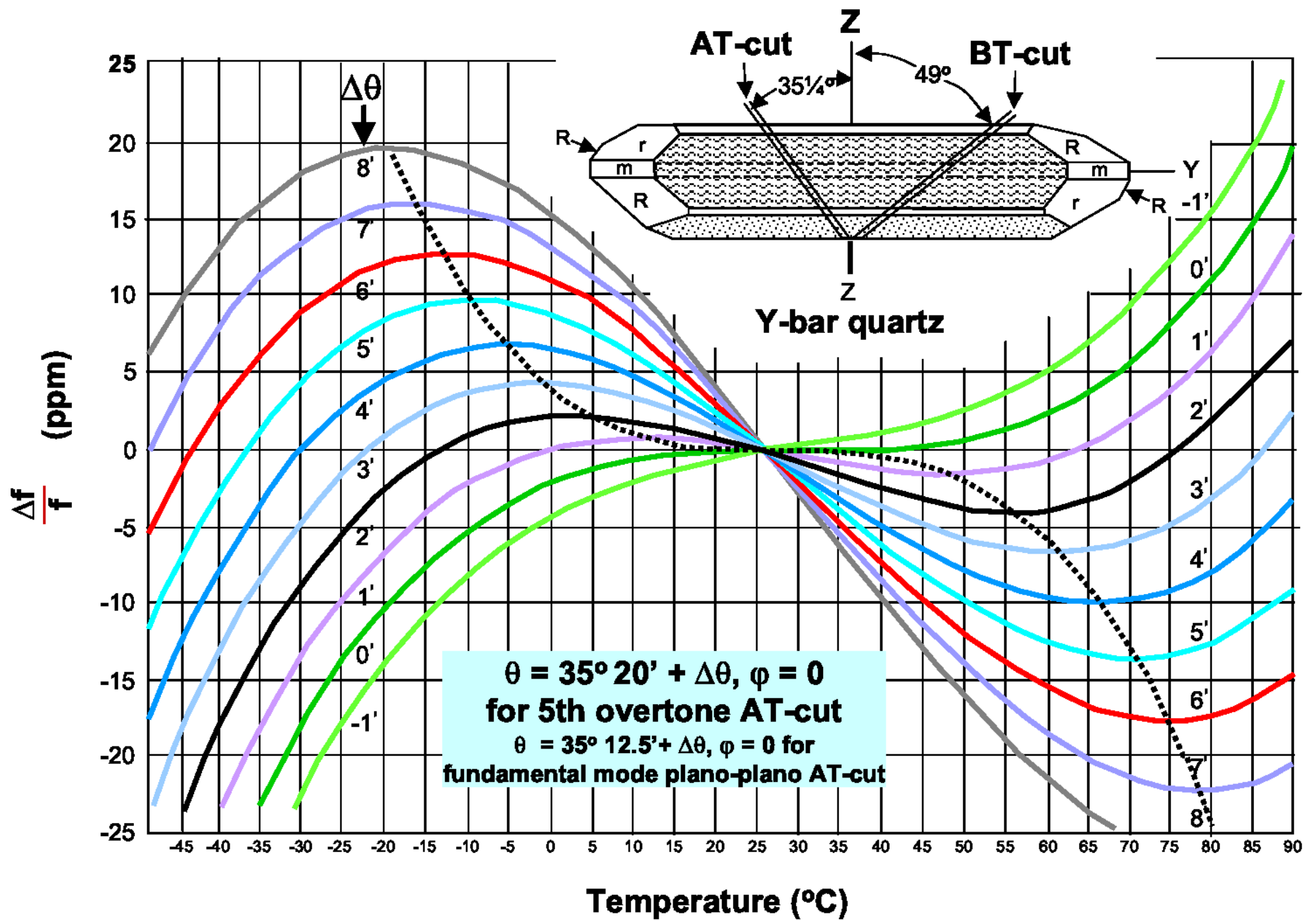
Osnovni prečni rod

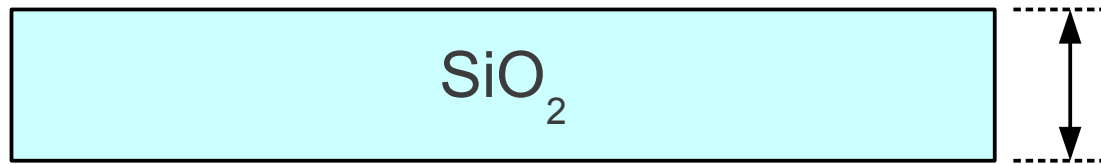


Višji prečni rodovi (anharmonics)

$$\frac{\Delta f}{f_1} \approx \frac{d}{2r} \quad \text{Velika odvisnost od temperature}$$

$$\Delta f \approx 100\text{kHz} < 1\text{MHz}$$

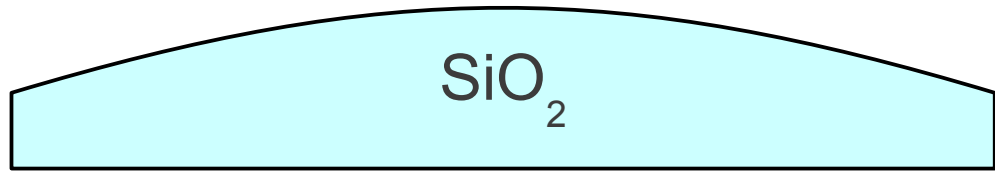




$$d \geq 50 \mu\text{m}$$

Plan-paralelna rezina

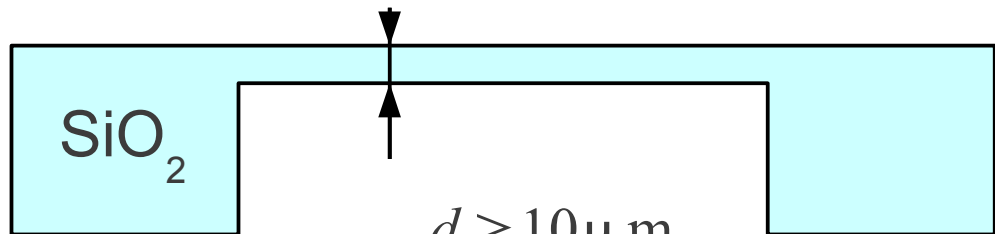
$$f_1 \leq 33\text{MHz}$$



Plan-konveksna rezina



Bi-konveksna rezina



$$d \geq 10 \mu\text{m}$$

Jedkana rezina "inverted mesa"

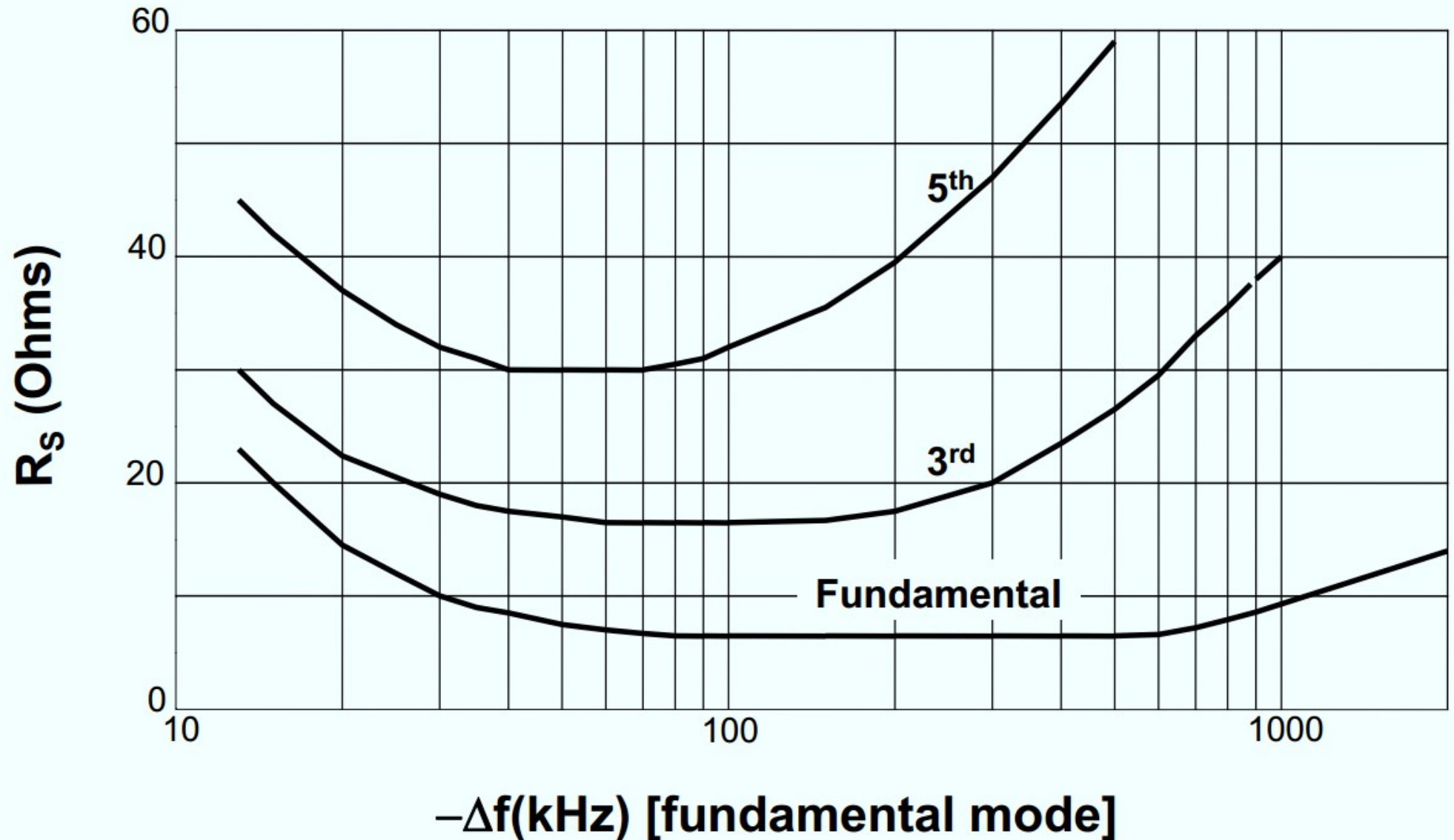
$$f_1 \leq 170\text{MHz}$$



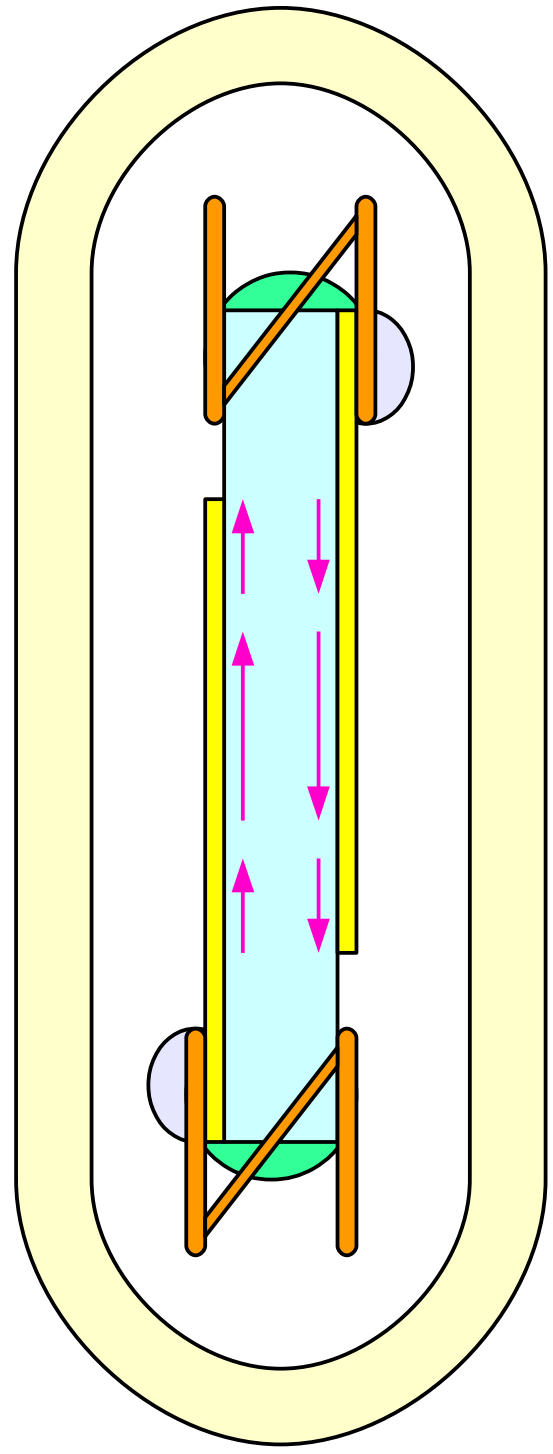
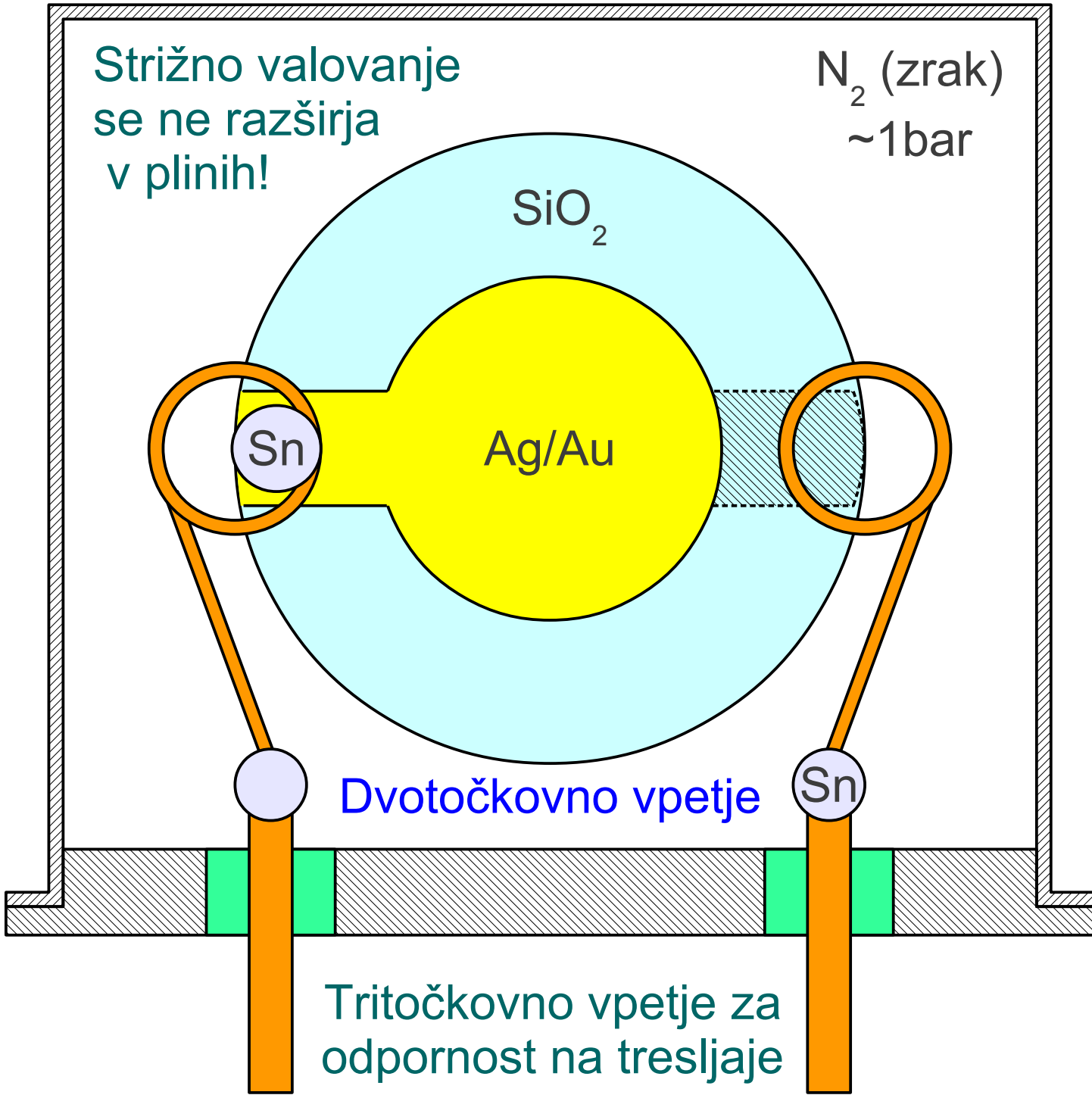
20 – Oblika preseka rezine AT

Resistance vs. Electrode Thickness

AT-cut; $f_1=12$ MHz; polished surfaces; evaporated 1.2 cm (0.490") diameter silver electrodes

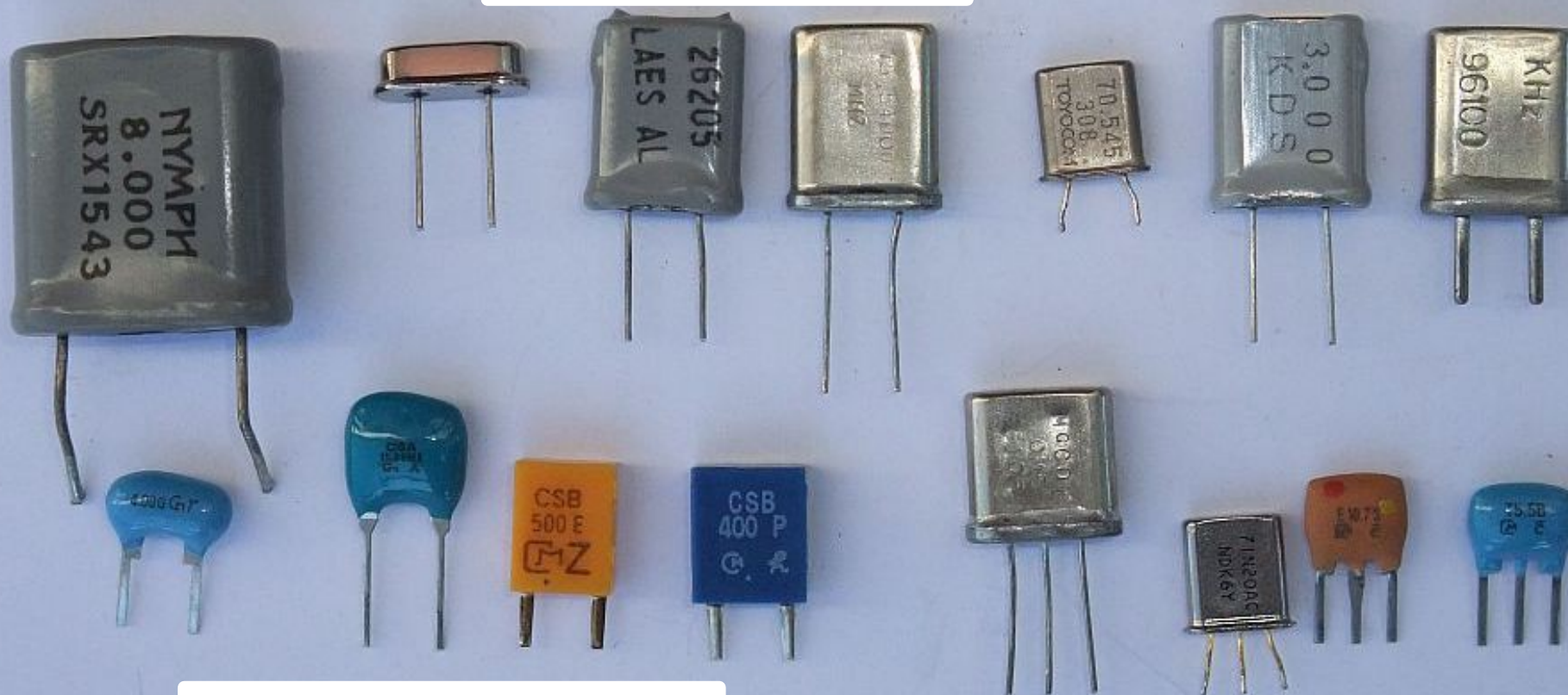


22 – Vgradnja rezine AT v ohišje



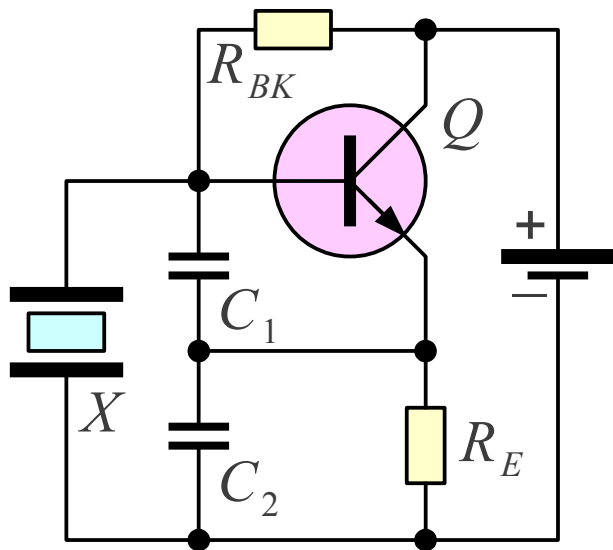


Kremenčevi kristali

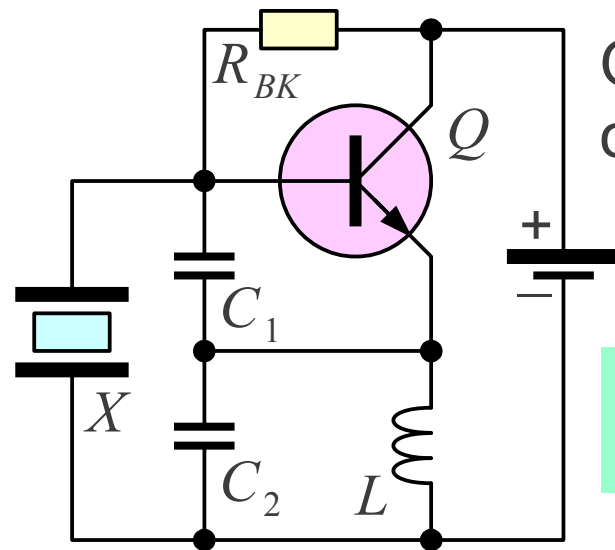


Keramični rezonatorji

Večkratni rezonatorji

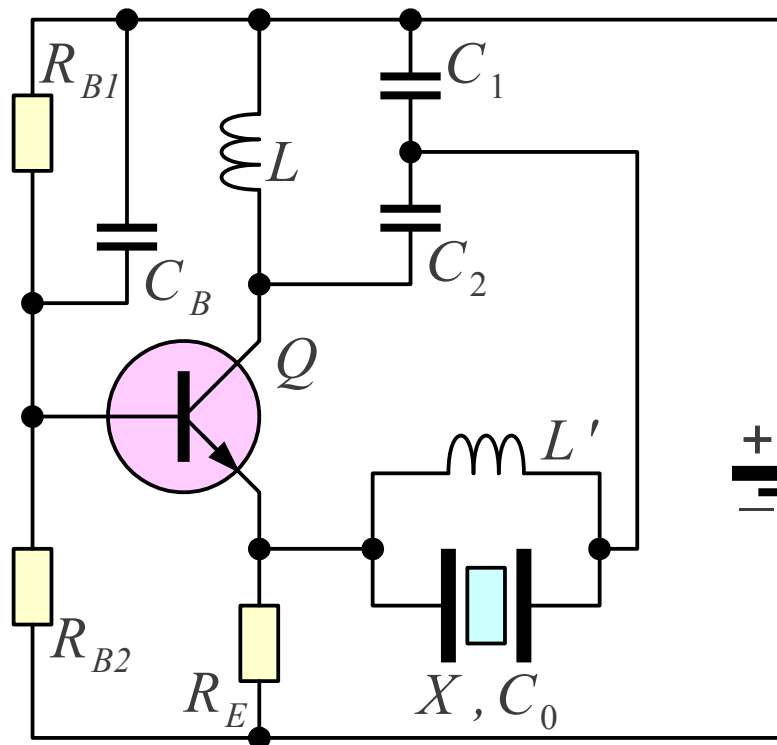
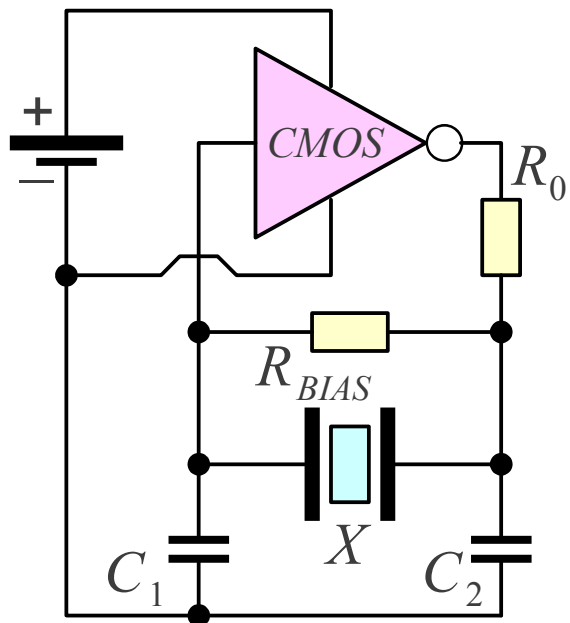


Pierce (Colpitts) na osnovni frekvenci f_1



Overtonski oscilator f_3

$$f_1 < \frac{1}{\sqrt{LC}} < f_3$$

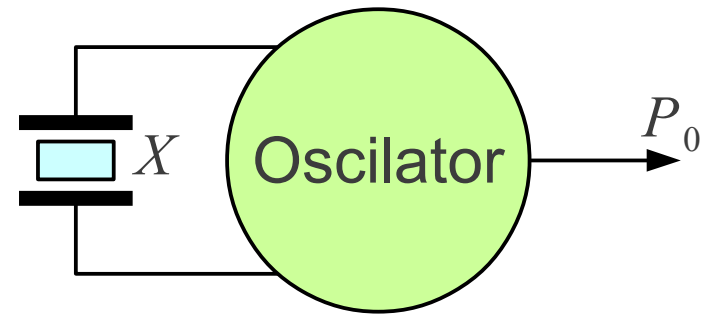
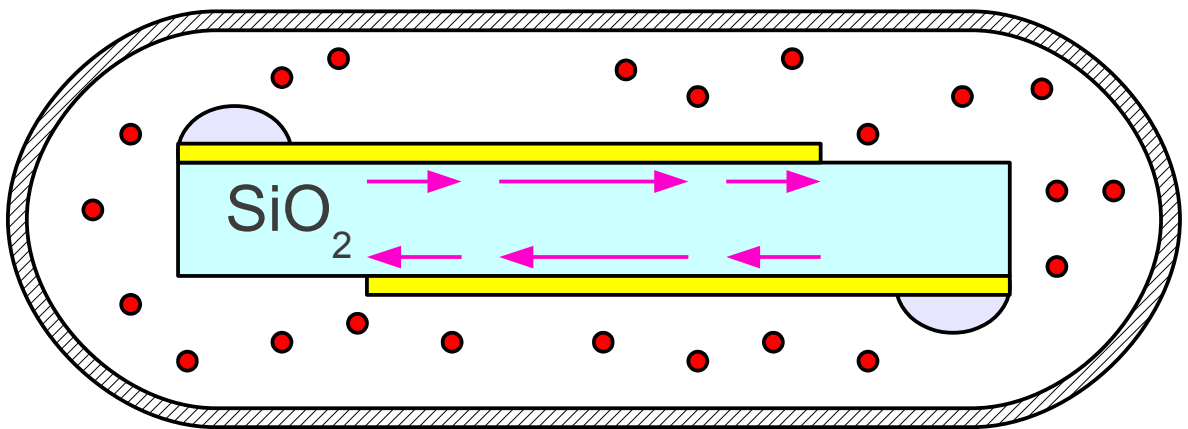


Overtonski oscilator f_5

$$f_5 = \frac{1}{\sqrt{L \frac{C_1 C_2}{C_1 + C_2}}}$$

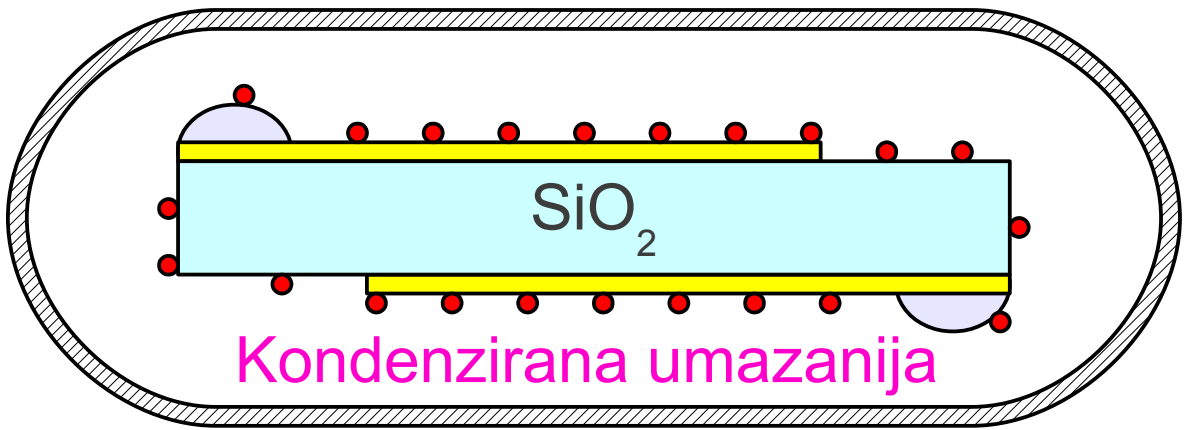
$$f_5 = \frac{1}{\sqrt{L' C_0}}$$

TOPLO

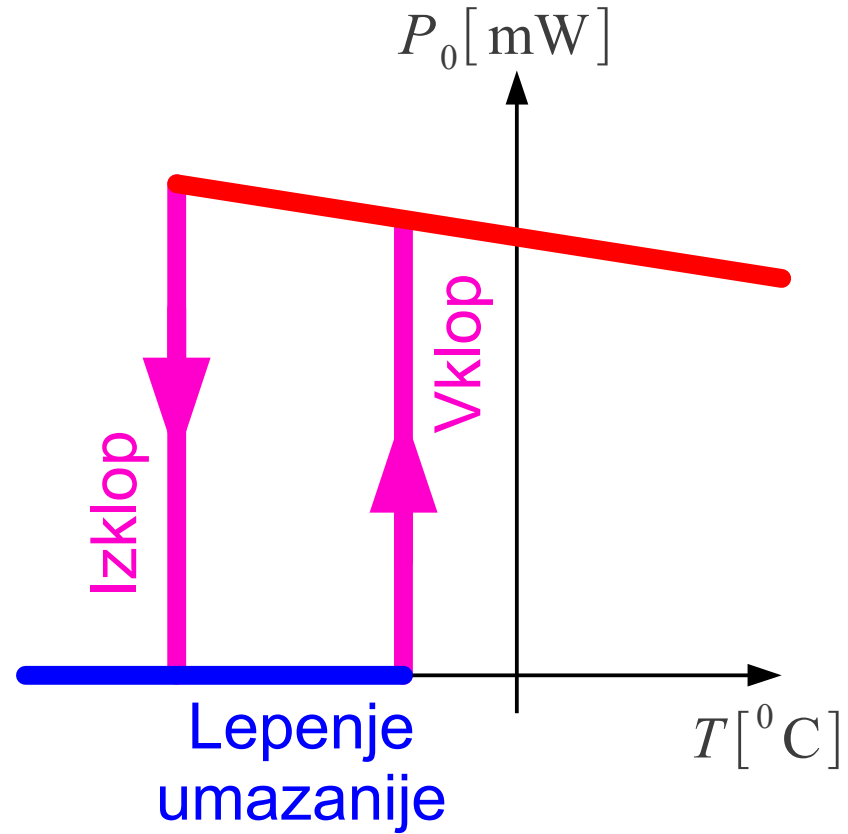


Ogrevanje

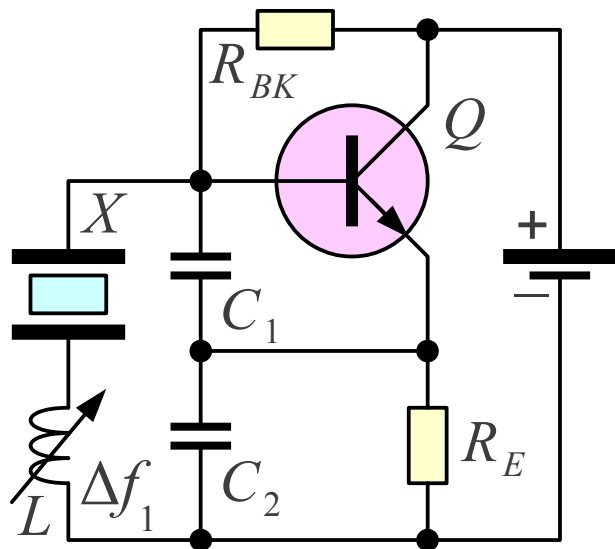
Ohlajanje



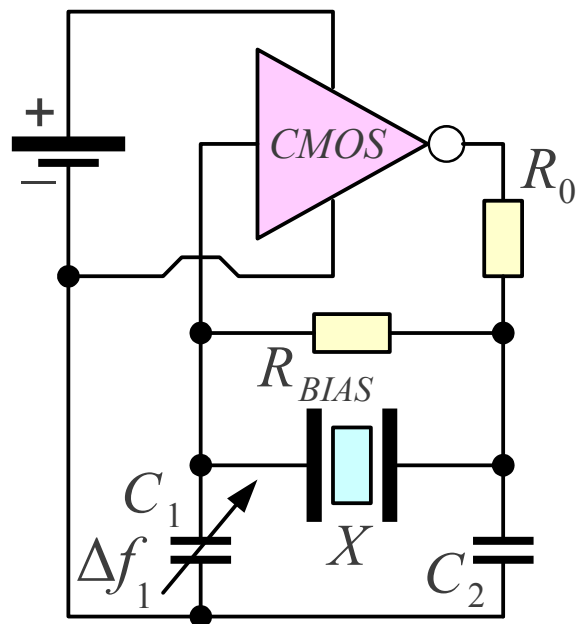
HLADNO



25 – Histereza lepenja umazanije v oscilatorju

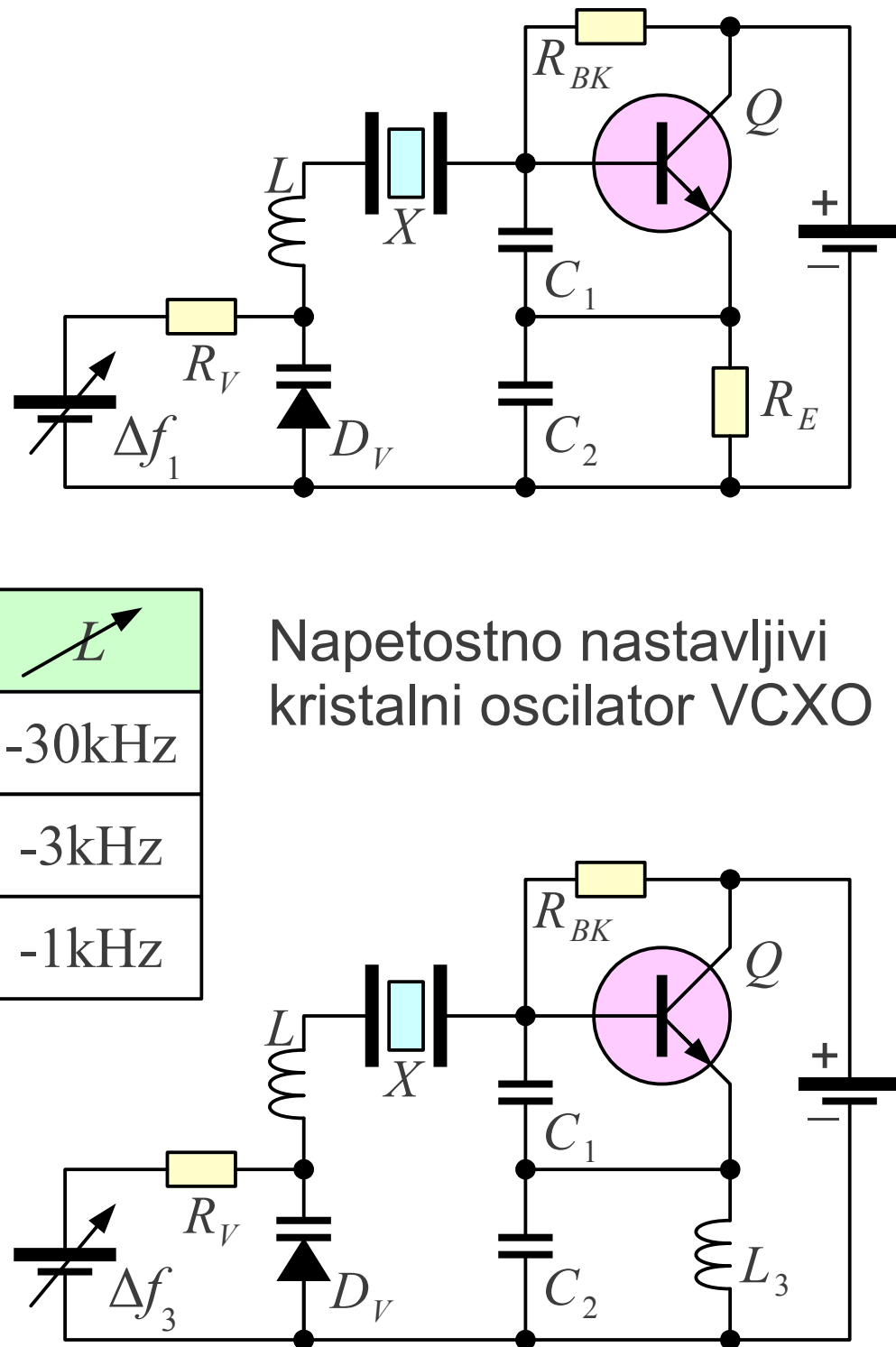


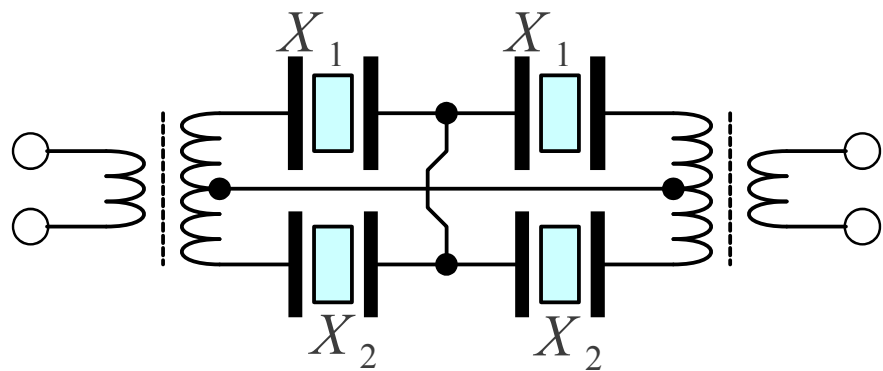
Nastavljivi kristalni oscilator VXO



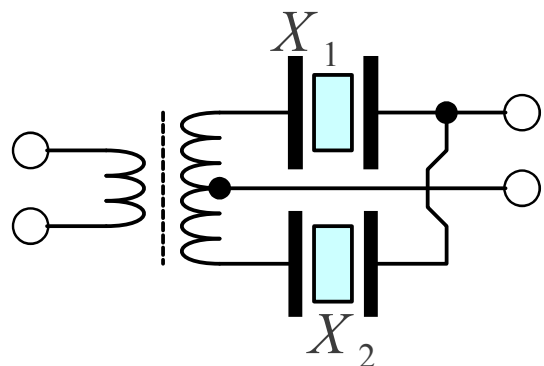
	C	L
Δf_1	+10kHz	-30kHz
Δf_3	+1kHz	-3kHz
Δf_5	+300Hz	-1kHz

Napetostno nastavljivi kristalni oscilator VCXO

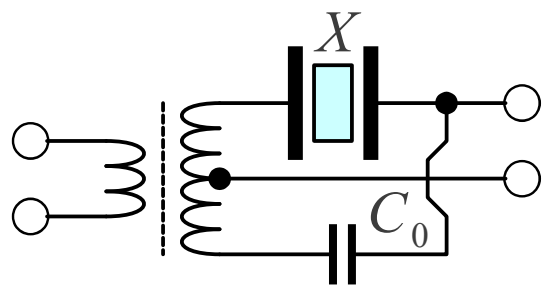




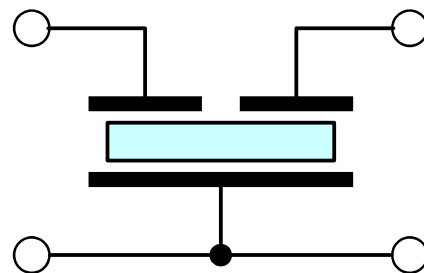
Dvojno mostično pasovno sito



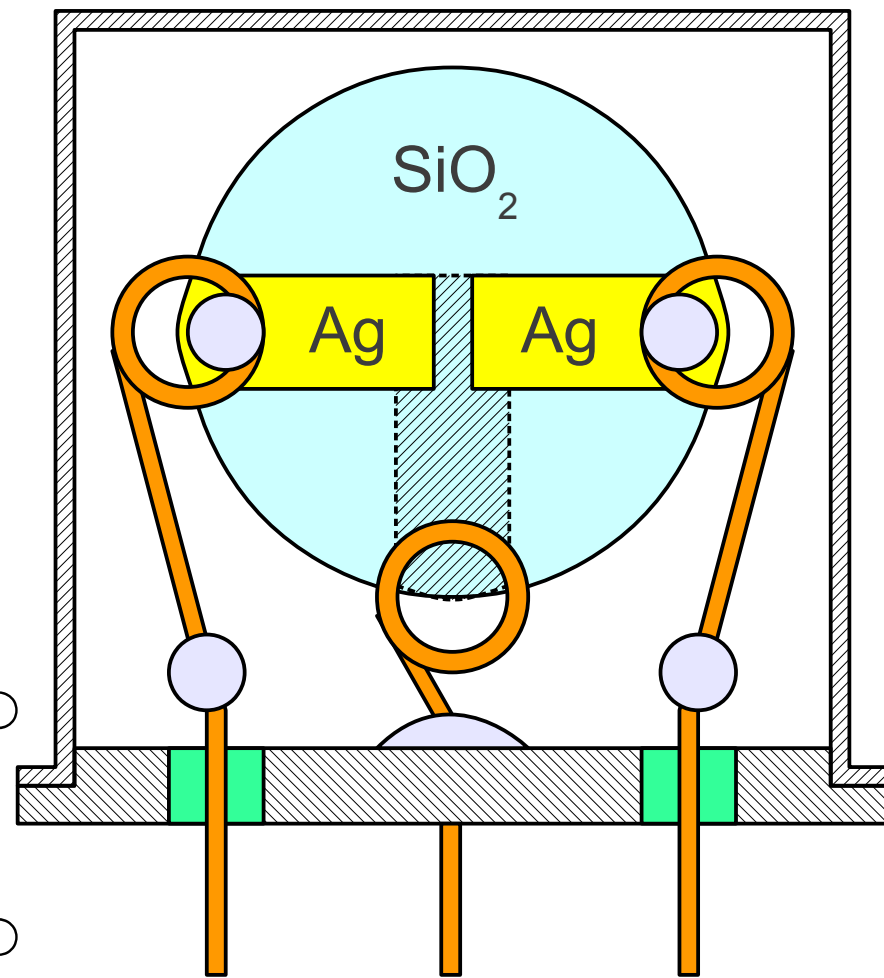
Mostično pasovno sito



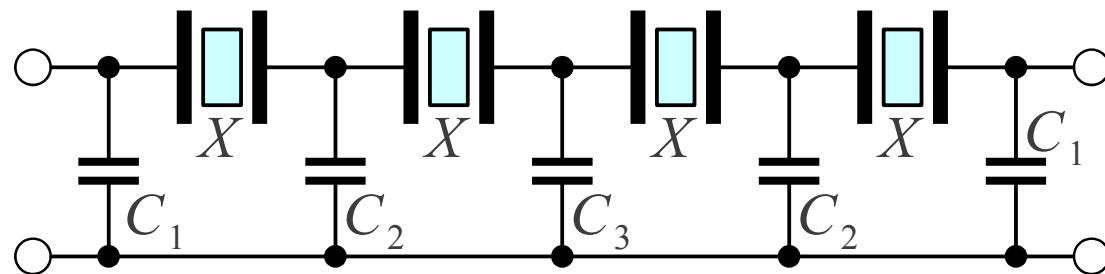
Preprosto pasovno sito



Monolitno pasovno sito

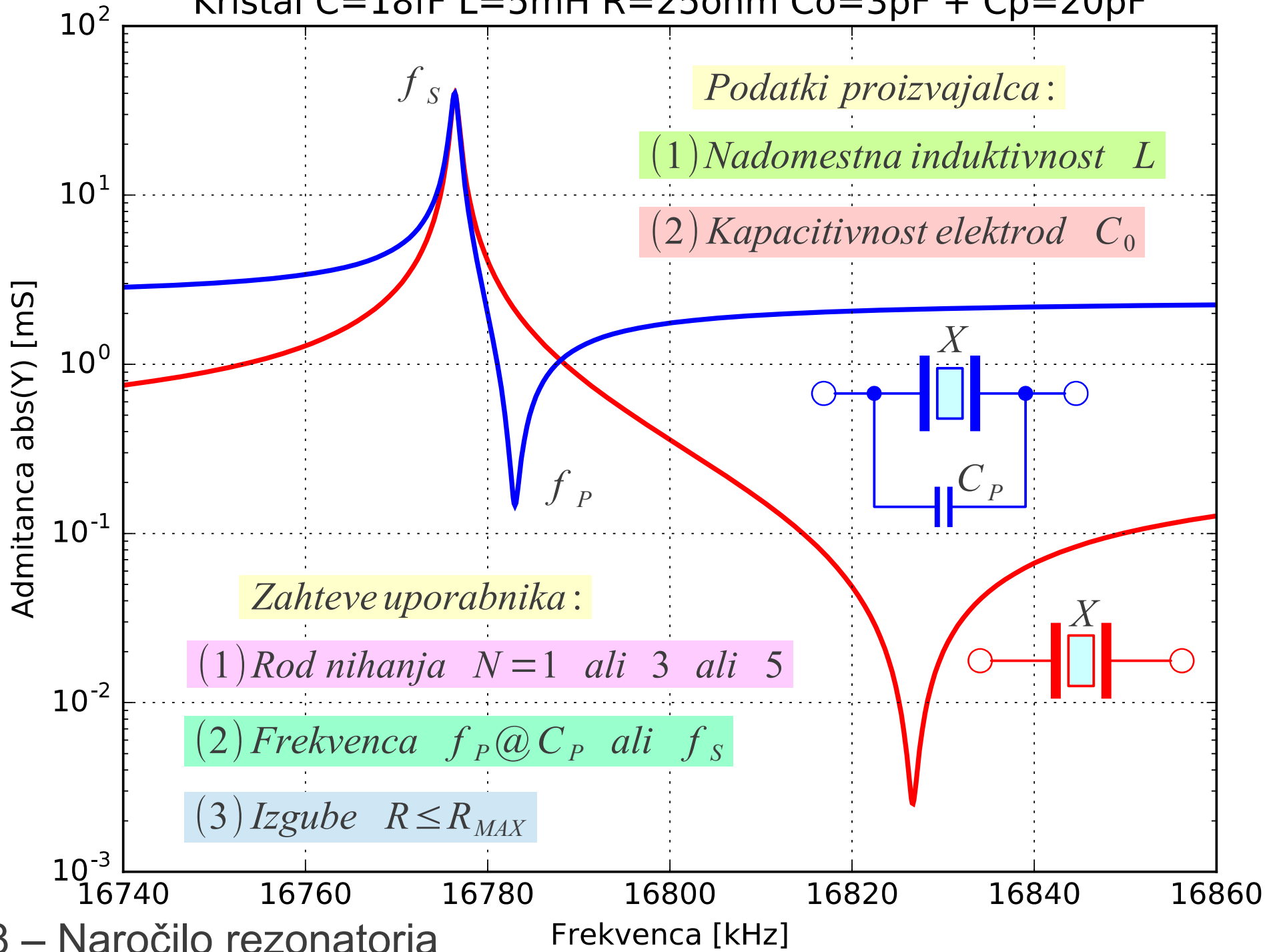


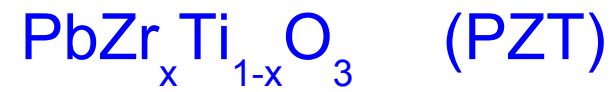
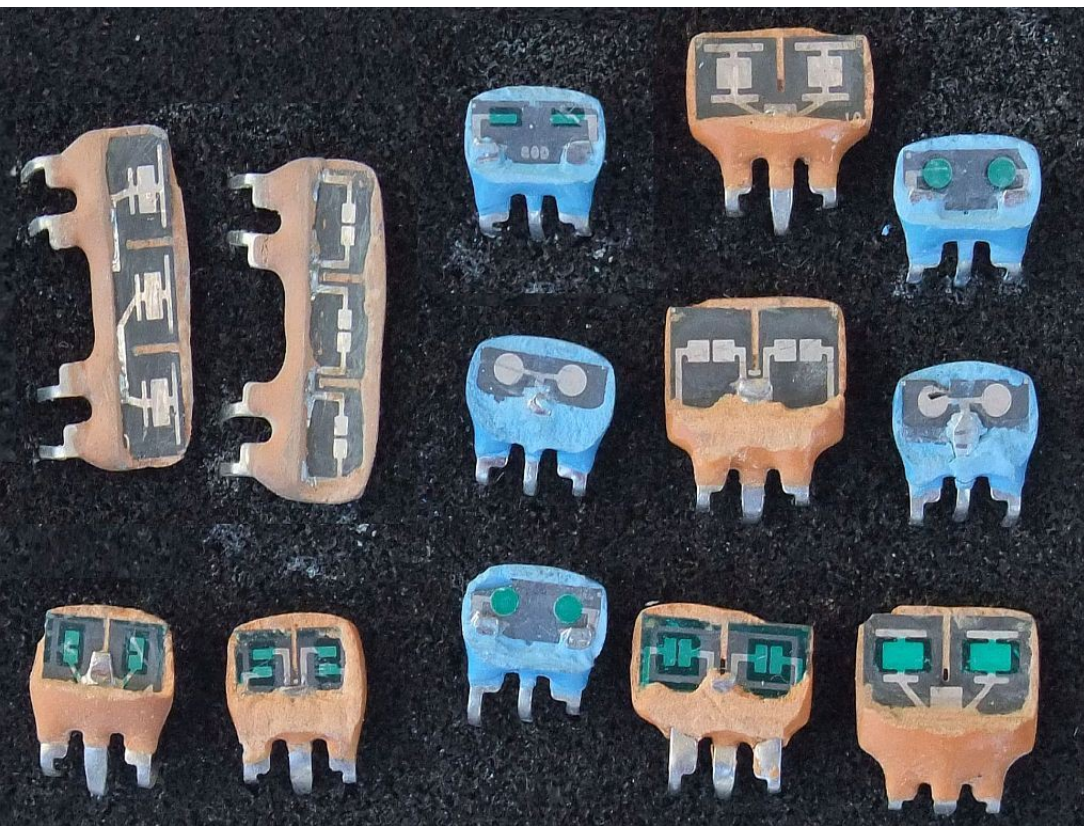
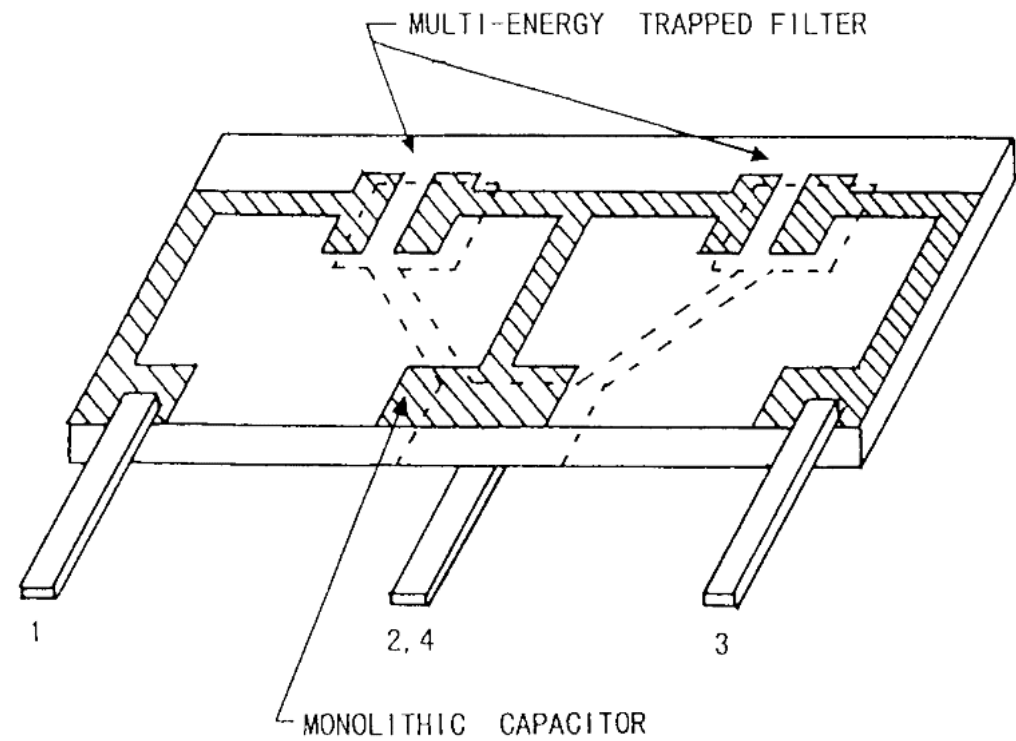
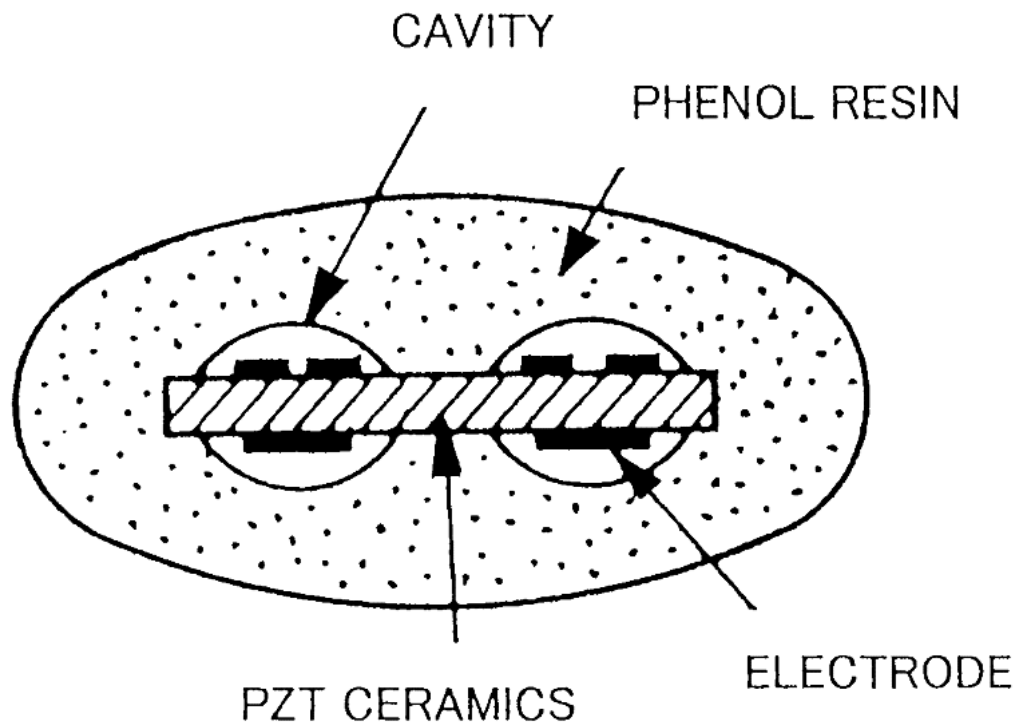
$200\text{Hz} \leq B \leq 50\text{kHz}$



Lestvičasto pasovno sito

Kristal $C=18\text{fF}$ $L=5\text{mH}$ $R=25\text{ohm}$ $C_0=3\text{pF}$ + $C_p=20\text{pF}$





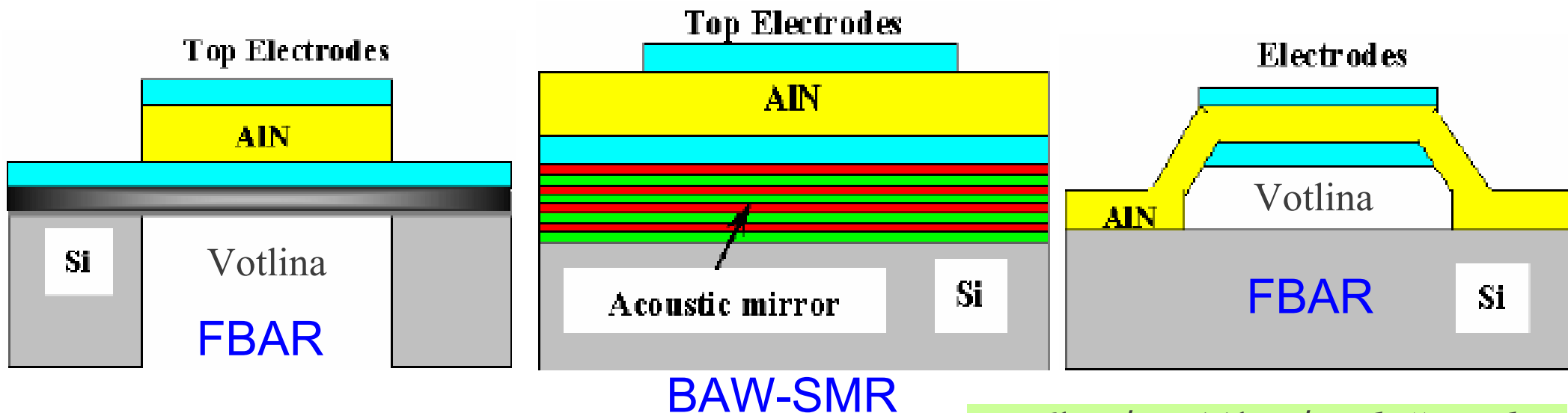
$$x \approx 0.52$$

$$v \approx 3\text{km/s} \dots 4\text{km/s}$$

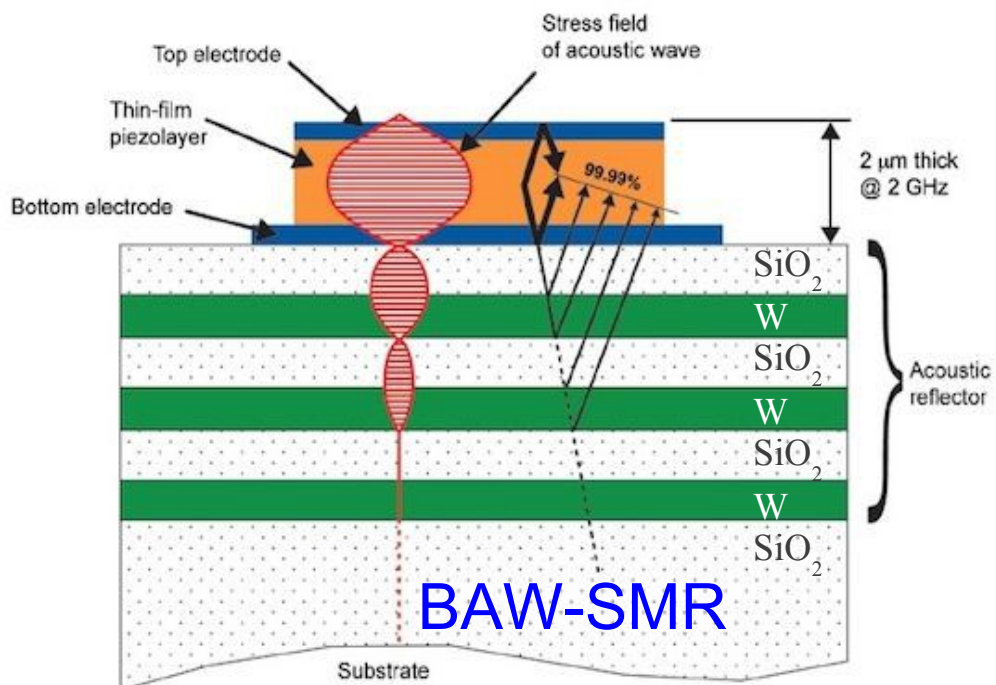
$$Q \approx 1000 \quad @ f=10\text{MHz}$$

Film Bulk Acoustic Resonator (FBAR)

$Q \approx 2000$ @ $f = 2\text{GHz}$

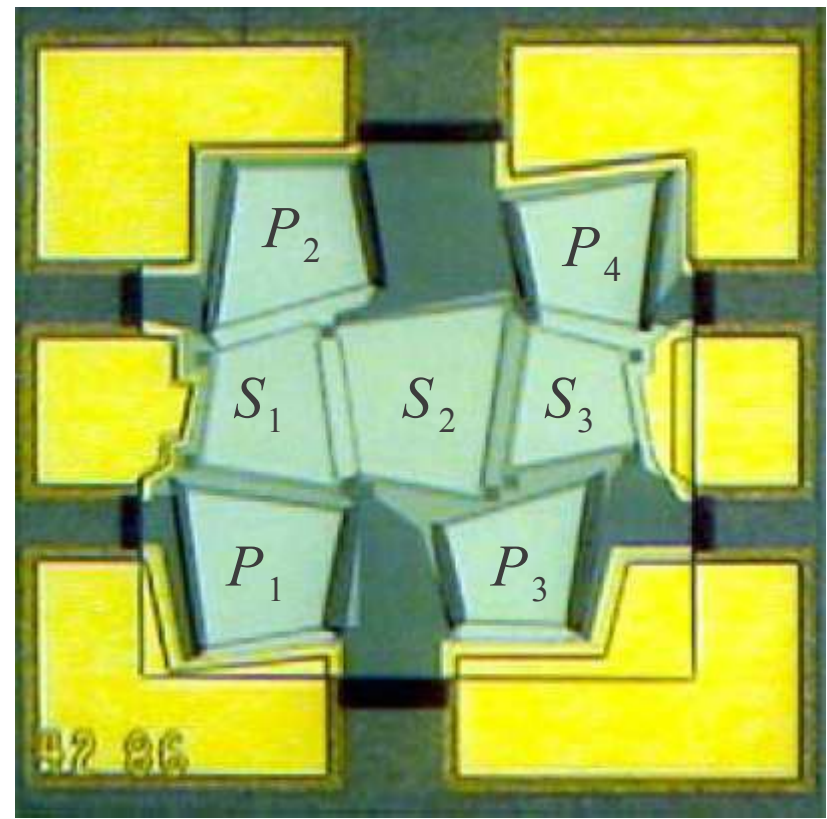
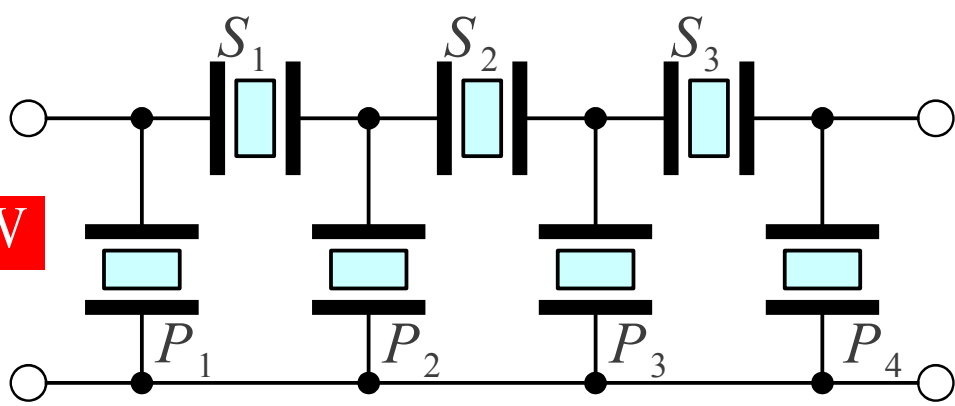


$v \approx 6\text{km/s} \dots 11\text{km/s}$ tlačni val P

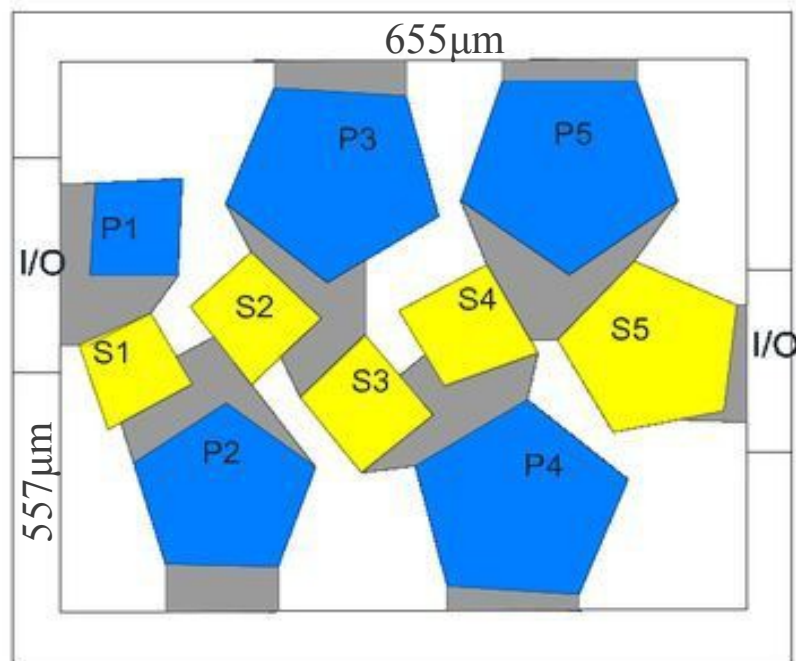
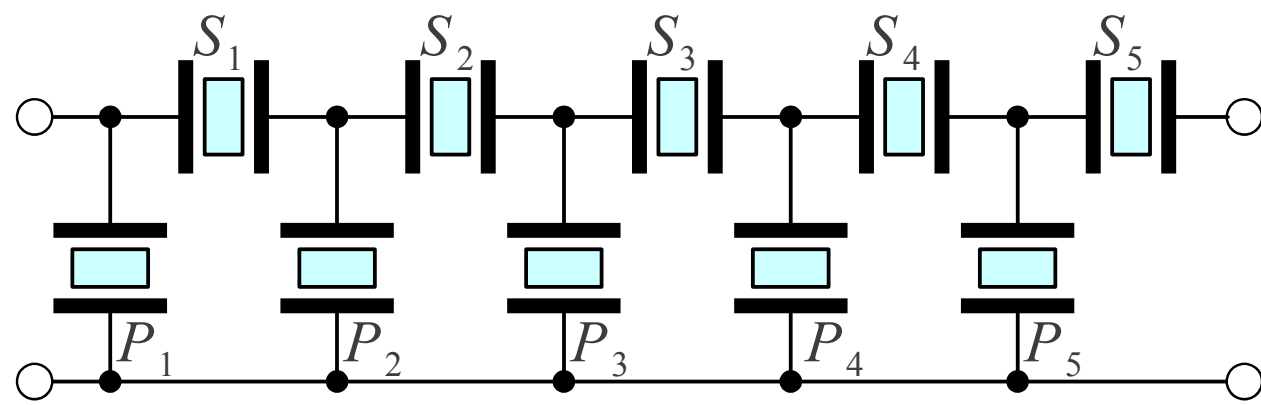
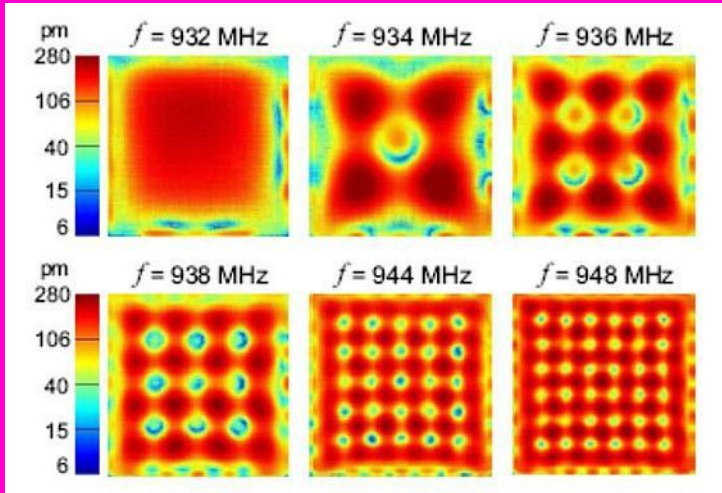


Material	Dielectric constant	Acoustic velocity (m/s)	Acoustic coupling	Acoustic loss dB/ μs At 1 GHz
AIN (novo)	8.5	10,400	0.17	~5
ZnO (staro)	8.8	6,330	0.28	8.3

$P_{MAX} \approx 1W$

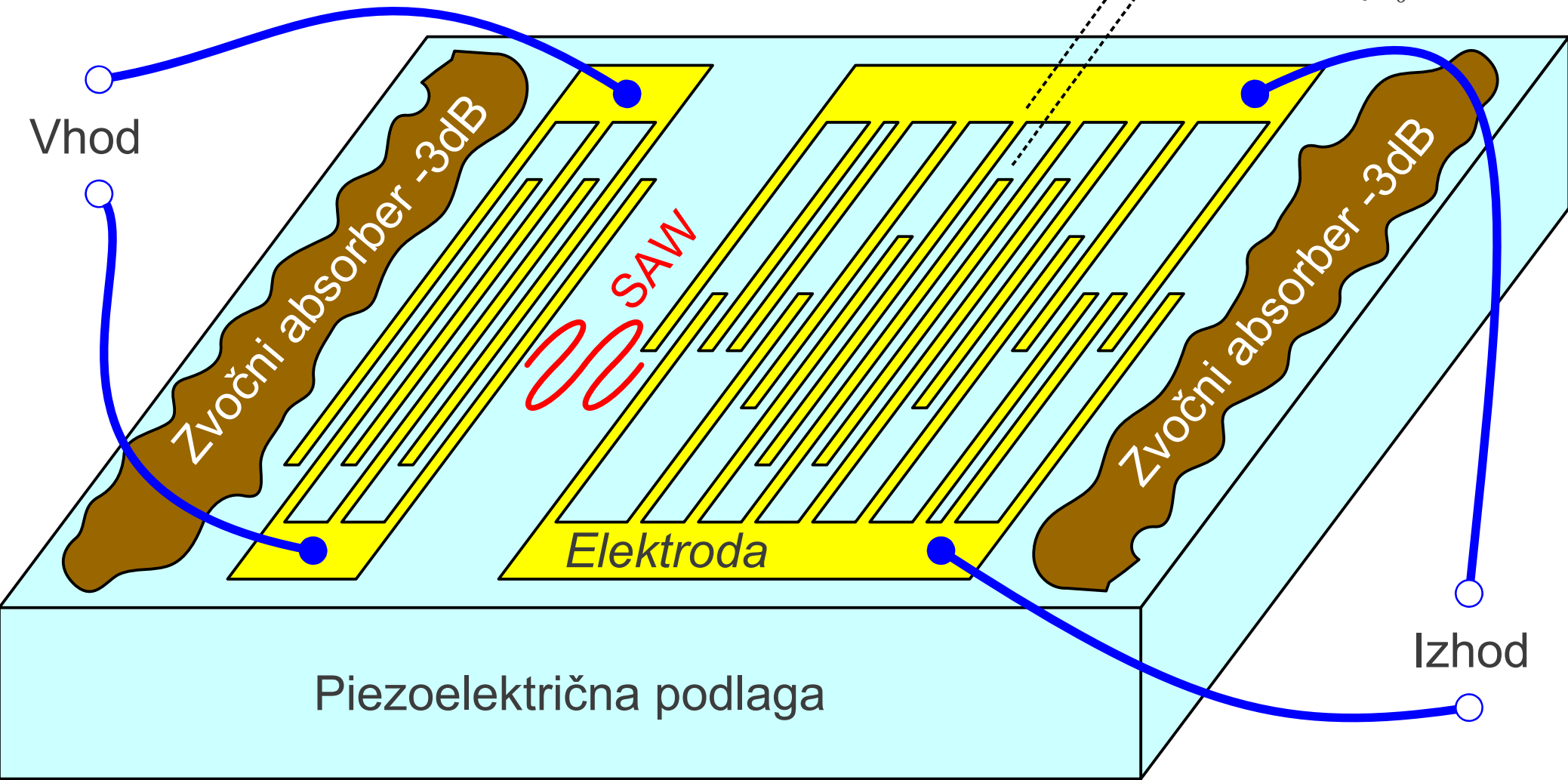


Prečni rodovi
v kvadratnem
rezonatorju
FBAR



Potujoči površinski val → sito s končnim odzivom FIR

$$\Delta/2 = \frac{v}{2f_0}$$

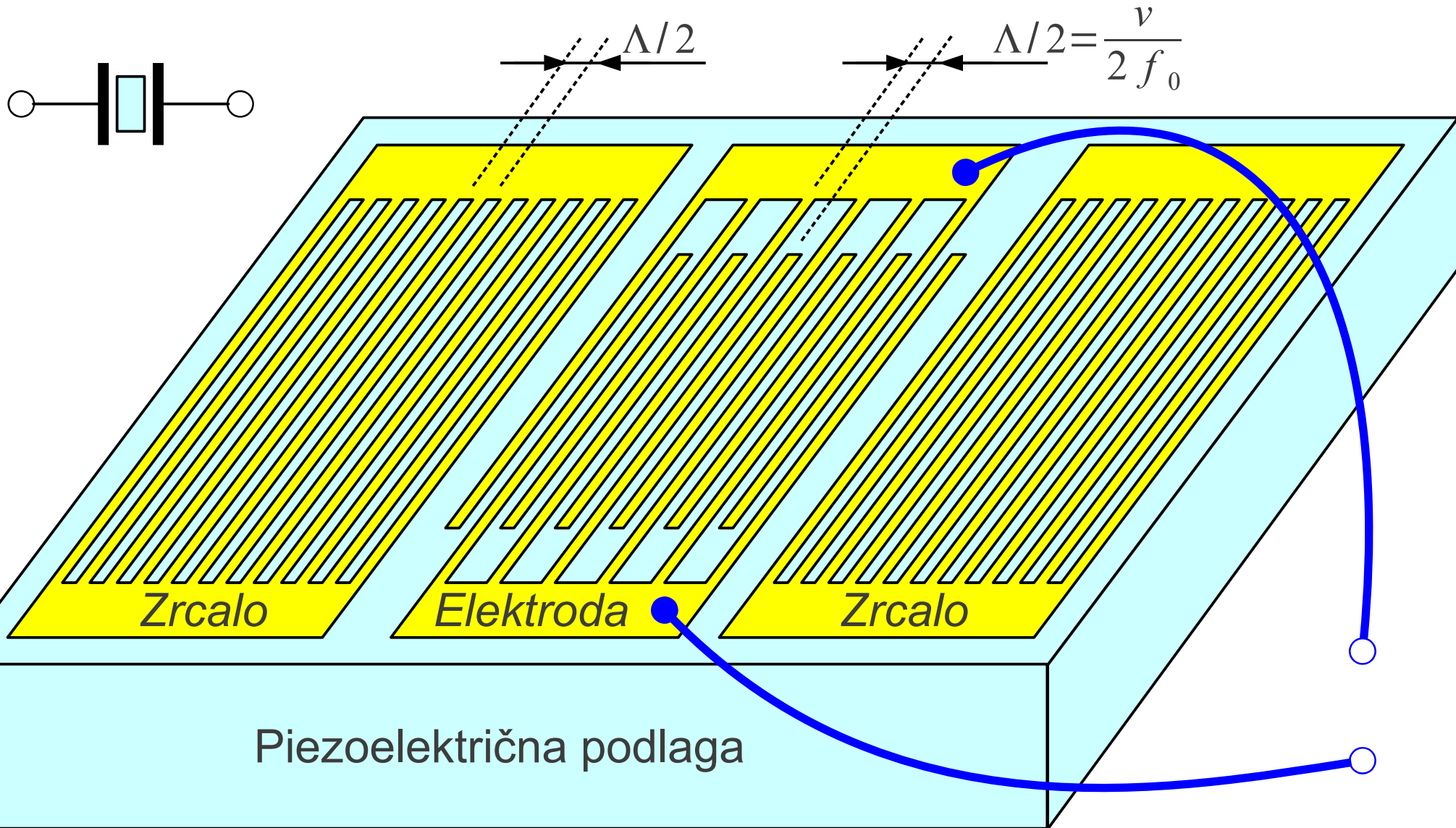


Kristalna podlaga: SiO_2 ali LiNbO_3 ali LiTaO_3 ali $\text{La}_3\text{Ga}_5\text{SiO}_{14}$
(kvarc) (langasite)



33 – SAW sito za 36MHz

Stojni površinski val → rezonator ≡ sito z neskončnim odzivom IIR



Kristalna podlaga: SiO_2 ali LiNbO_3 ali LiTaO_3 ali $\text{La}_3\text{Ga}_5\text{SiO}_{14}$
(kvarc) (langasite)

$v \approx 2\text{km/s} \dots 5\text{km/s}$