

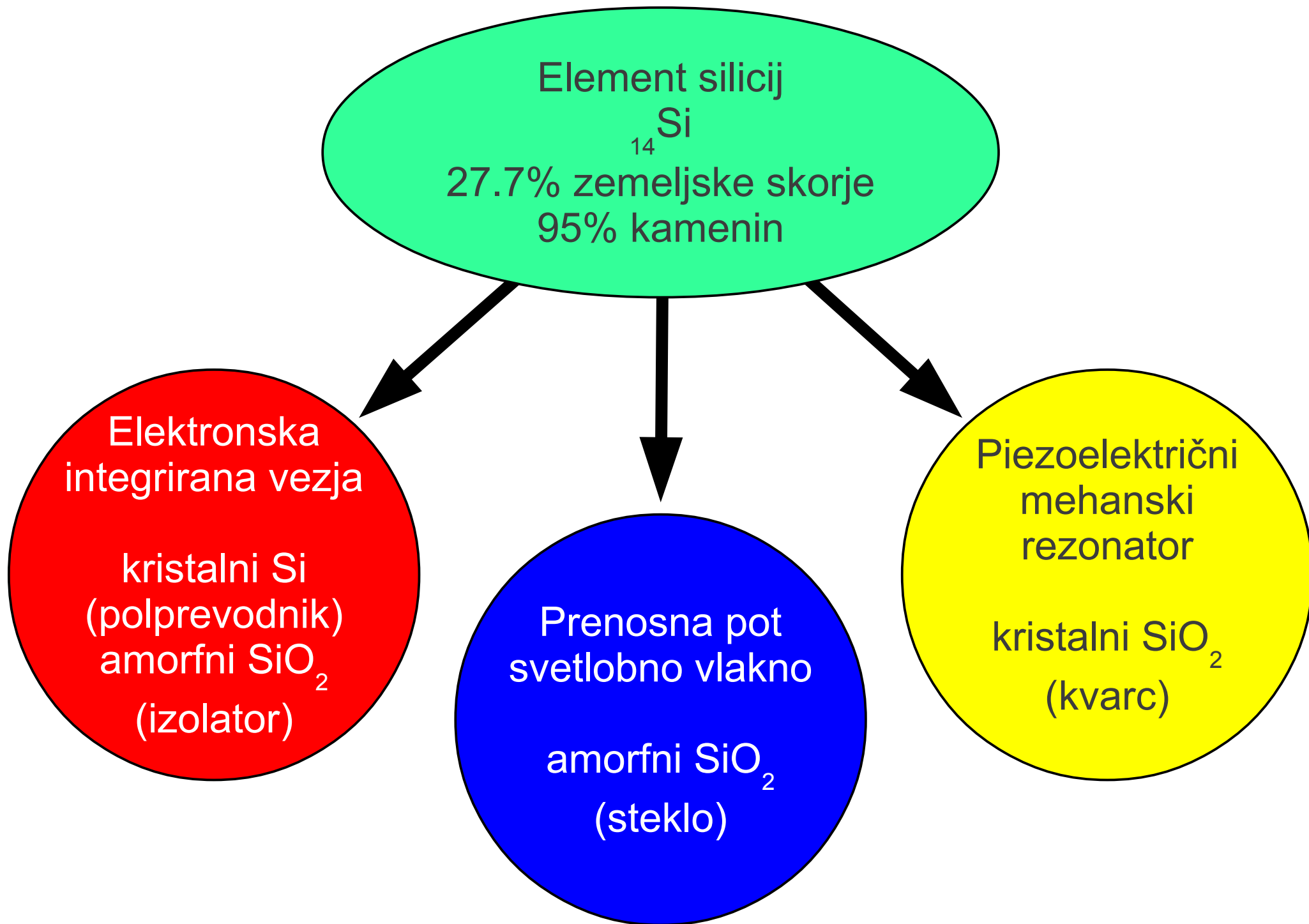
Piezoelektrični rezonatorji v radijski tehniki

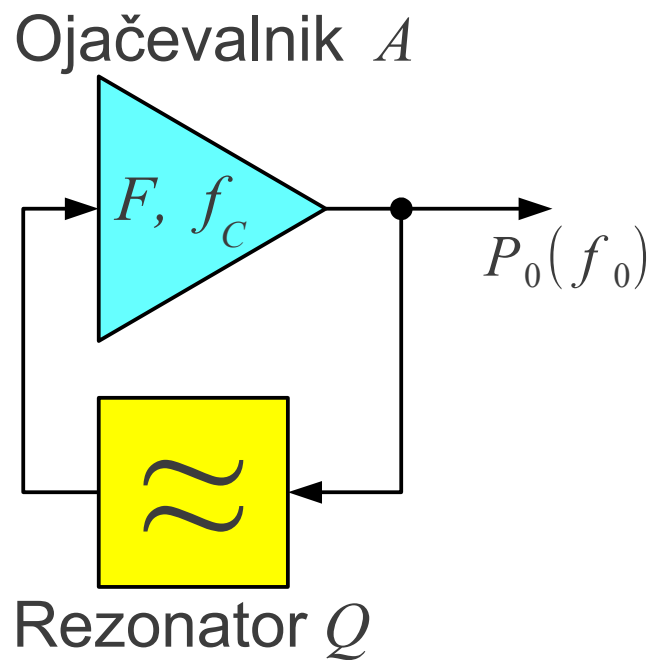
Matjaž Vidmar

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 - Vpliv debeline kovinskih elektrod na površini rezine
- 21 - Vgradnja rezine AT v ohišje
- 22 - Ohišja piezoelektričnih rezonatorjev
- 23 - Kristalni oscilatorji
- 24 - Histereza lepenja umazanije v oscilatorju
- 25 - Nastavljivi kristalni oscilatorji
- 26 - Kristalna pasovna sita
- 27 - Piezokeramika
- 28 - Tehnologije FBAR
- 29 - FBAR pasovna sita
- 30 -
- 31 -
- 32 -
- 33 -
- 34 -
- 35 -
- 36 -
- 37 -





Leesonova enačba: spektralna gostota faznega šuma

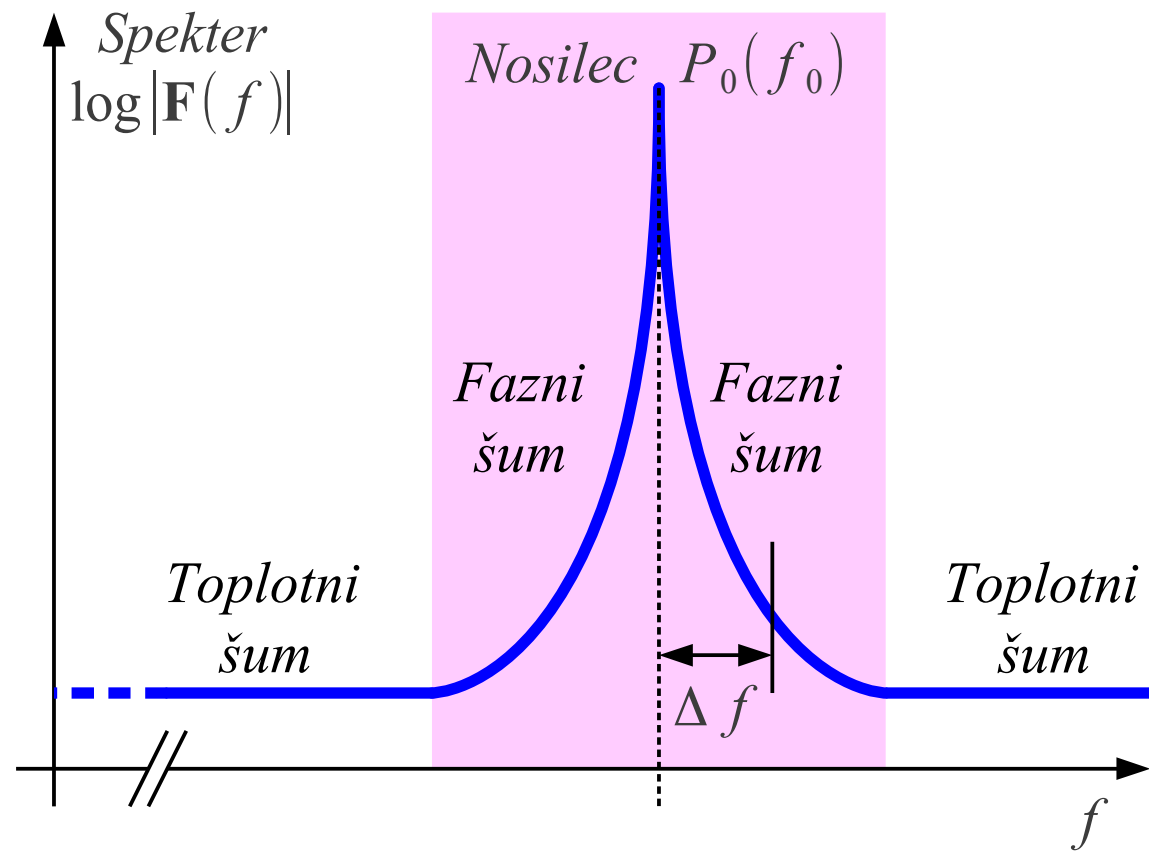
$$L(\Delta f) = \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left(1 + \frac{f_c}{|\Delta f|} \right)$$

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

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

$F \equiv \text{šumno število ojačevalnika}$

$f_c \equiv \text{mejna frekvenca šuma } 1/f$



$Q_L \equiv \text{obremenjeni } Q \text{ rezonatorja}$

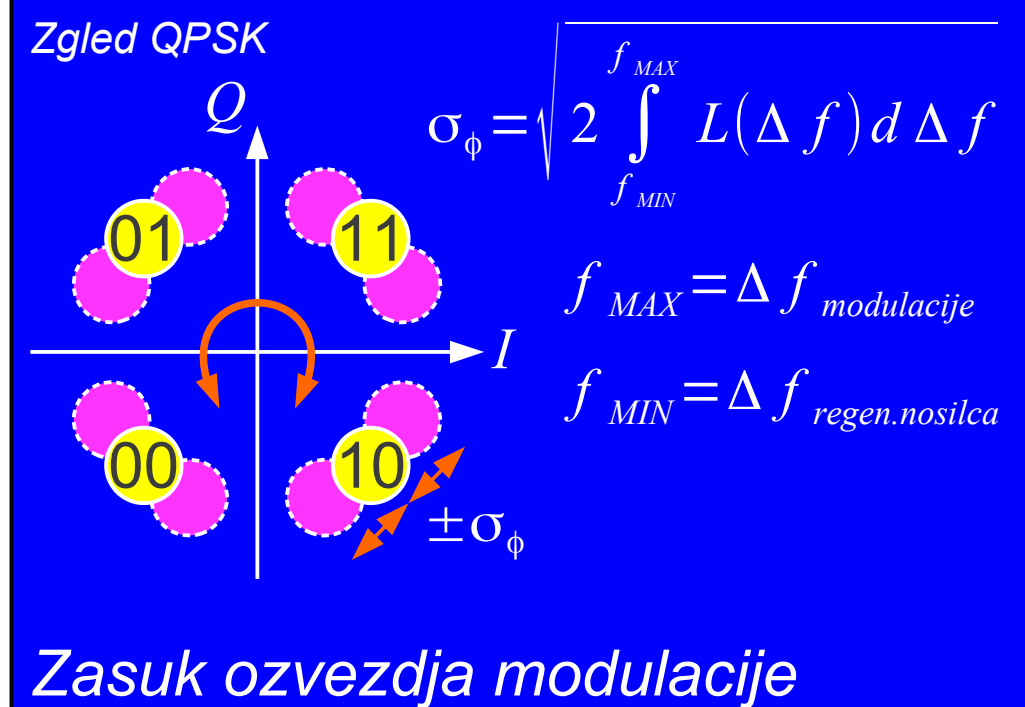
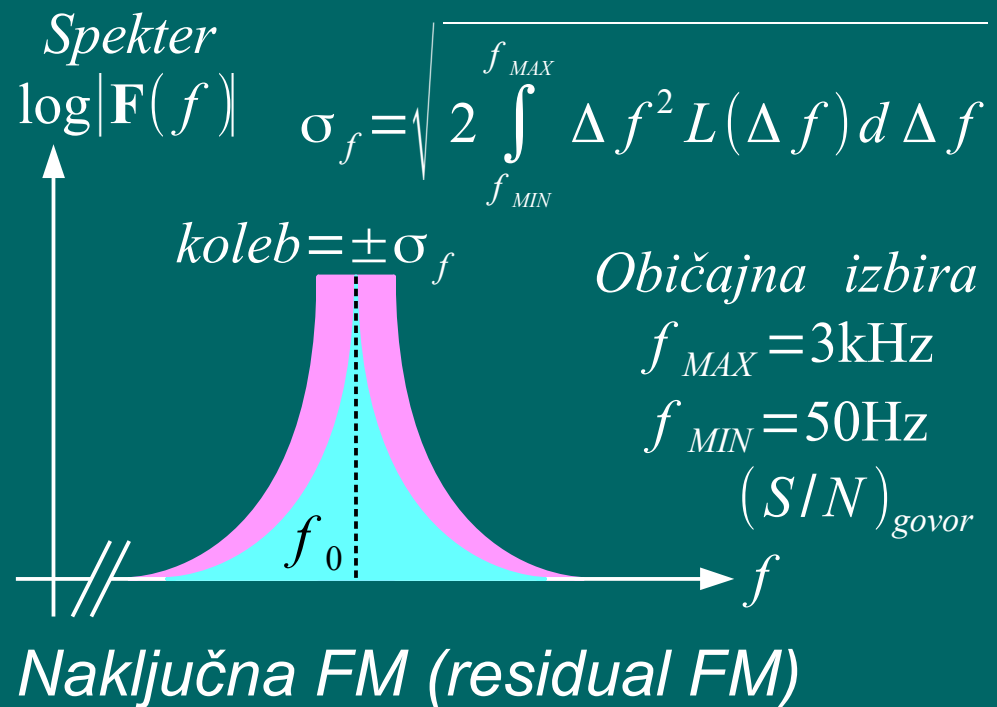
$Q_L \approx 30 \text{ (LC nihajni krog)}$

$Q_L \approx 1000 \text{ (električna votlina)}$

$Q_L \approx 30000 \text{ (kremenov kristal)}$

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

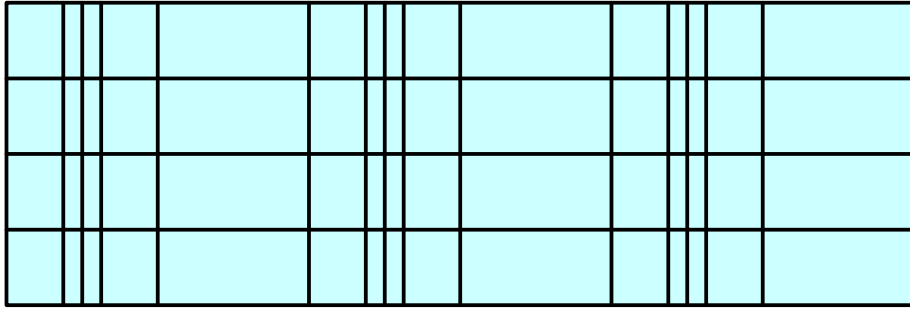
Preprost QPSK $\rightarrow f_0 < 100\text{GHz}$

3 – Omejitve faznega šuma

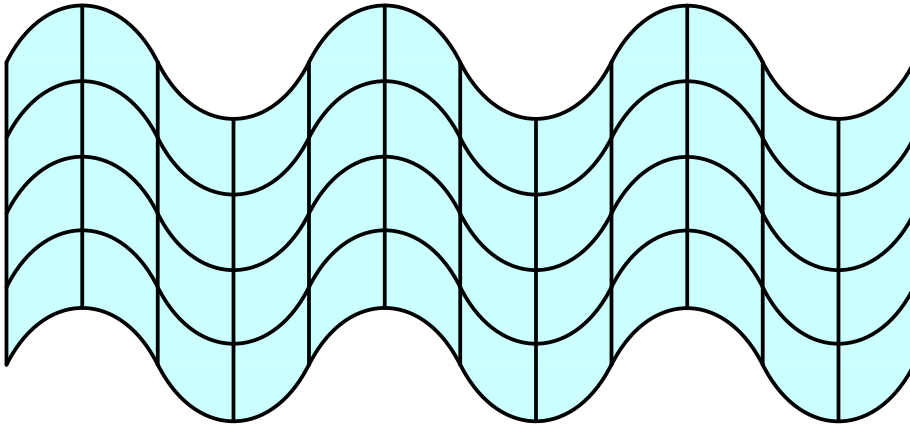
- 1880 – Jacques in Pierre Curie odkrijeta piezoelektrični pojav
- 1905 – G. Spezia hidrotermalna rast kremenovih kristalov v laboratoriju
- 1917 – Prva uporaba piezoelektričnega pojava v sonarju
- 1918 – Prva uporaba piezoelektričnega kristala v oscilatorju
- 1926 – Prvi radiodifuzni oddajnik s kremenovim 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

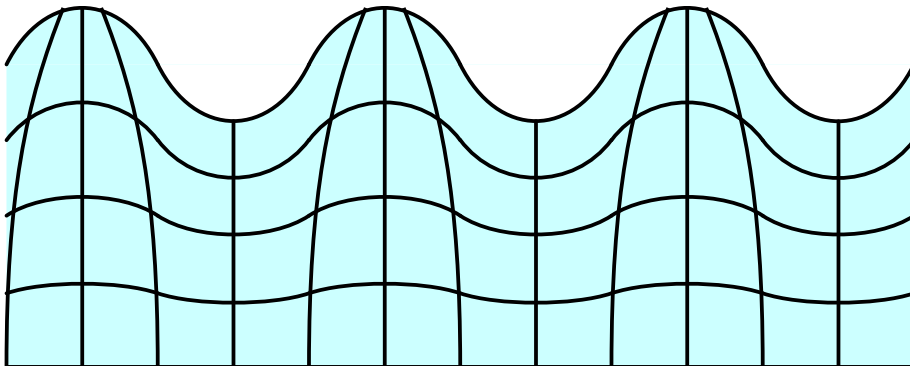
5 – Mehanska valovanja





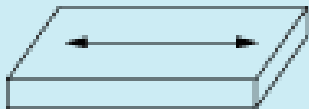
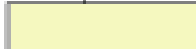

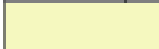
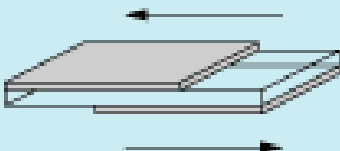
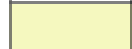
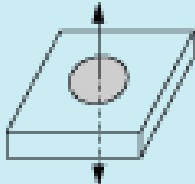
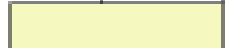
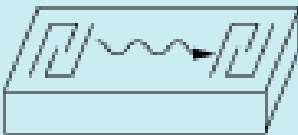
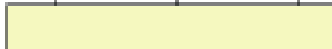
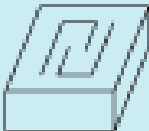
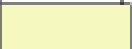
Tlačni val "P" (pressure wave)
plini, tekočine, trdne snovi
("BAW" bulk acoustic wave)



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



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

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

←→ Vibration Modes

Tališče
1670°C

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

$T > 573^\circ\text{C}$
 β -kvarc

Mehanski
 $Q > 10^6$

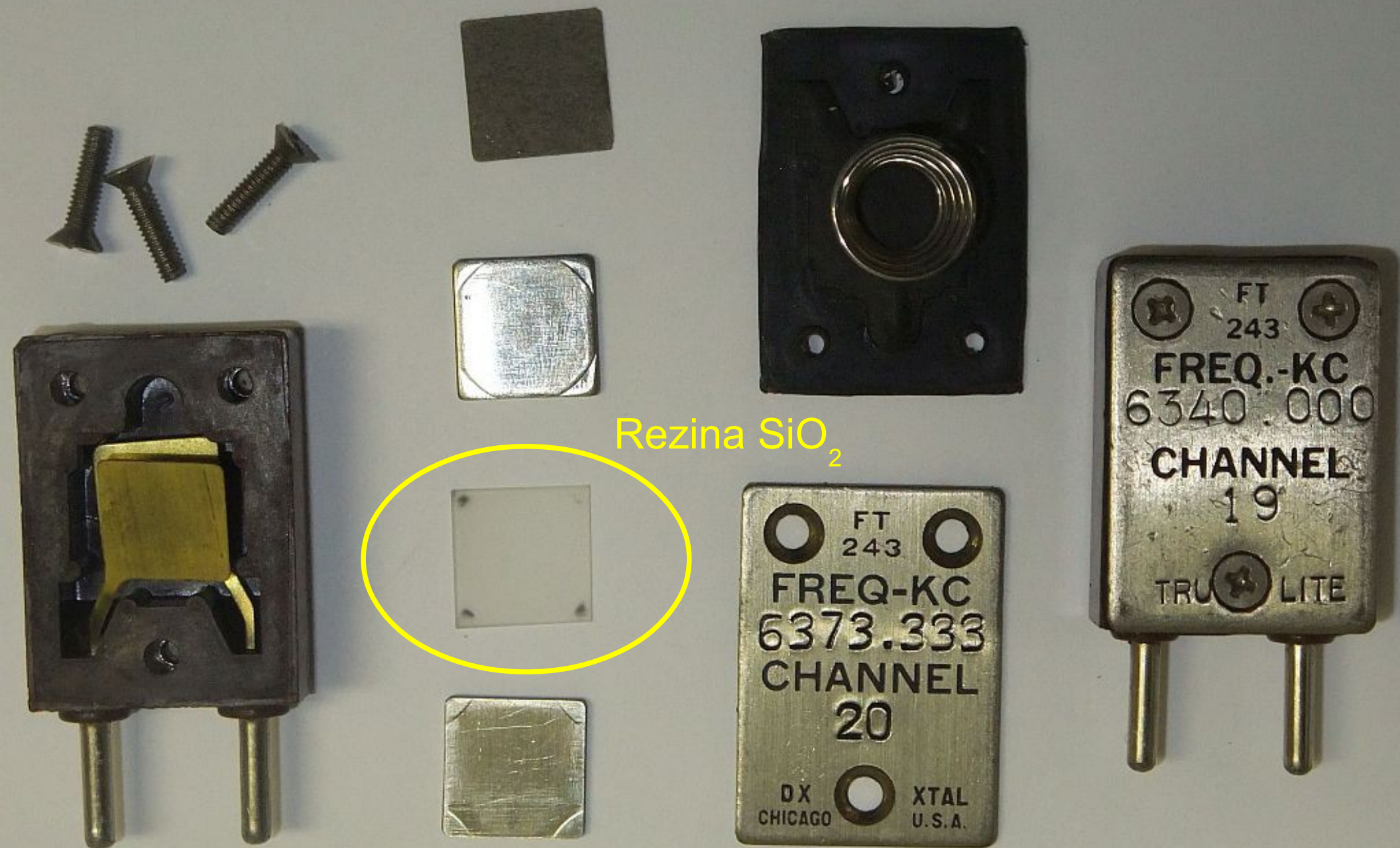
Piezoelektrik



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



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

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

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

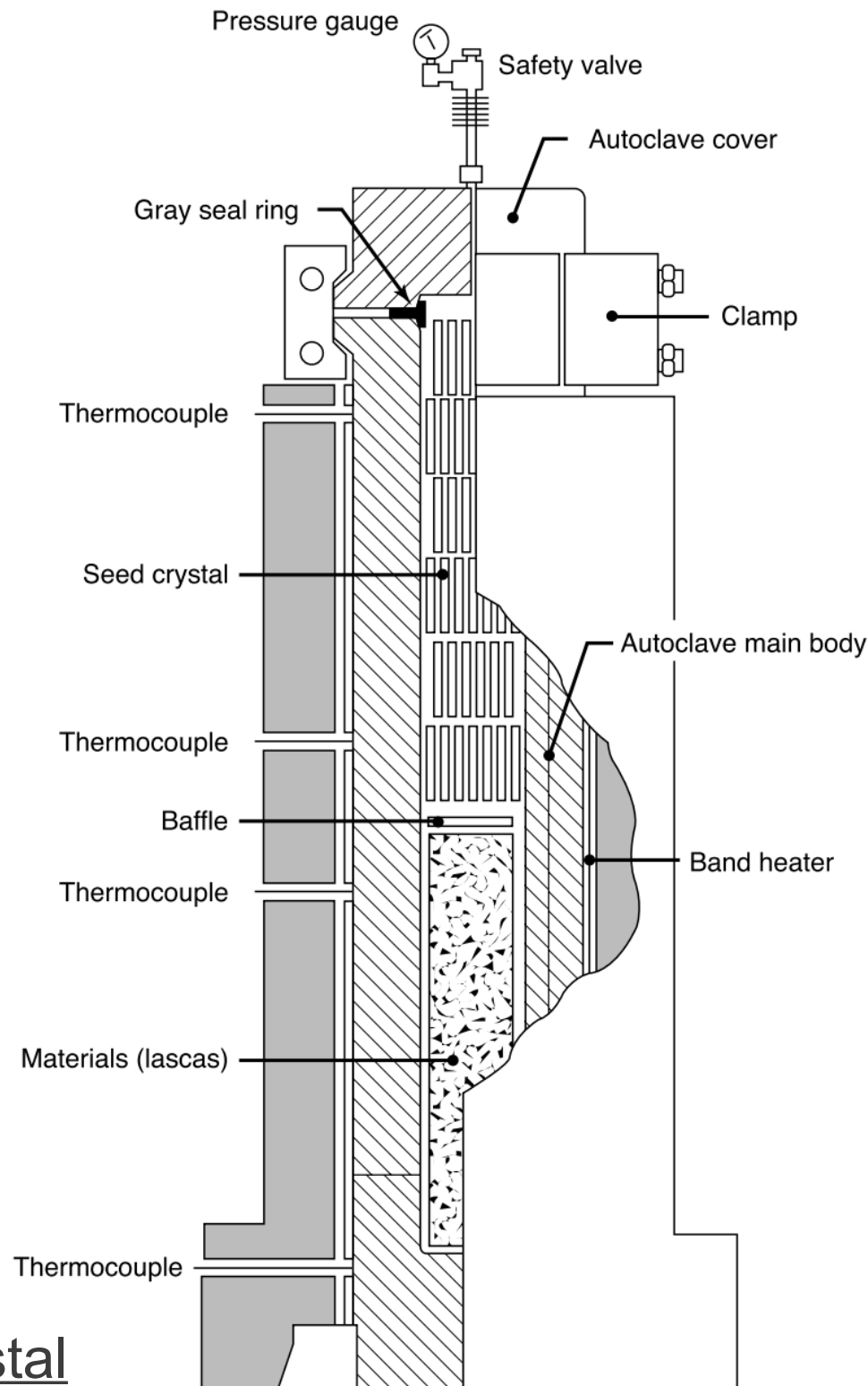


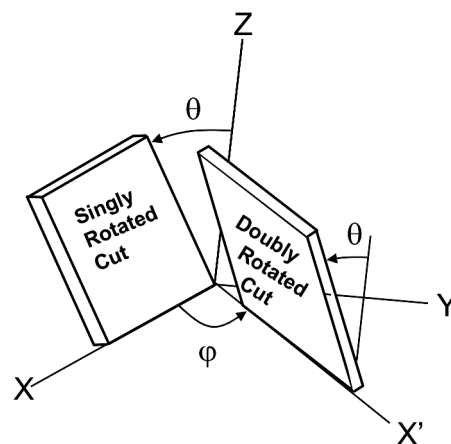
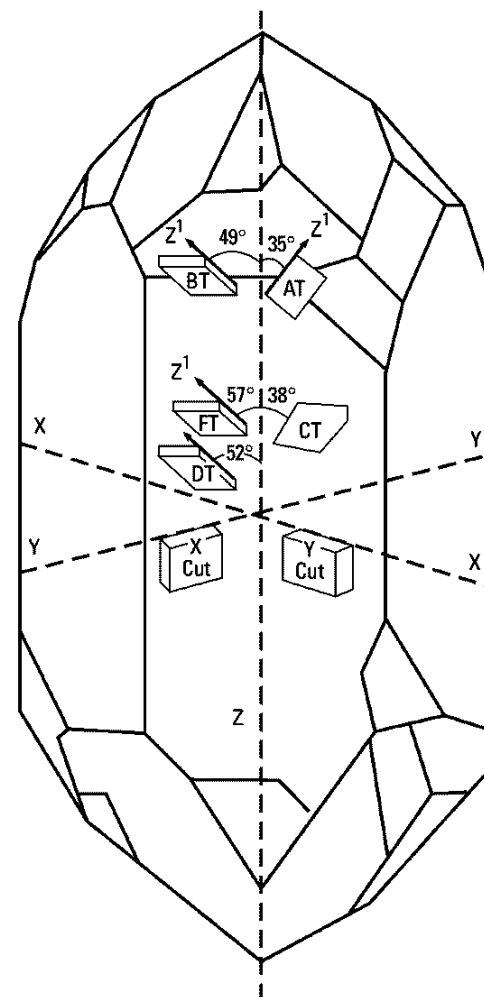
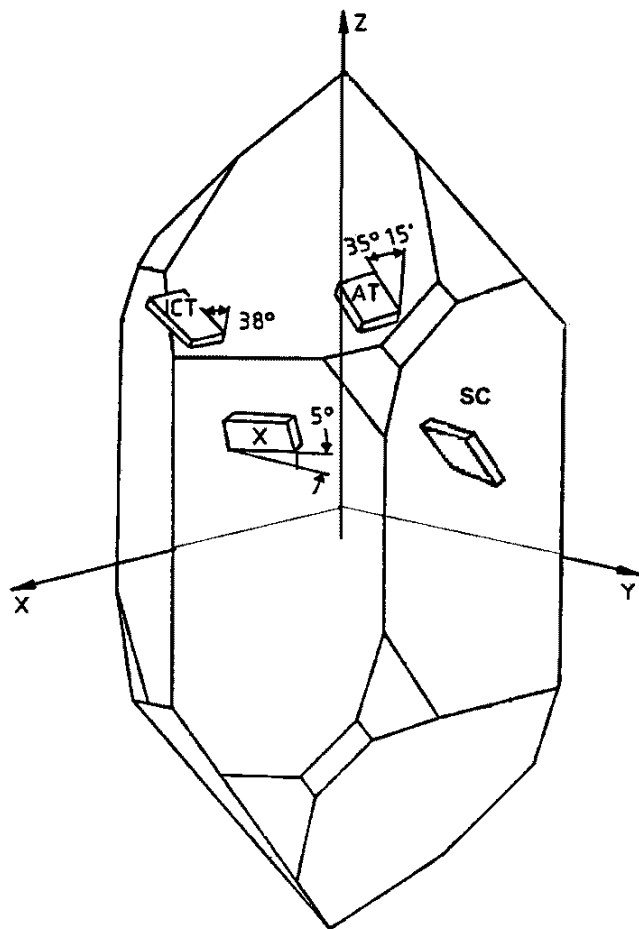
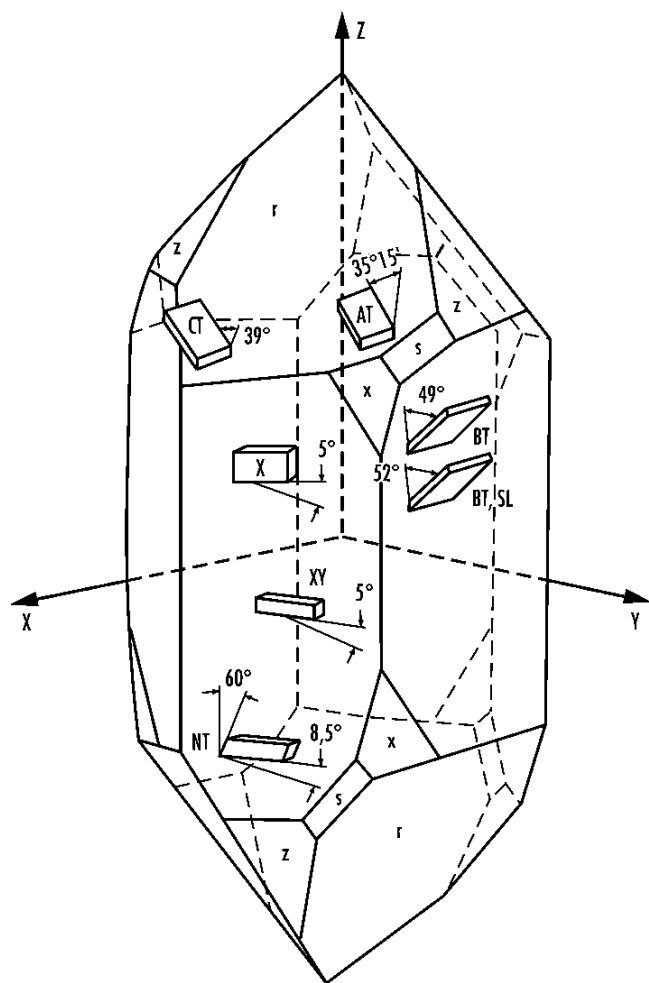
$p \approx 1000\text{--}1500\text{bar}$

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

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

9 – Umetni kremenov kristal



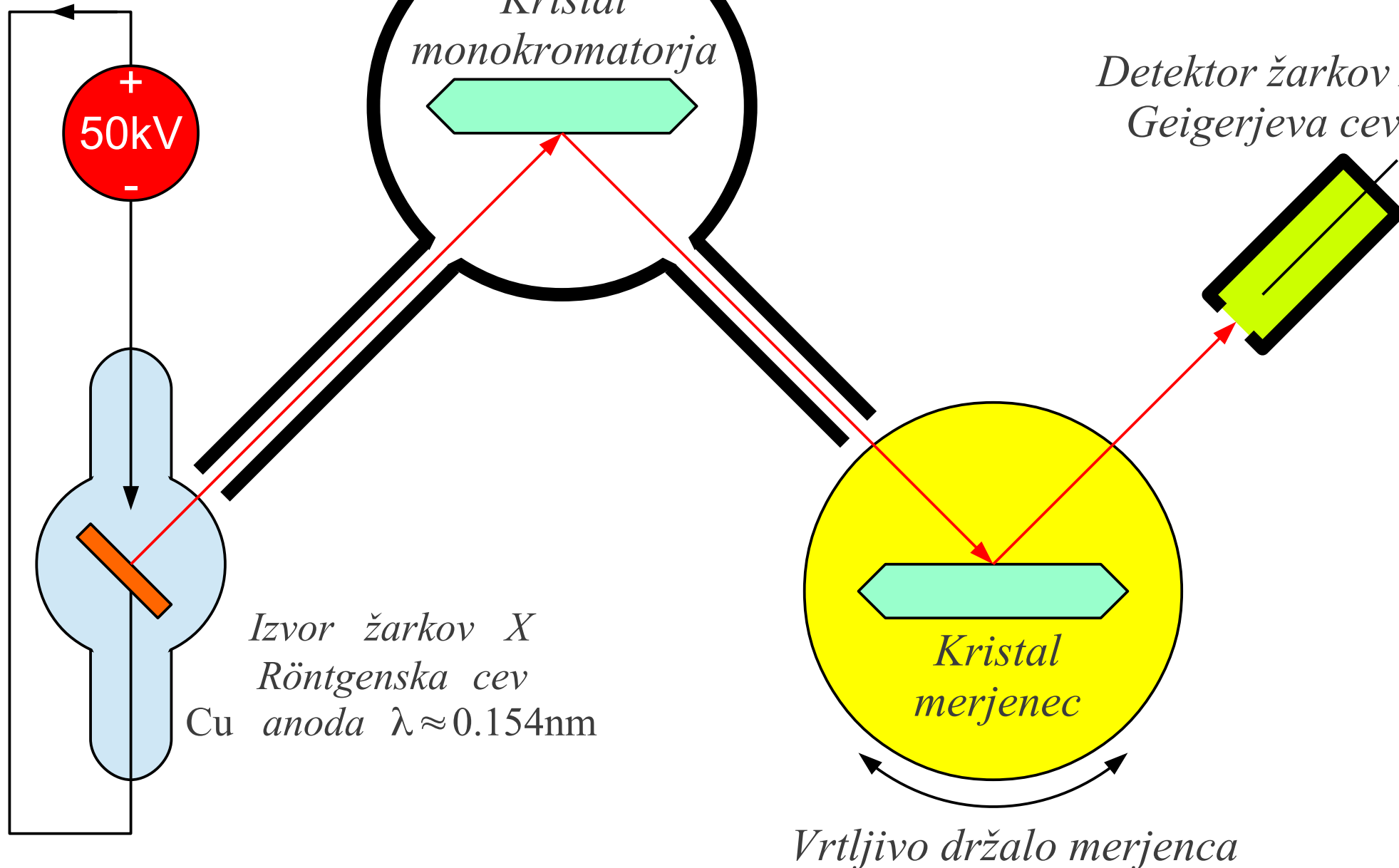


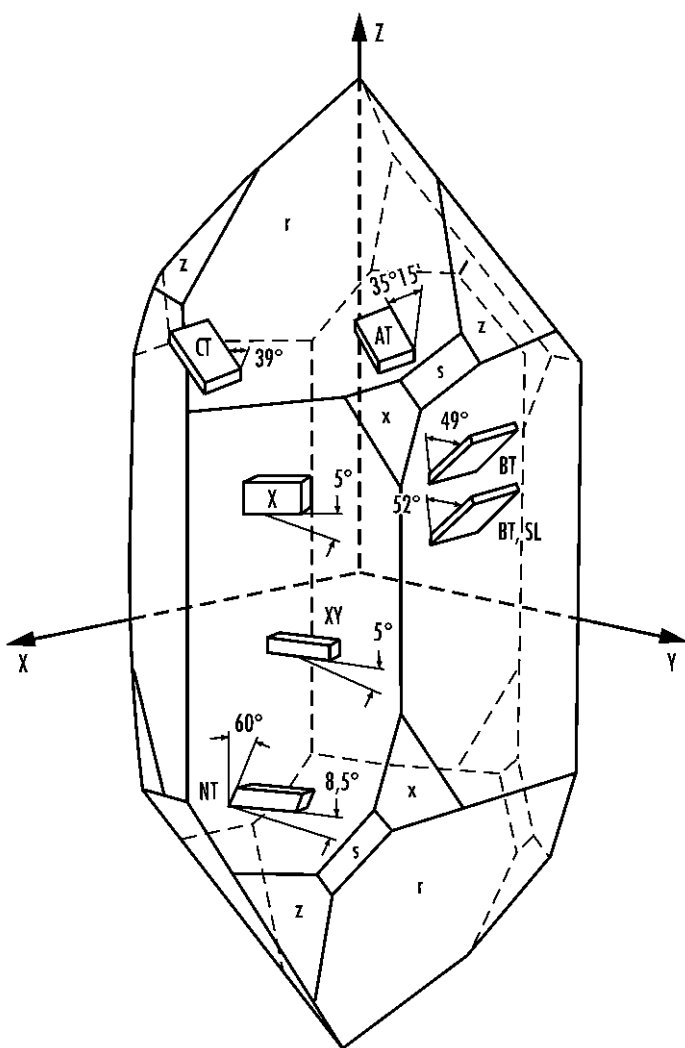
Pb oklop za žarke X

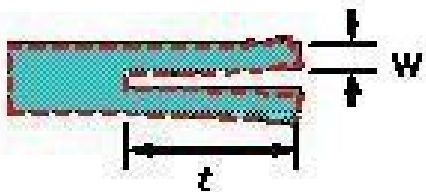
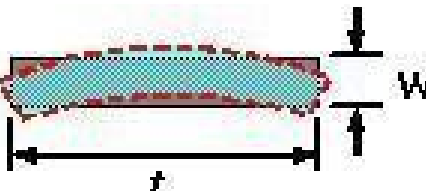
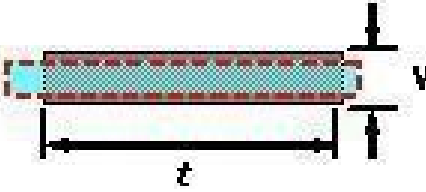
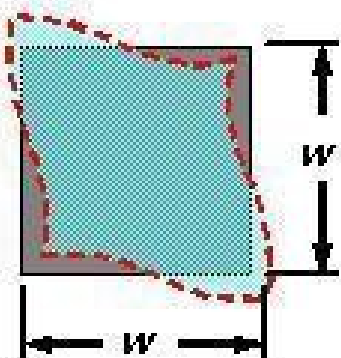

$I \approx 10\text{mA}$

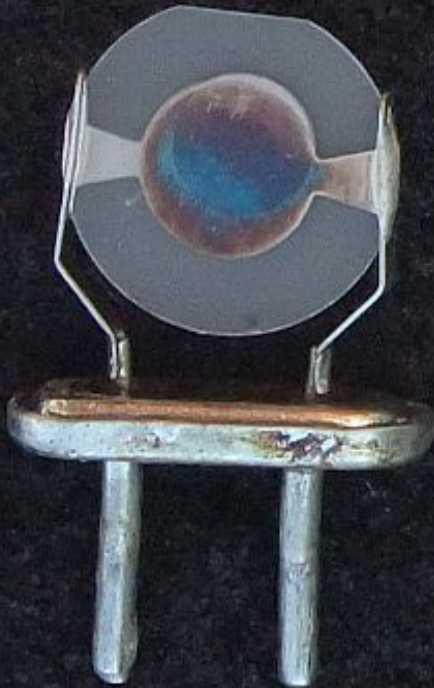
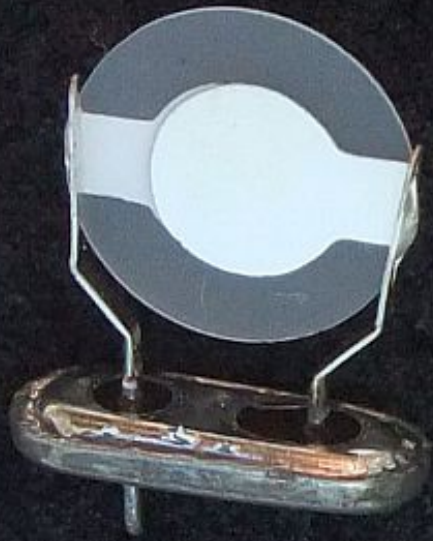
*Kristal
monokromatorja*

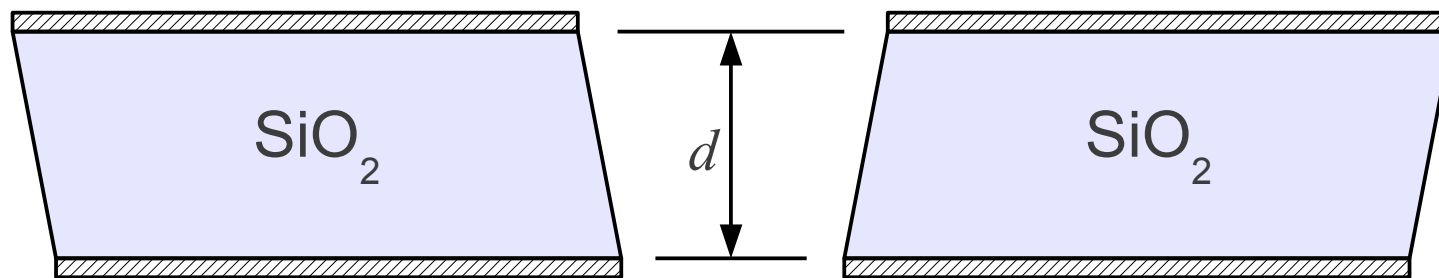
*Detektor žarkov X
Geigerjeva cev*



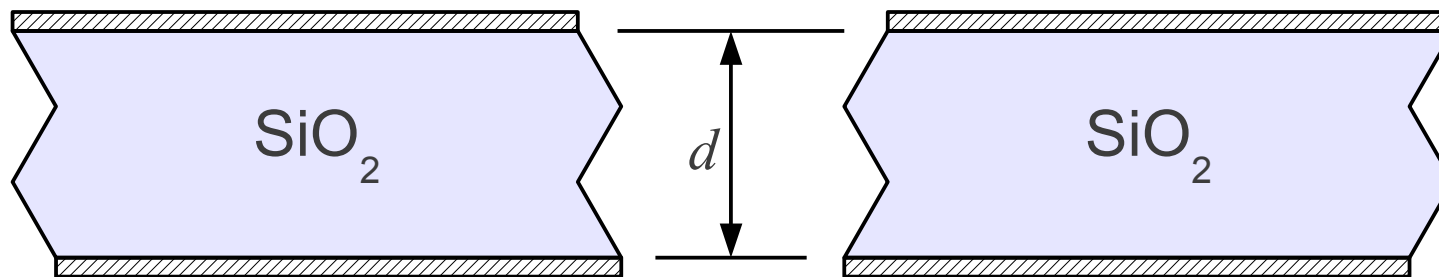


Vibration Mode	Orientation Angle
Tuning Fork 	$+ 2^\circ X$
Flexure 	XY NT
Extension 	$+ 5^\circ X$ $- 18.5^\circ X$
Face Shear  Thickness Shear 	DT CT SL AT Fundamental AT 3 rd Overtone AT 5 th Overtone BT Fundamental

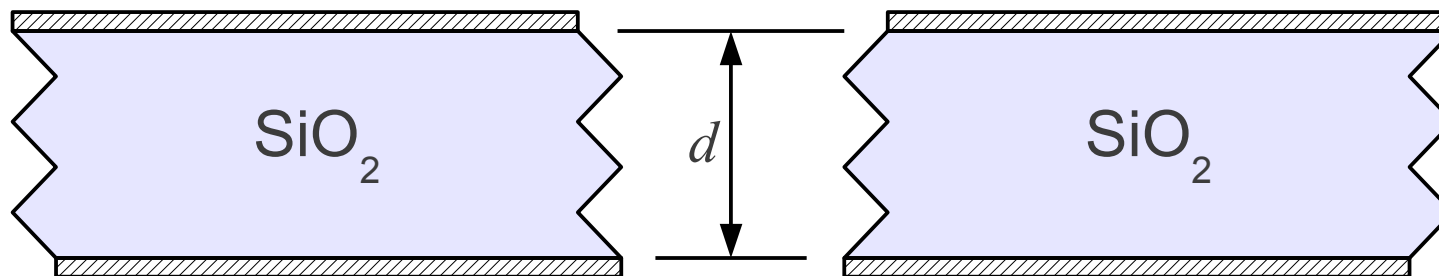




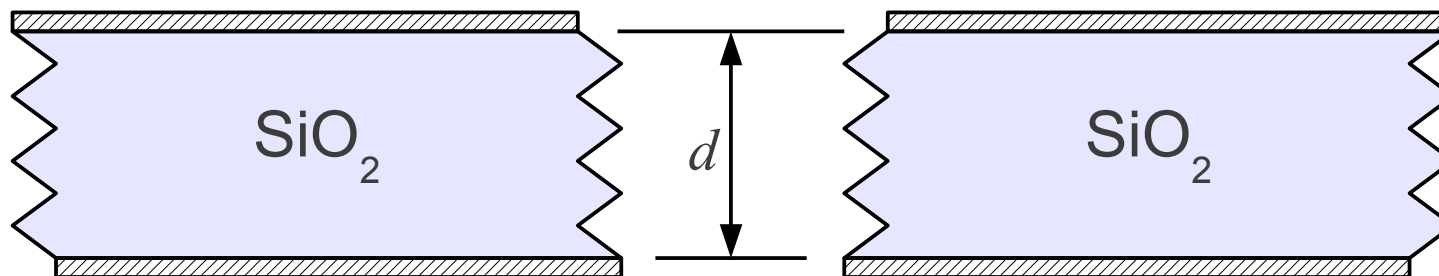
Osnovna
rezonanca
 $f_1 \approx v/2d$



Tretji
overton $\sim 3f_1$

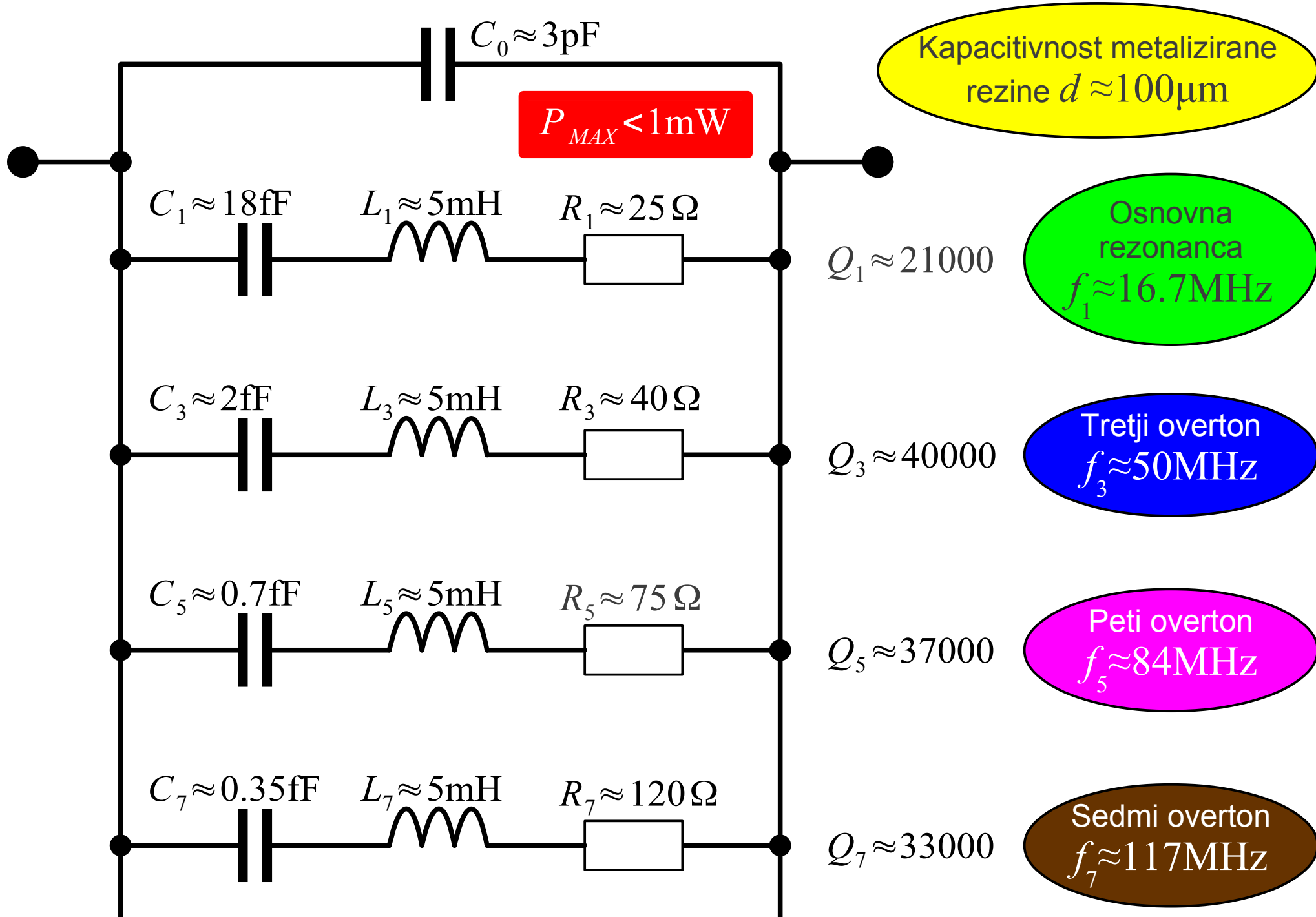


Peti
overton $\sim 5f_1$



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**

$1/R_3$

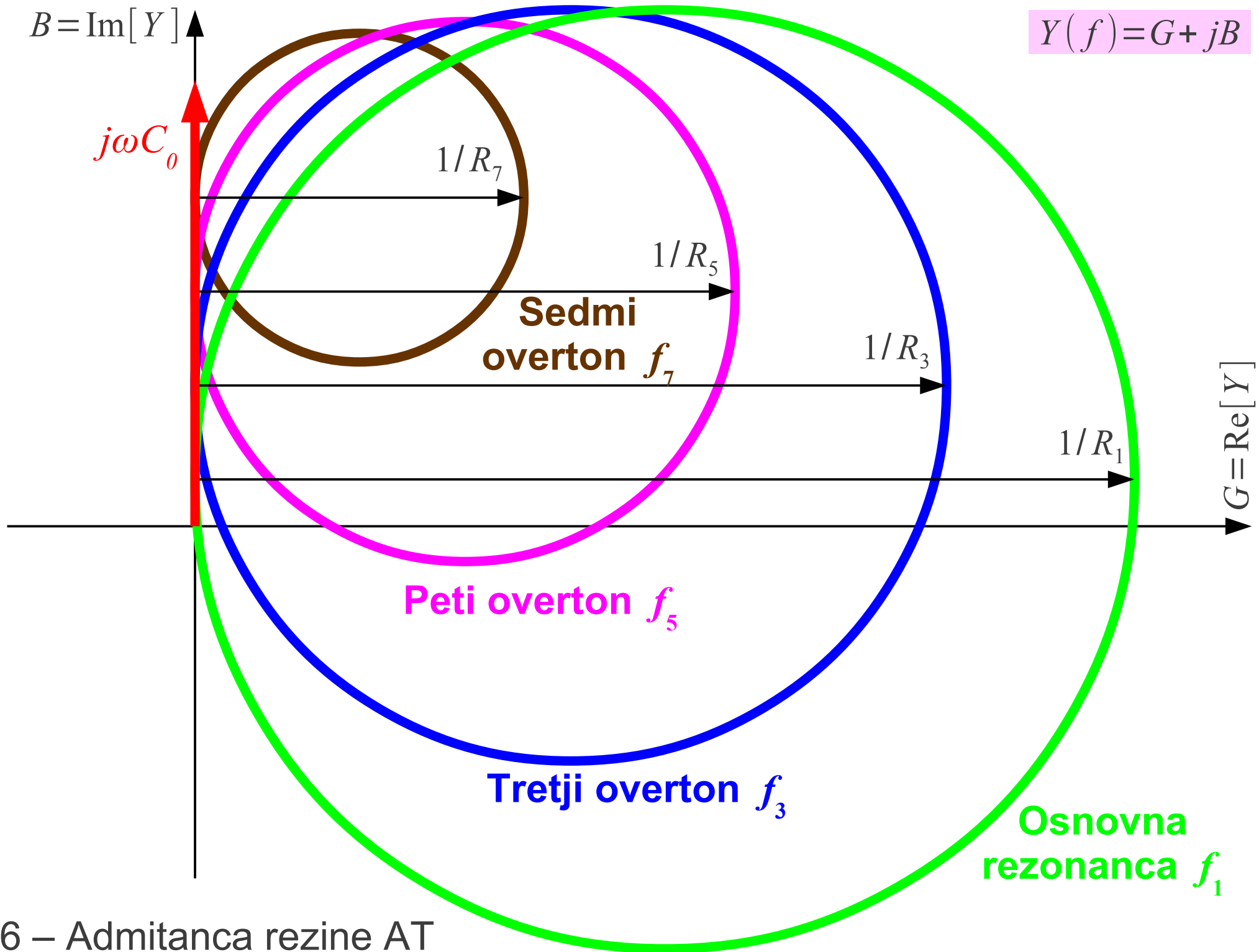
$1/R_1$

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

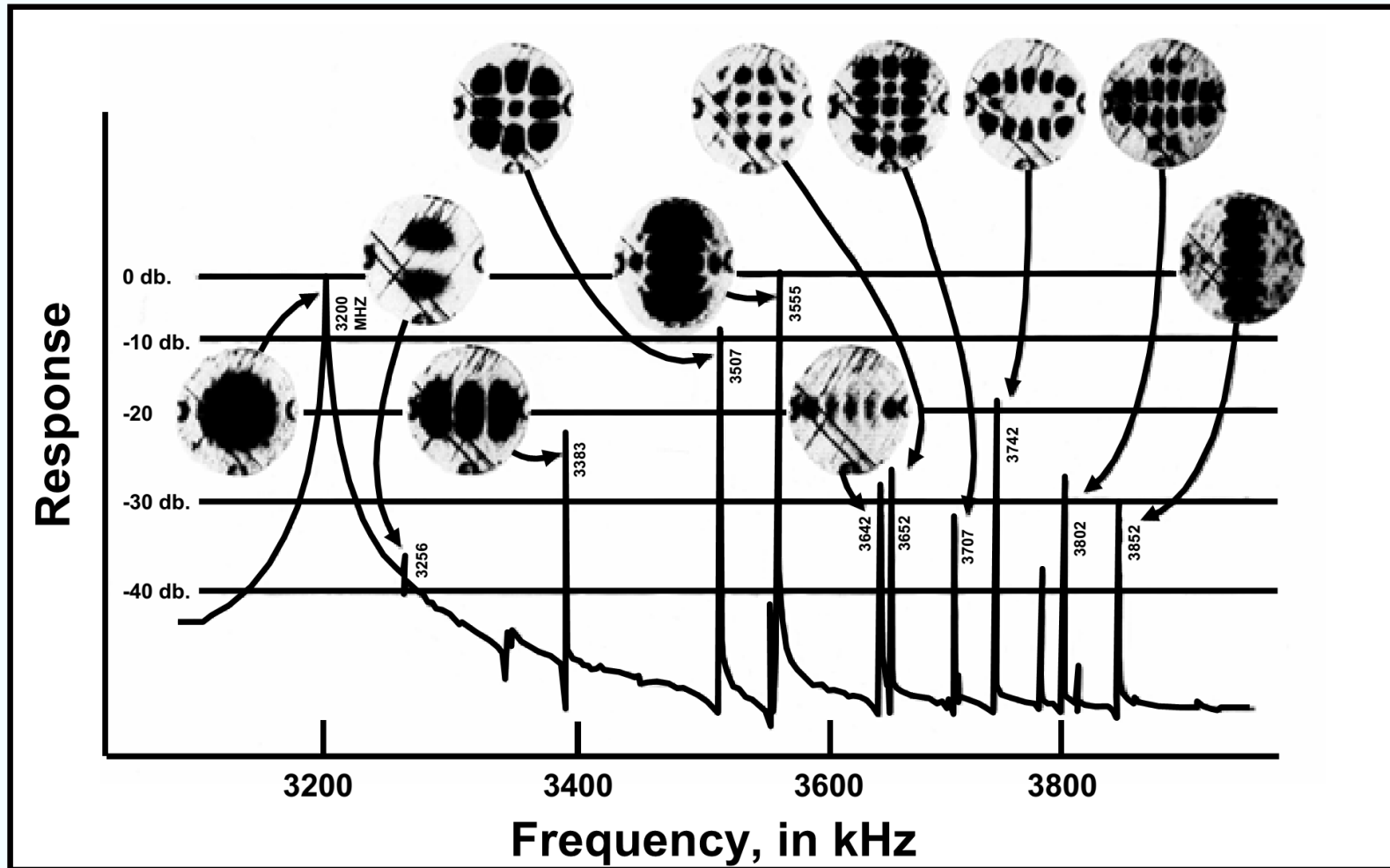
Peti overtone f_5

Tretji overtone f_3

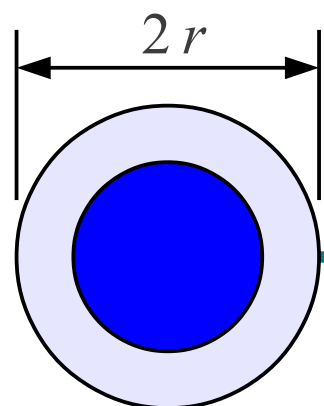
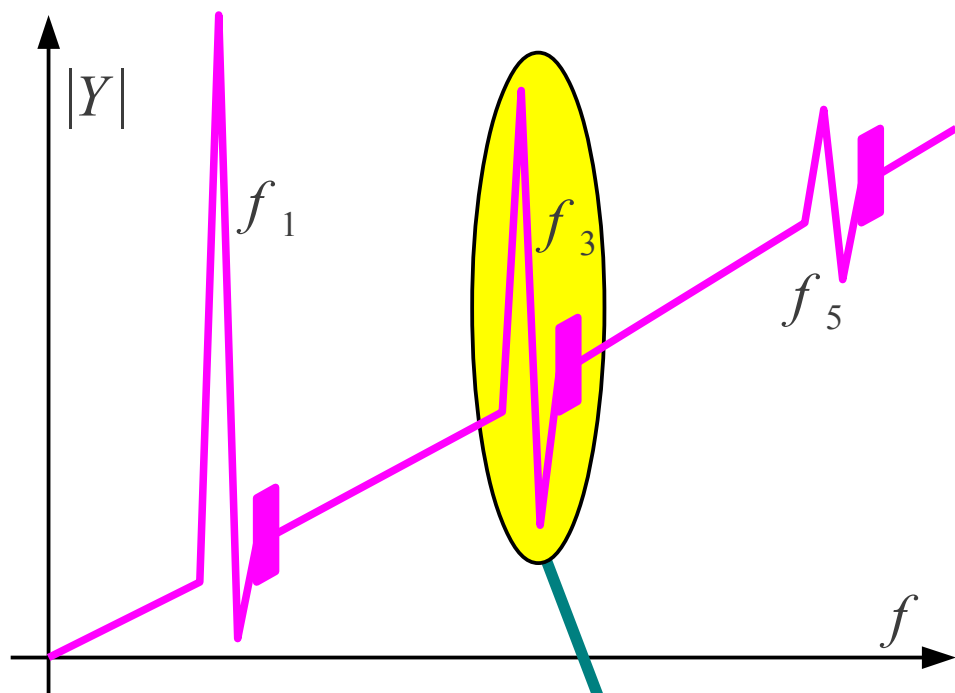
**Osnovna
rezonanca f_1**



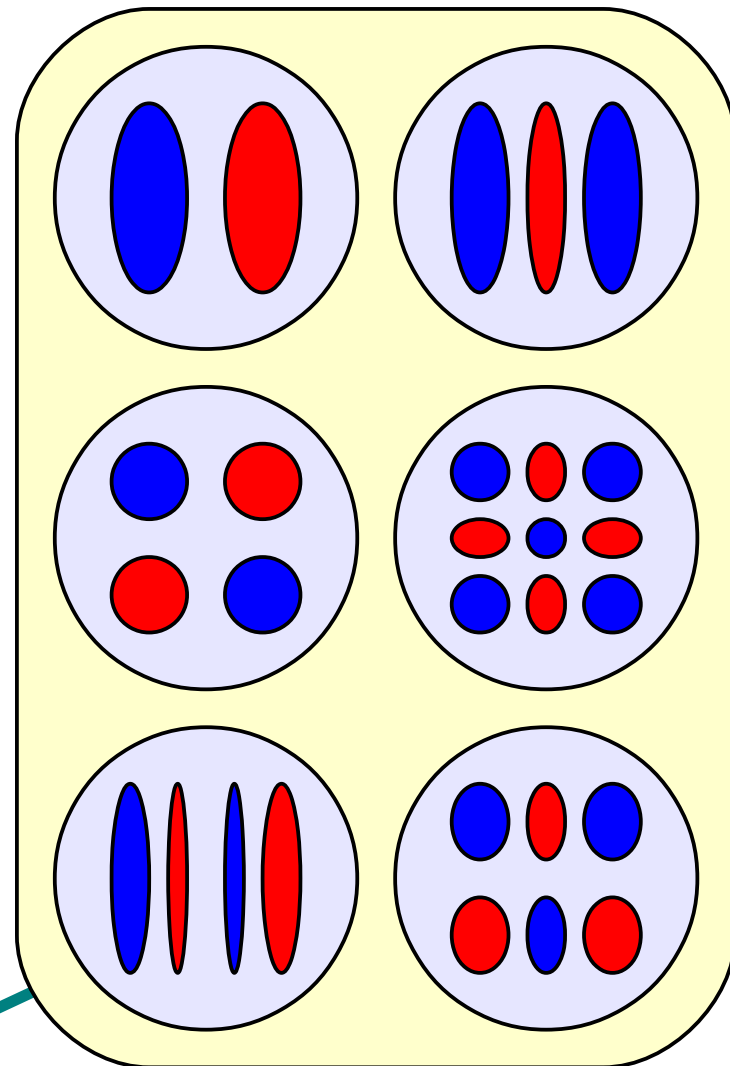
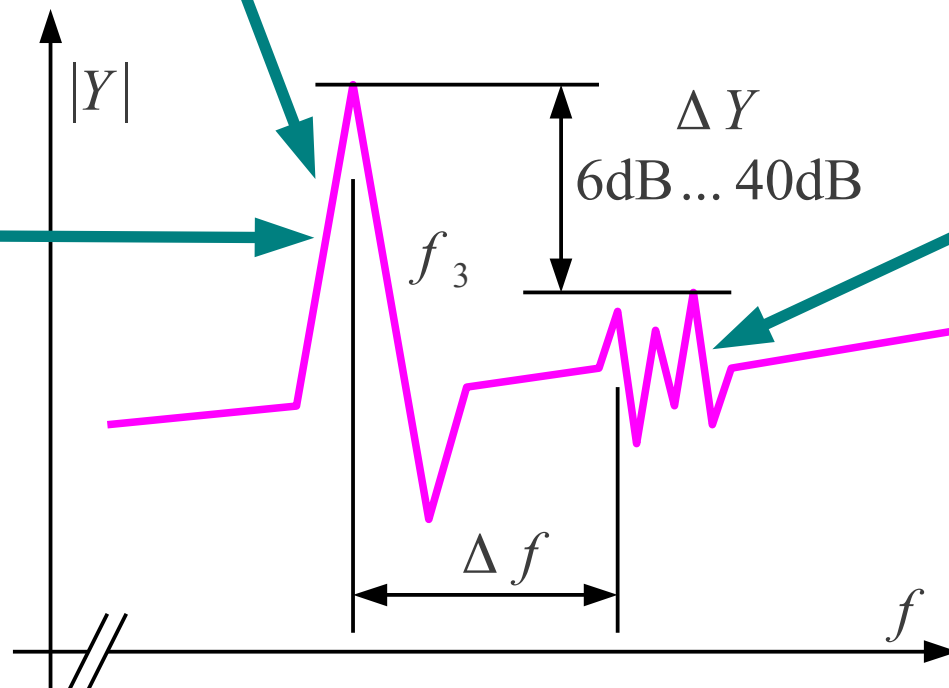
Resonant Vibrations of a Quartz Plate



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.



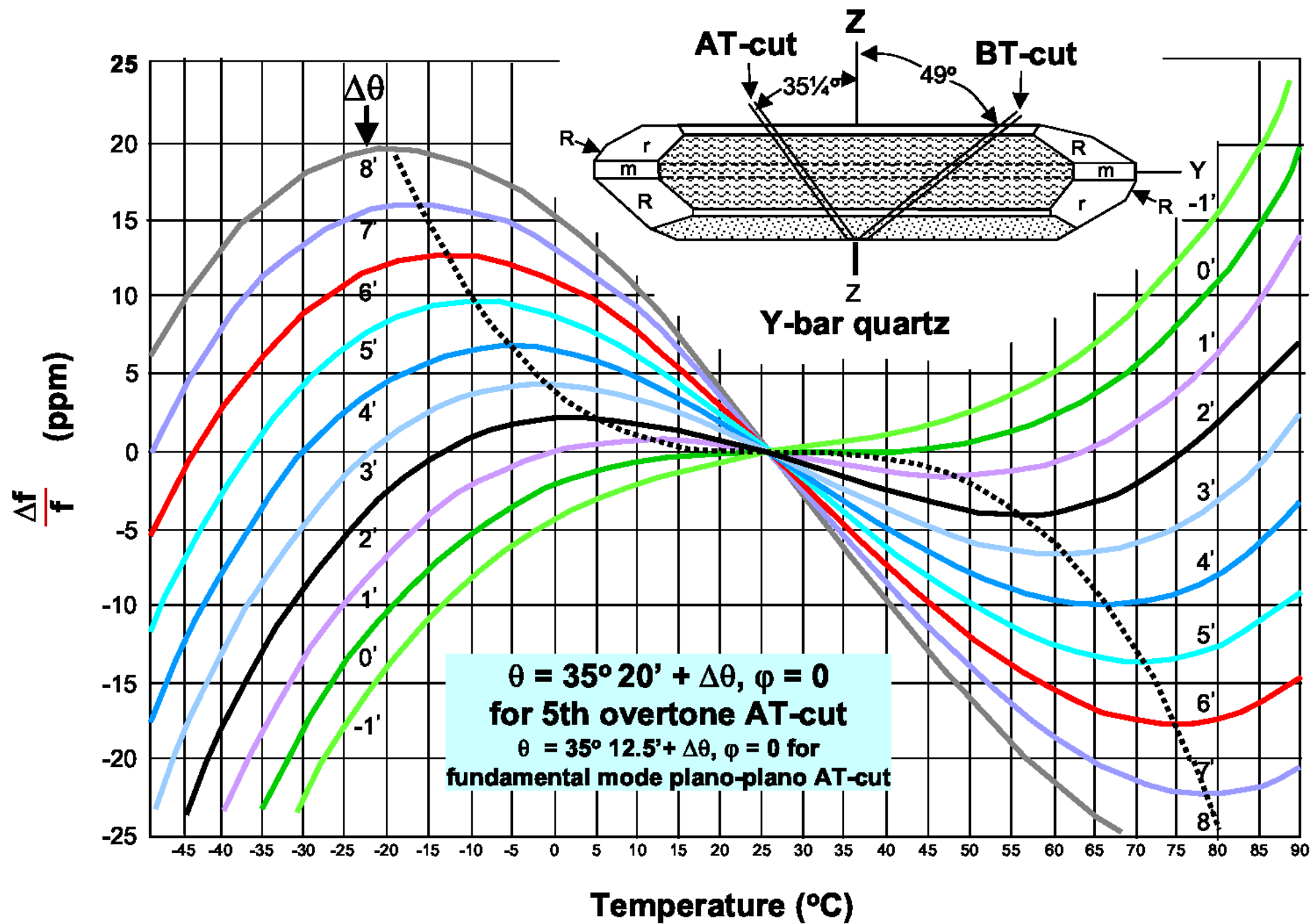
Osnovni prečni rod



Višji prečni rodovi (anharmonics)

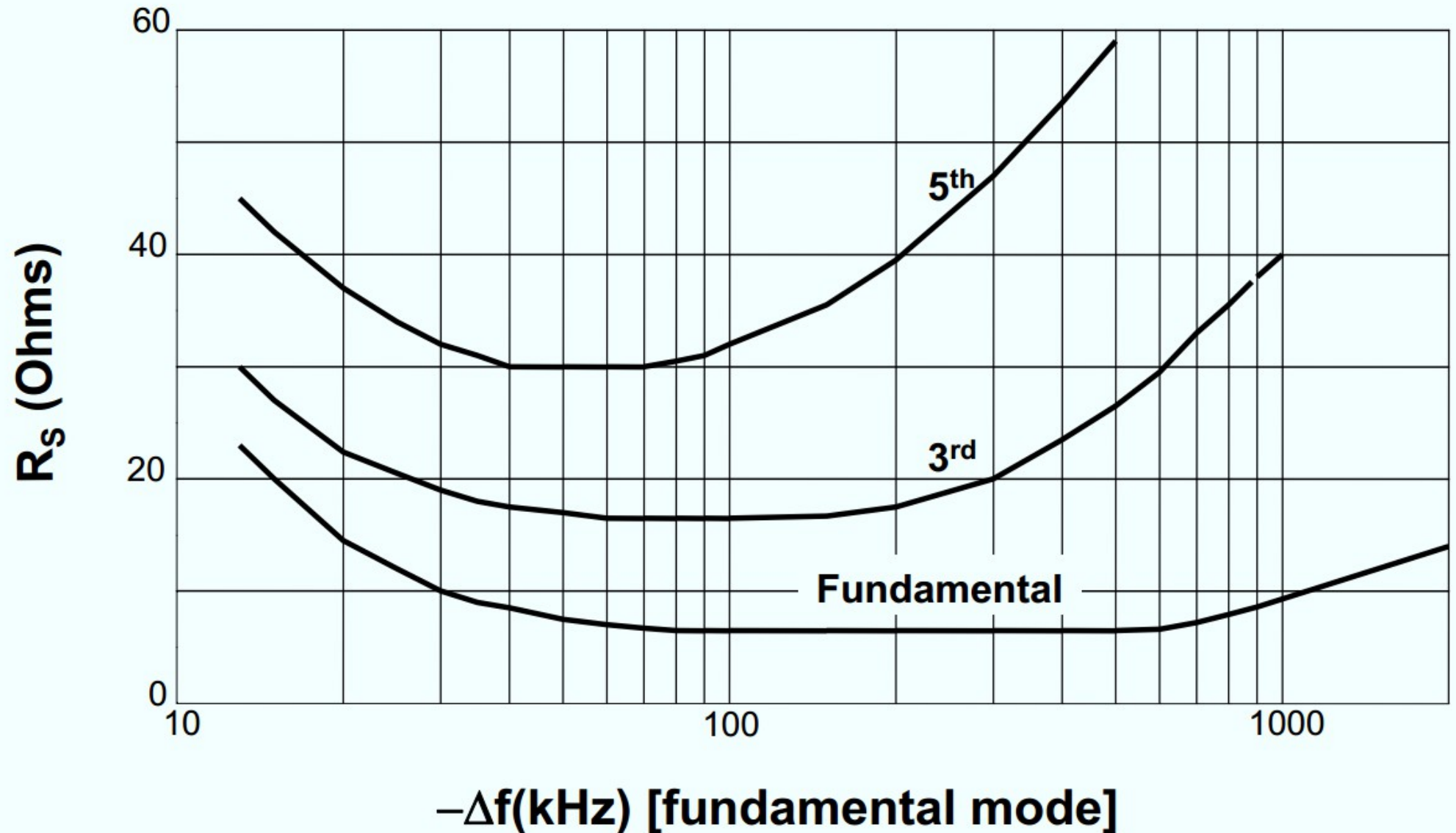
$$\frac{\Delta f}{f_1} \approx \frac{d}{2r} \quad \text{Velika odvisnost od temperature}$$

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

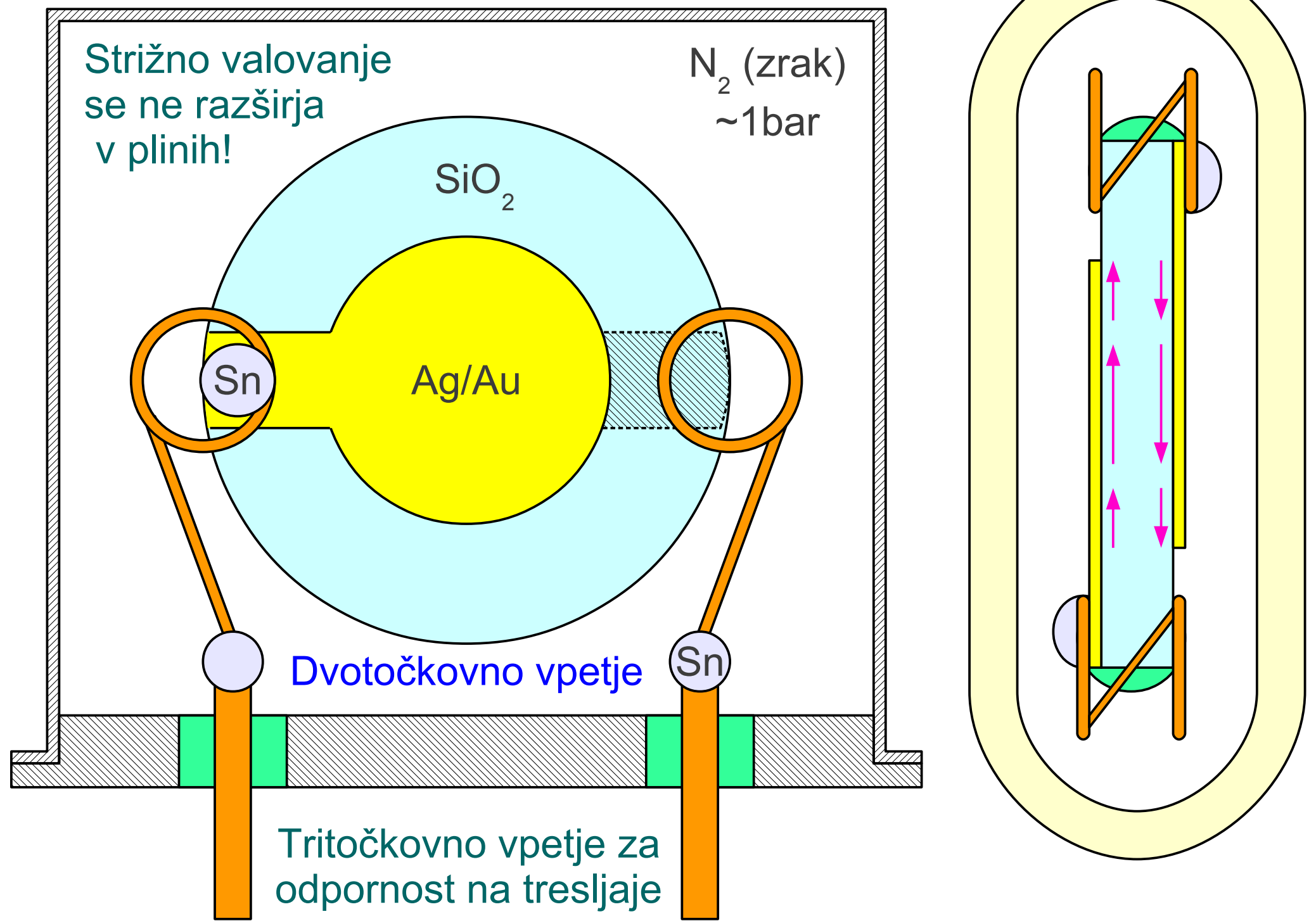


Resistance vs. Electrode Thickness

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

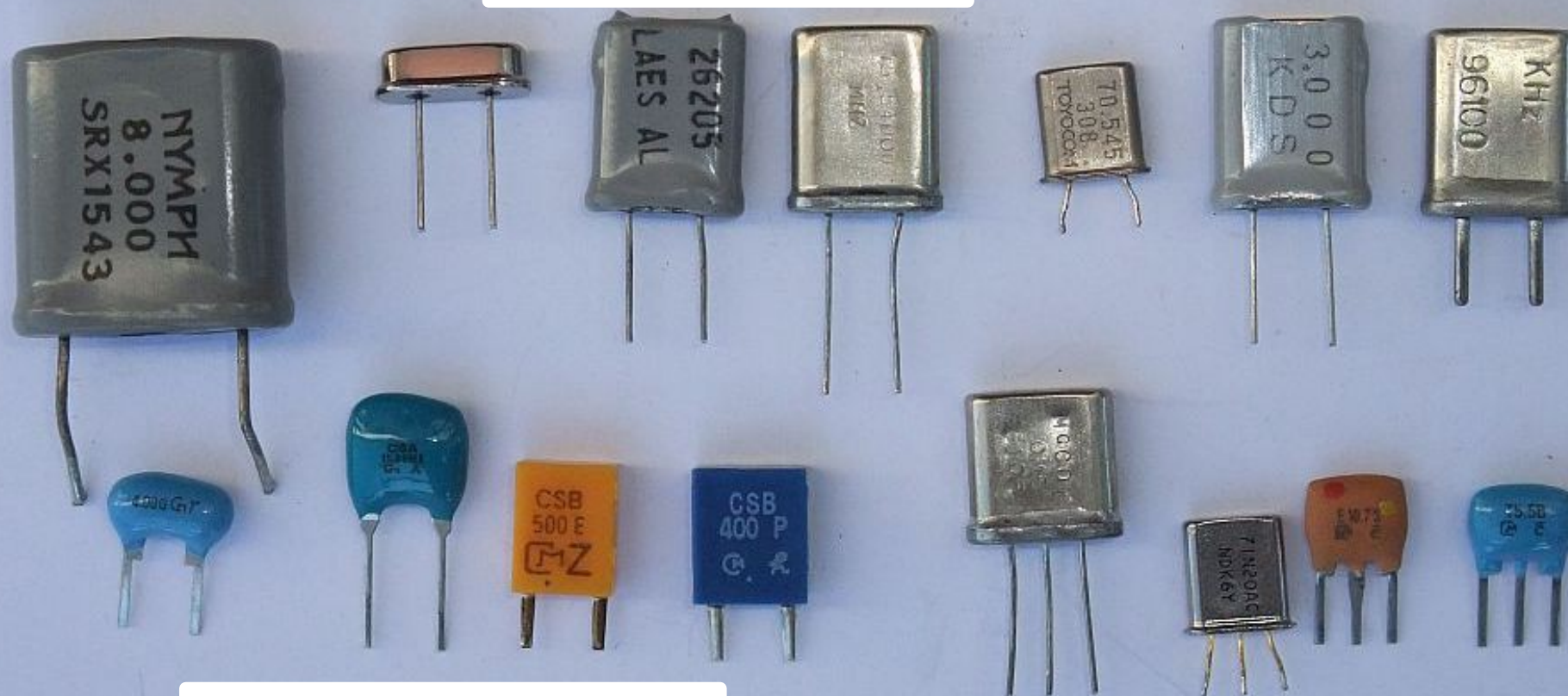


21 – Vgradnja rezine AT v ohišje



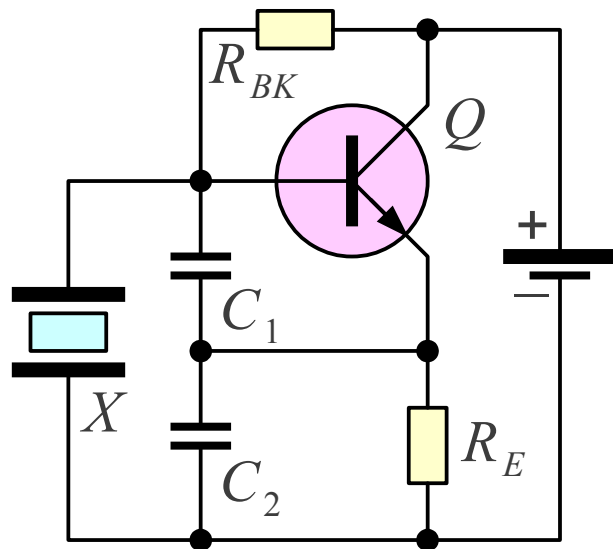


Kremenčevi kristali

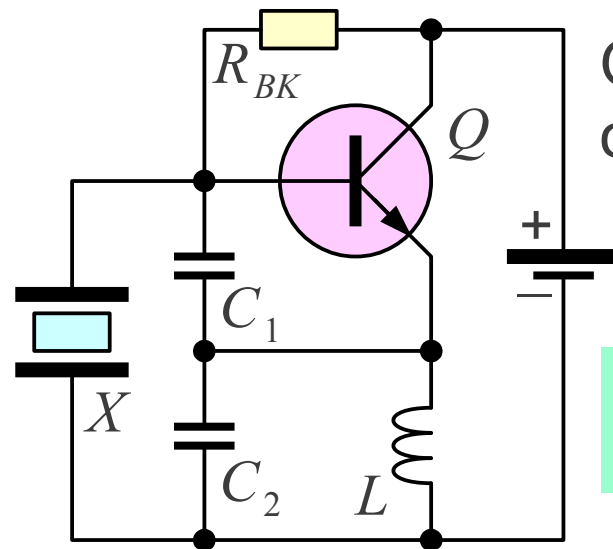


Keramični rezonatorji

Večkratni rezonatorji

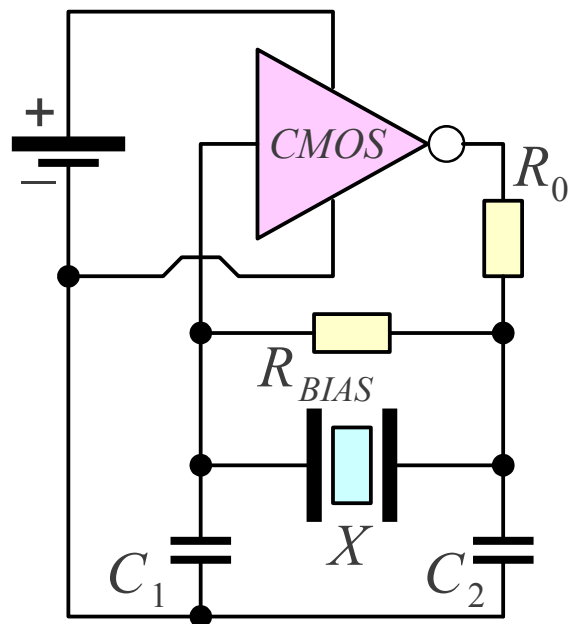


Pierce (Colpitts) na osnovni frekvenci f_1



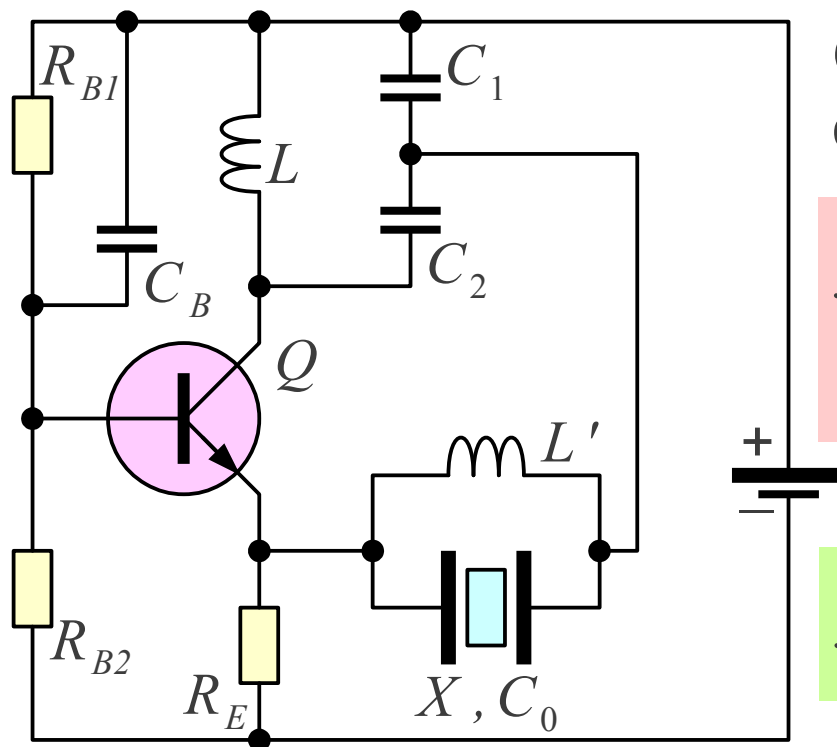
Overtonski oscilator f_3

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

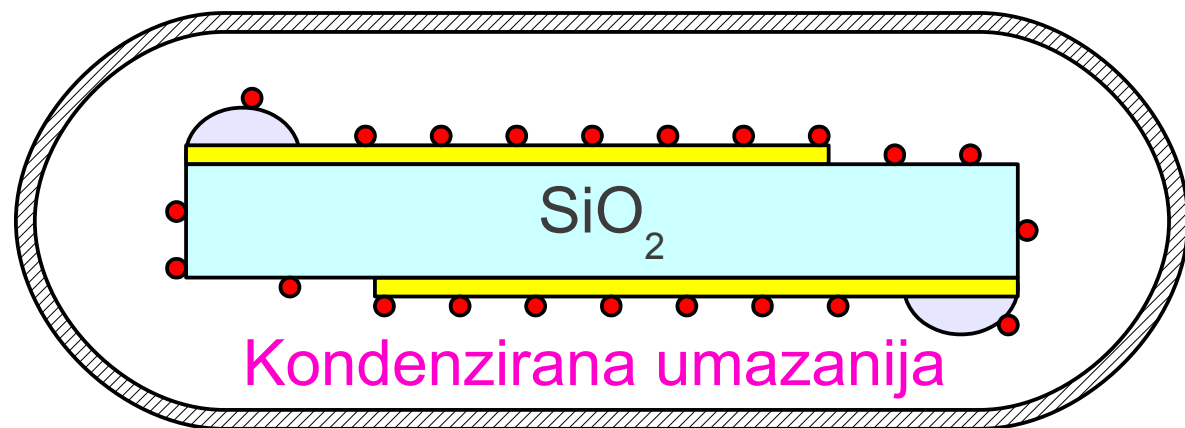
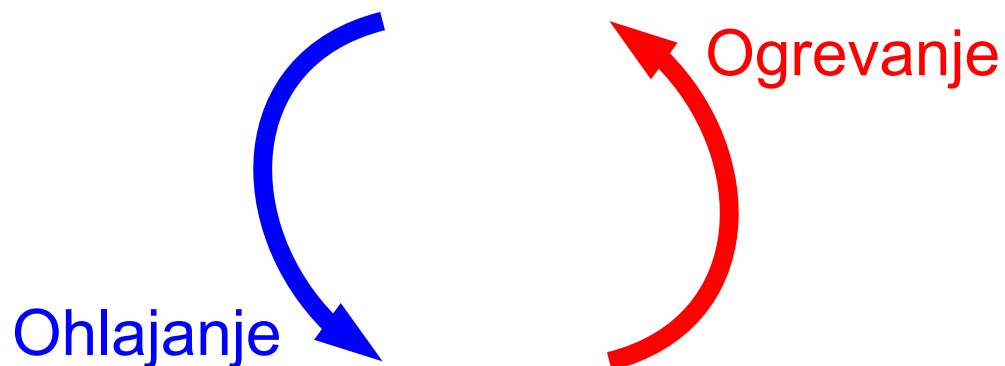
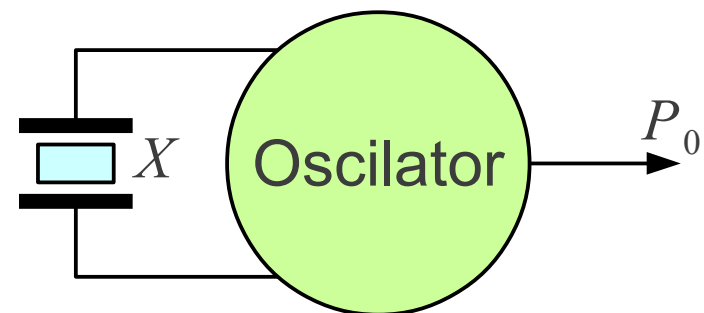
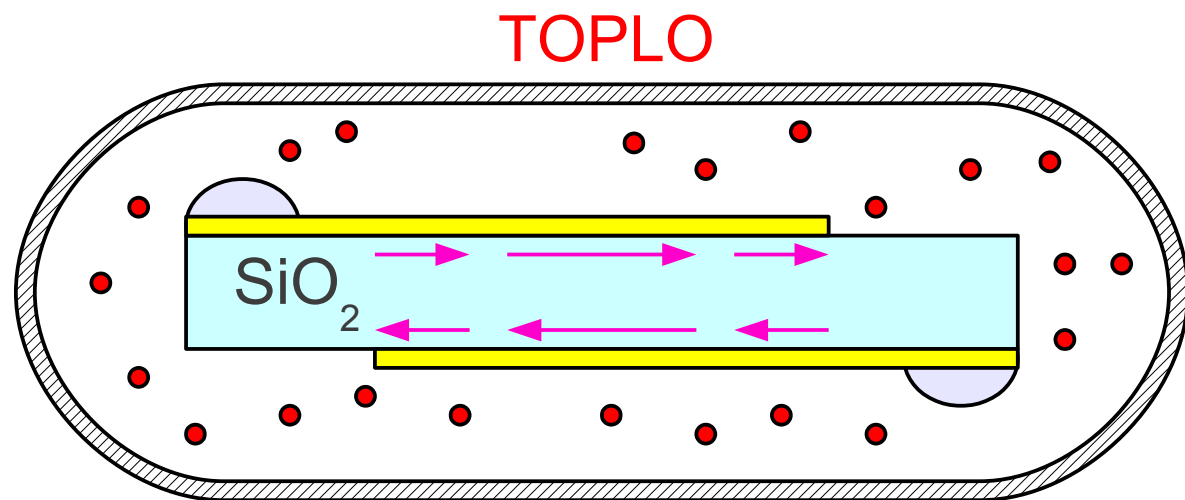


Overtonski oscilator f_5

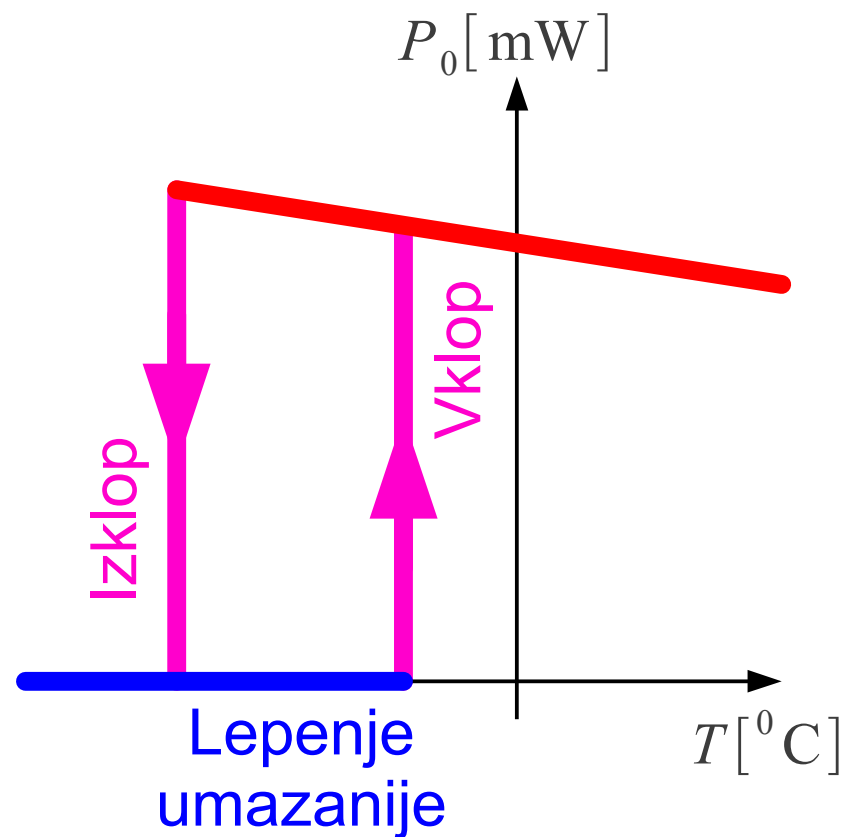
$$f_5 = \frac{1}{\sqrt{L \frac{C_1 C_2}{C_1 + C_2}}}$$

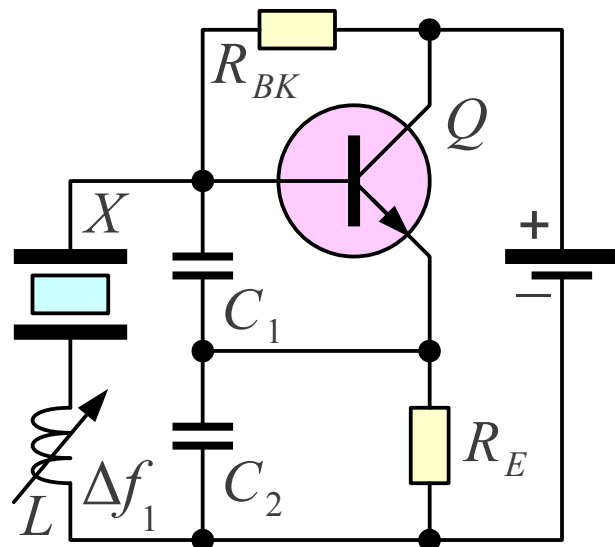


$$f_5 = \frac{1}{\sqrt{L' C_0}}$$

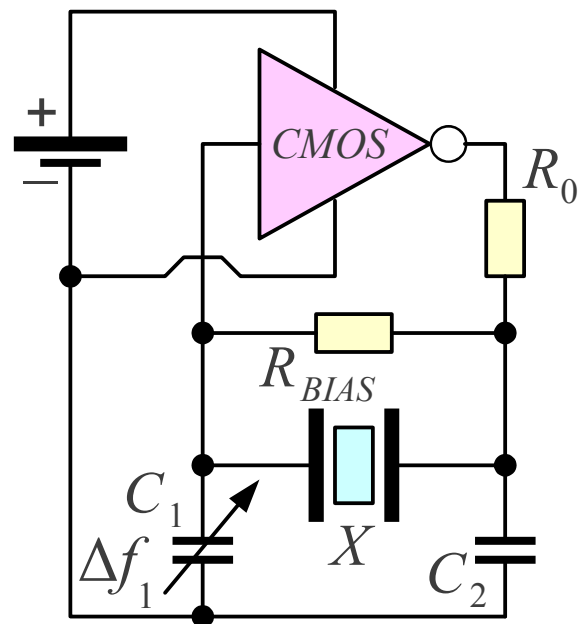


HLADNO



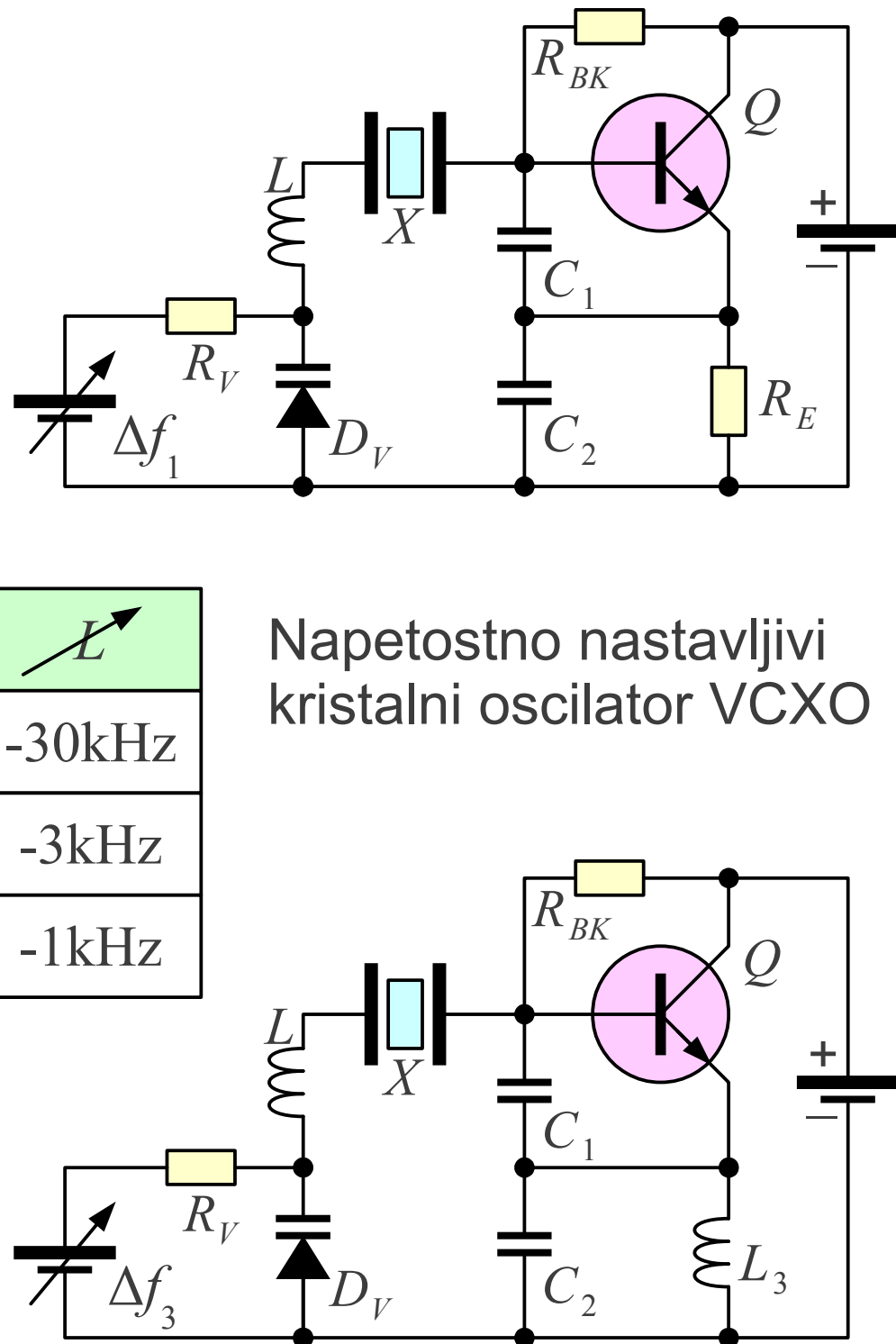


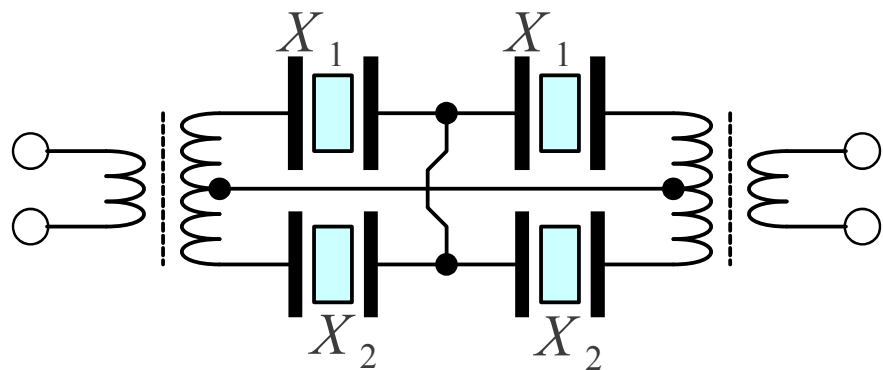
Nastavljivi kristalni oscilator VXO



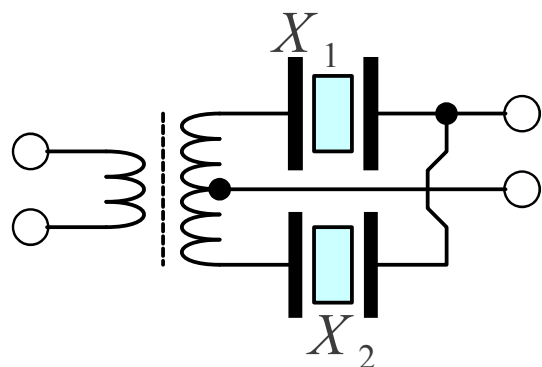
	ϵ	L
Δf_1	+10kHz	-30kHz
Δf_3	+1kHz	-3kHz
Δf_5	+300Hz	-1kHz

Napetostno nastavljivi kristalni oscilator VCXO

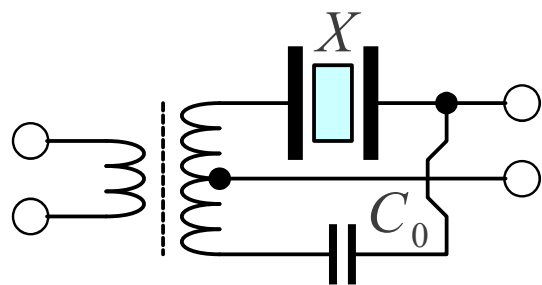




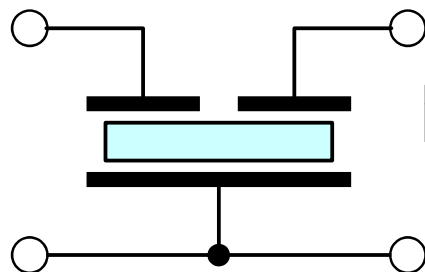
Dvojno mostično pasovno sito



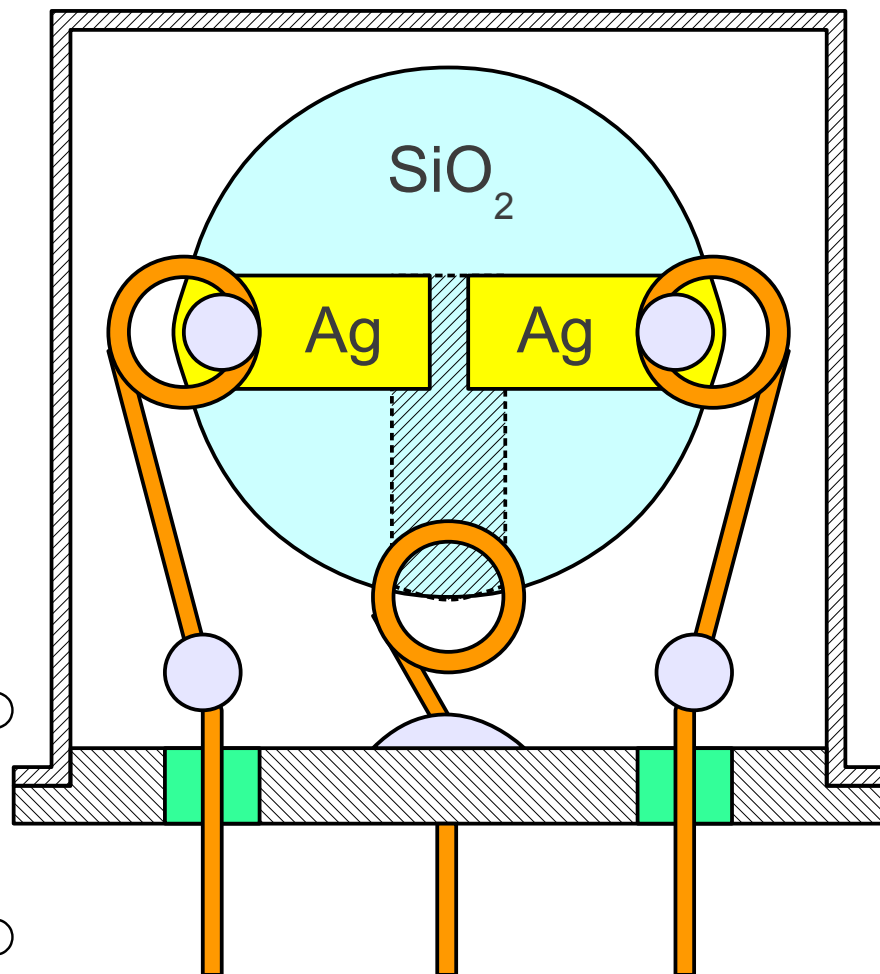
Mostično pasovno sito



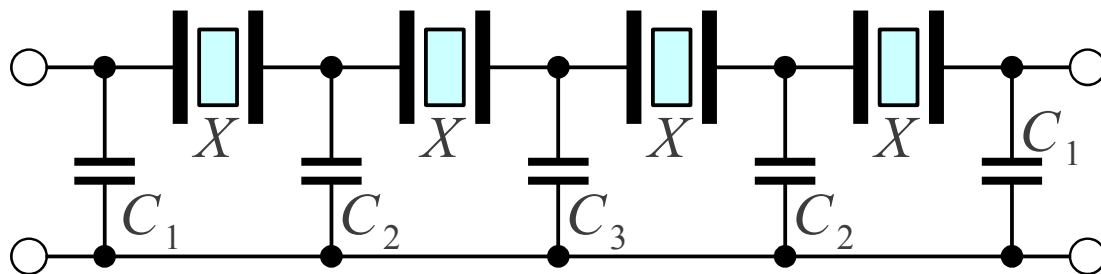
Preprosto pasovno sito



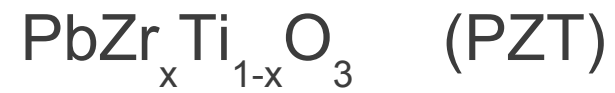
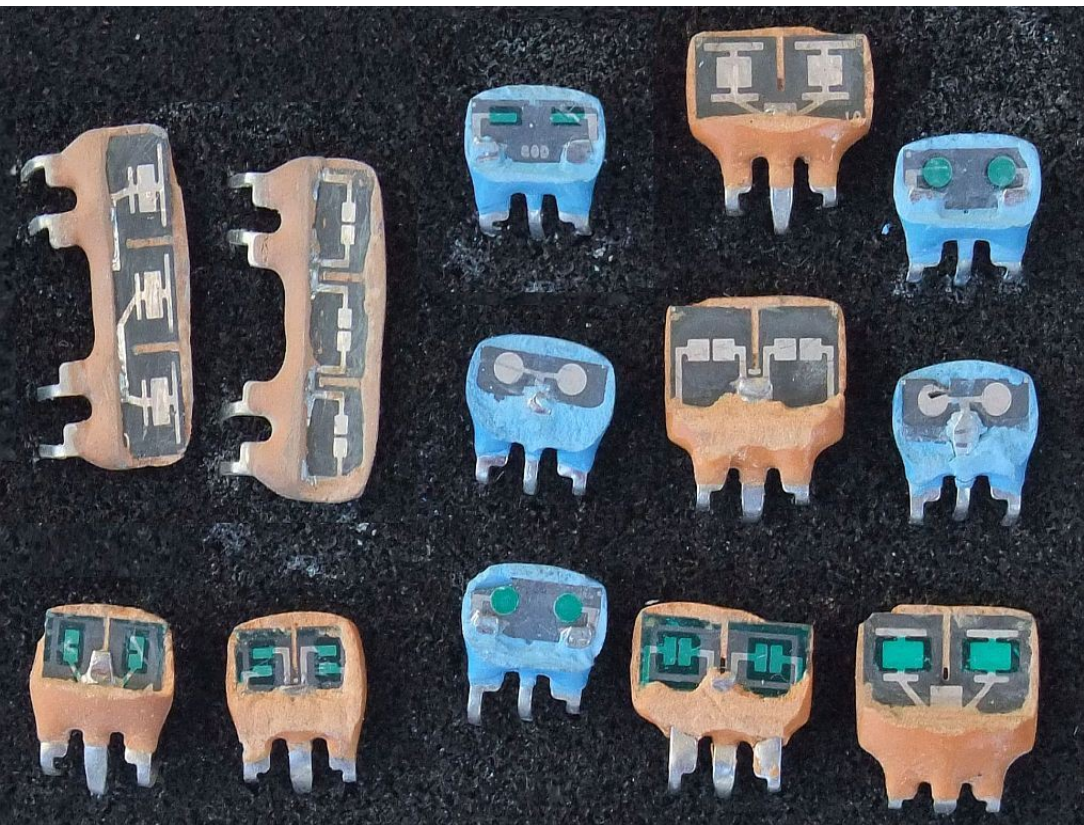
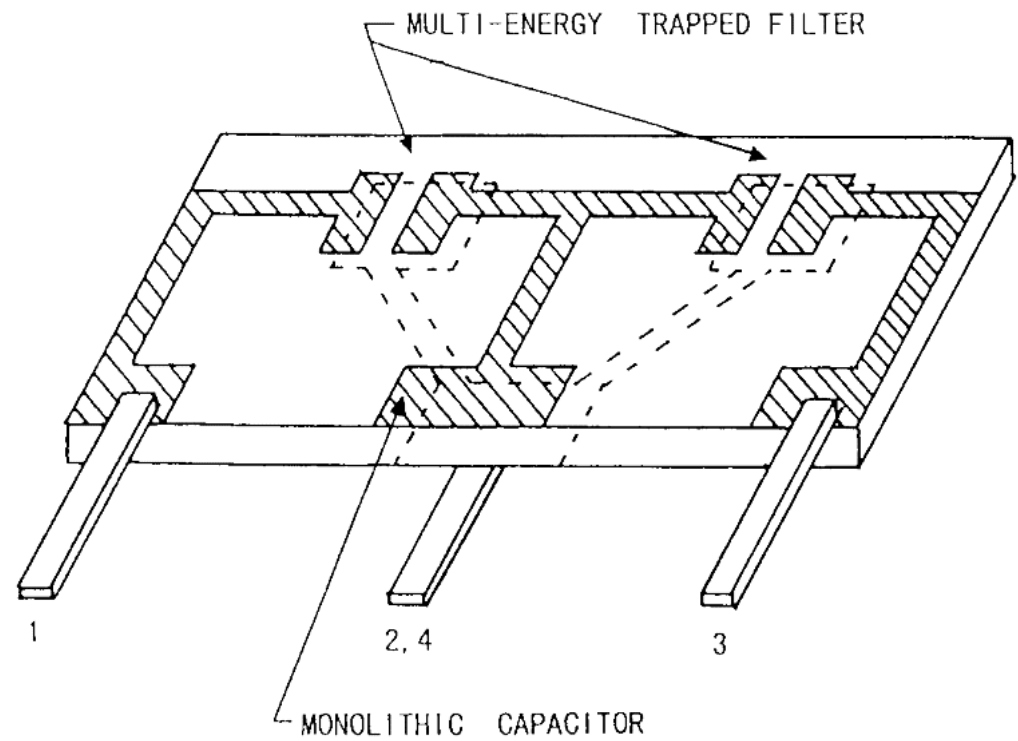
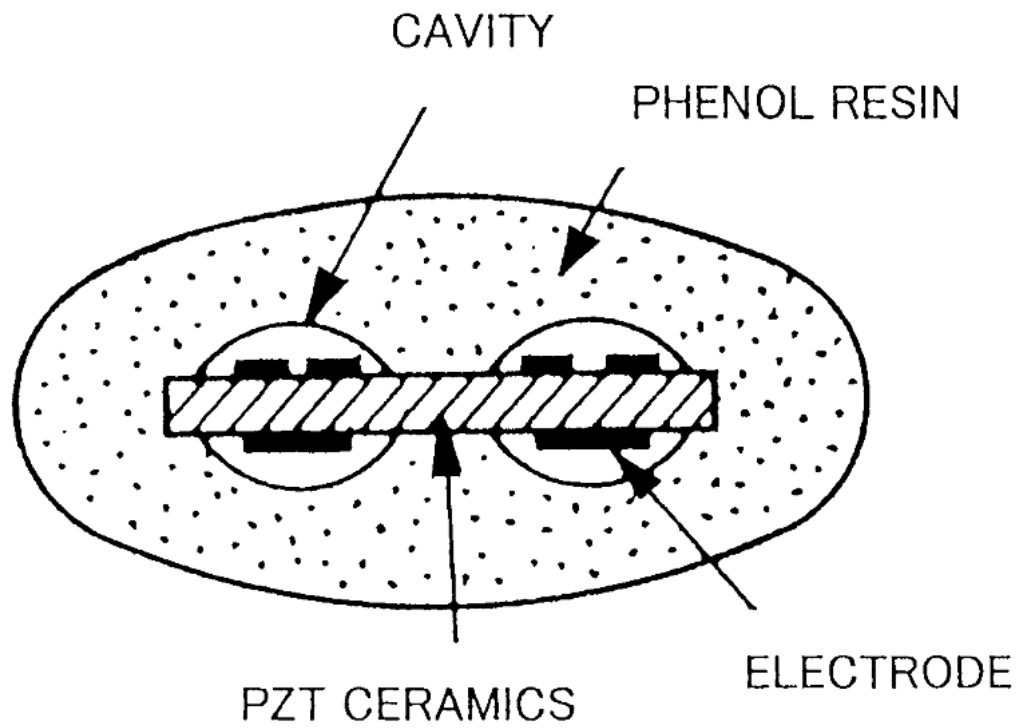
Monolitno pasovno sito



$$500\text{Hz} \leq B \leq 50\text{kHz}$$



Lestvičasto pasovno sito

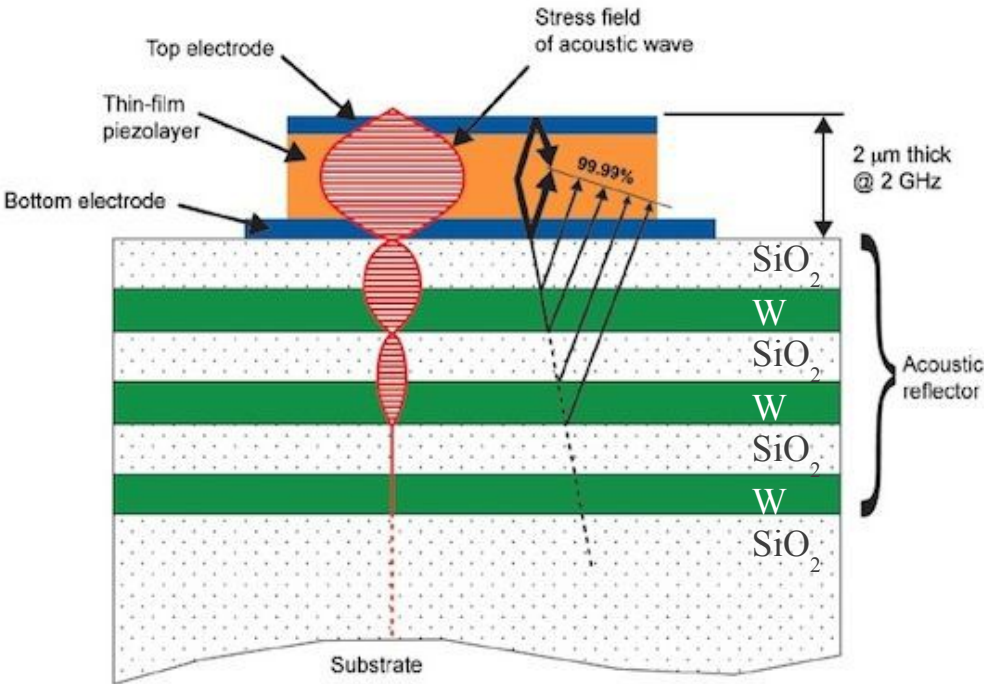
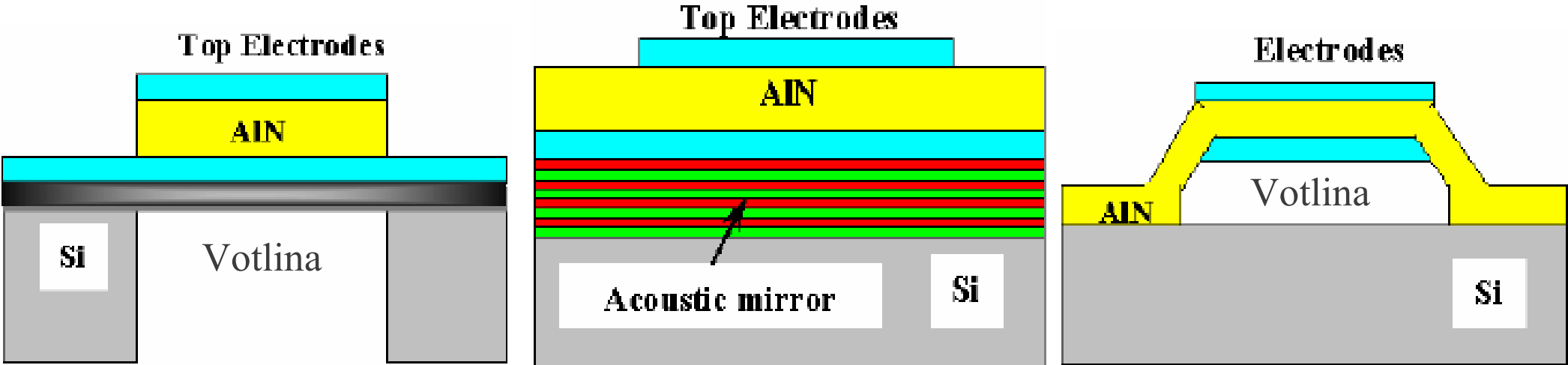


$$x=0.52$$

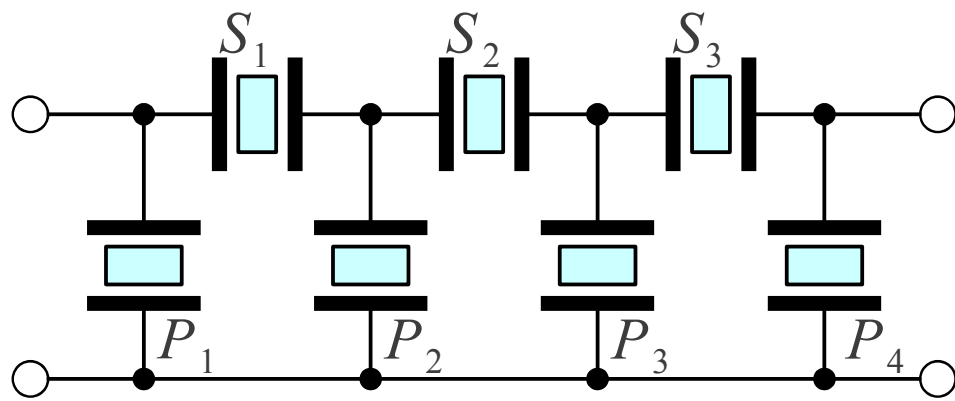
$$Q \approx 1000 \quad @ f = 10 \text{ MHz}$$

Film Bulk Acoustic Resonator (FBAR)

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



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



Prečni rodovi
v kvadratnem
rezonatorju
FBAR

