

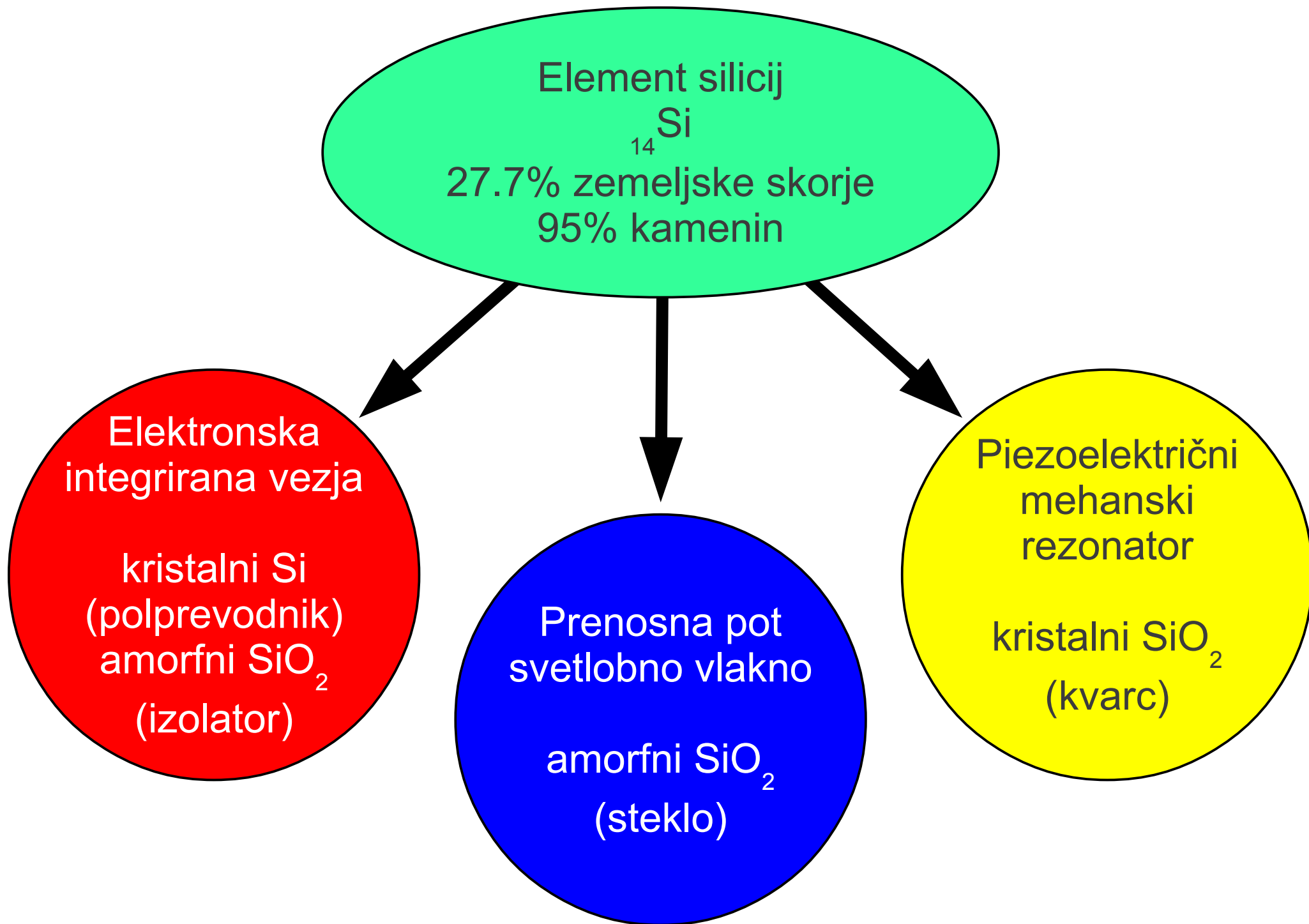
Piezoelektrični rezonatorji v radijski tehniki

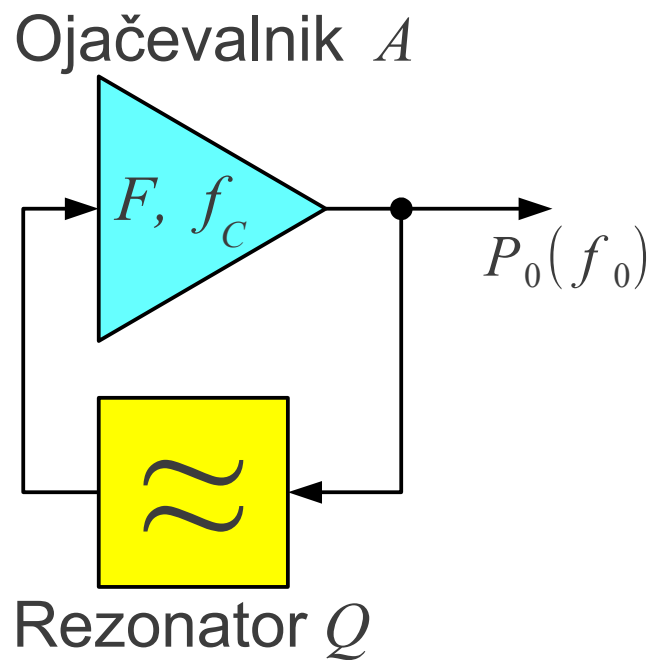
Matjaž Vidmar

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 – Režine kremenovega kristala
- 11 – Določanje kristalnih osi z žarki X
- 12 – Rodovi nihanja rezin kremena
- 13 – Režine AT
- 14 – Stržni 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

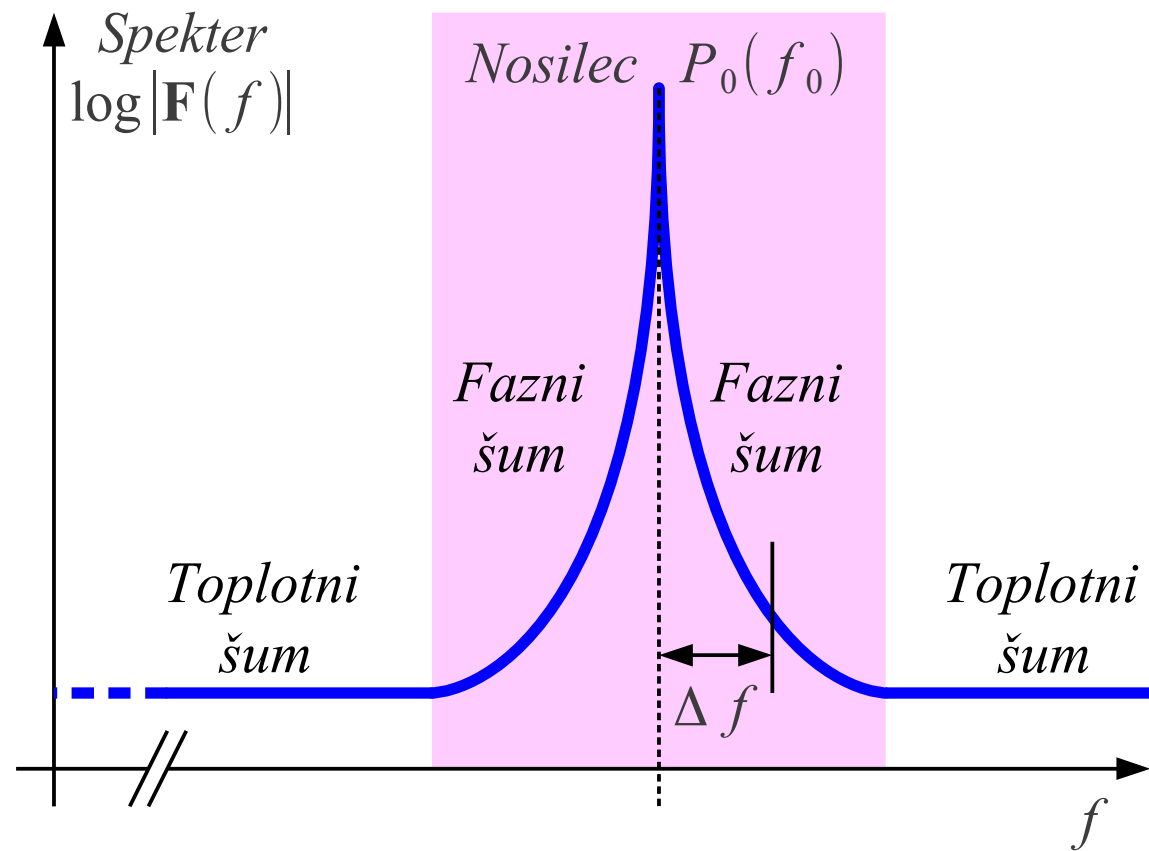
$$L(\Delta f) = \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left(1 + \frac{f_c}{|\Delta f|} \right)$$

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

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

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

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



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

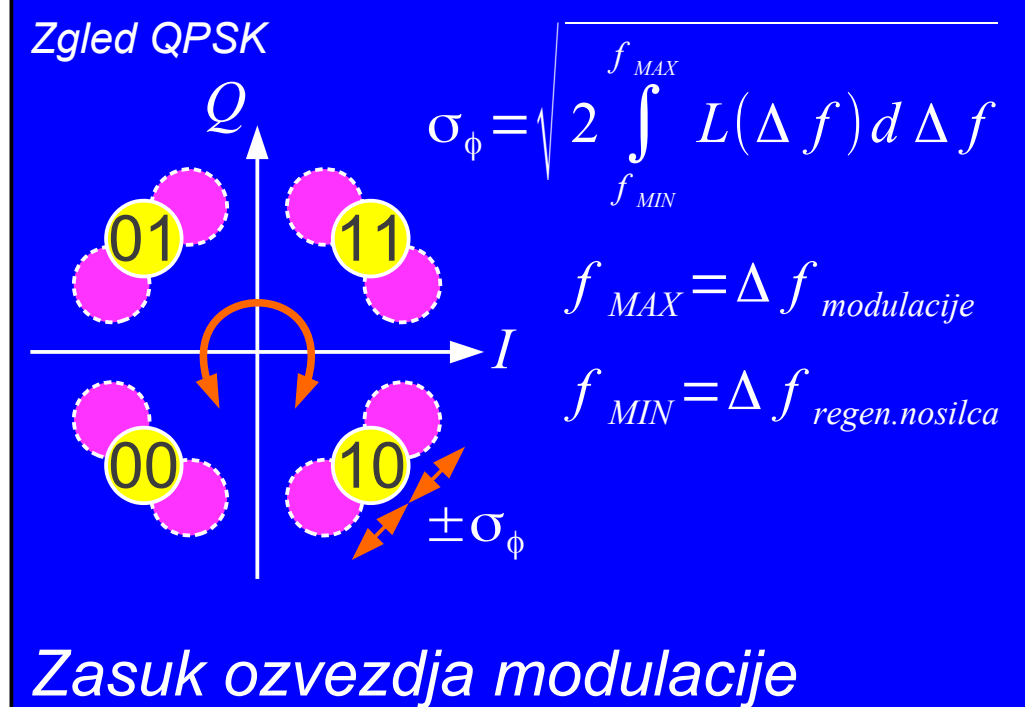
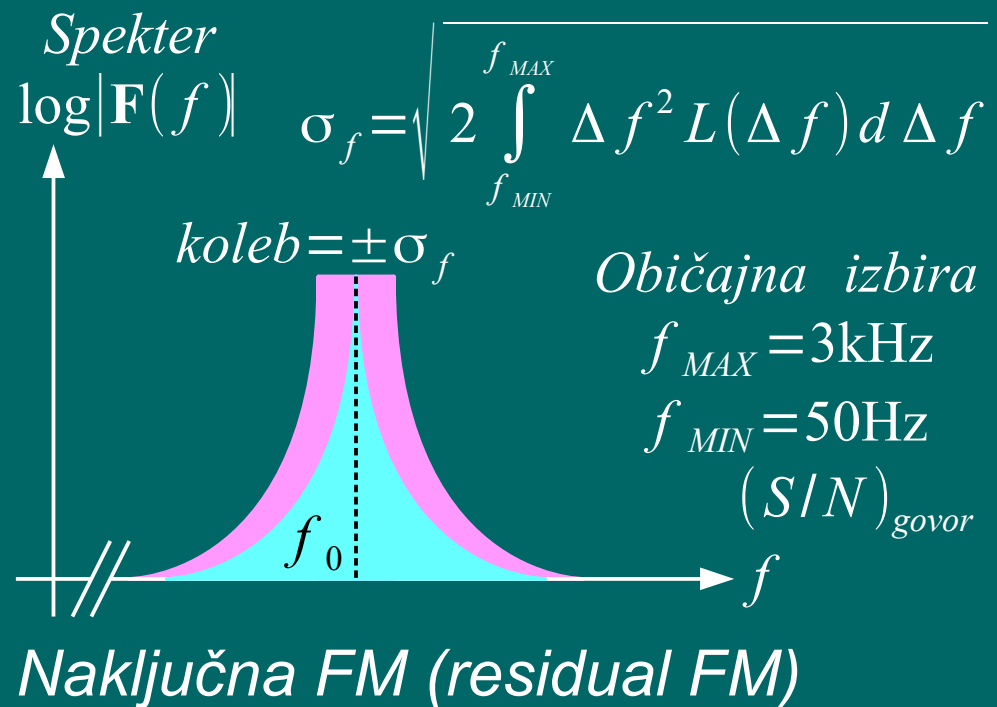
$Q_L \approx 30 \text{ (LC nihajni krog)}$

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

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

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

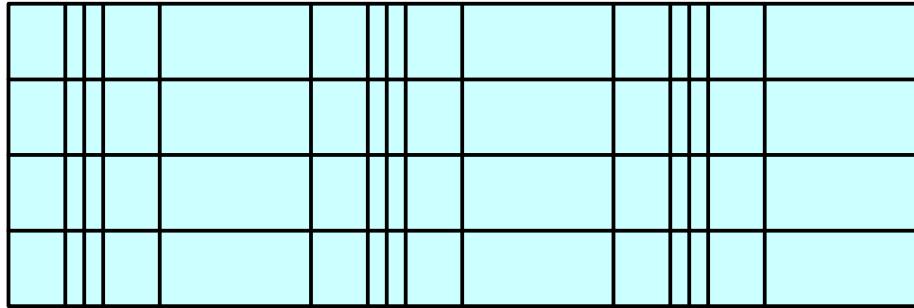
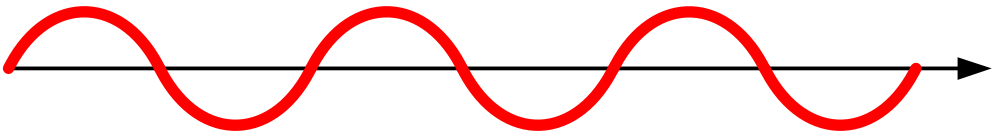
3 – Omejitve faznega šuma

- 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

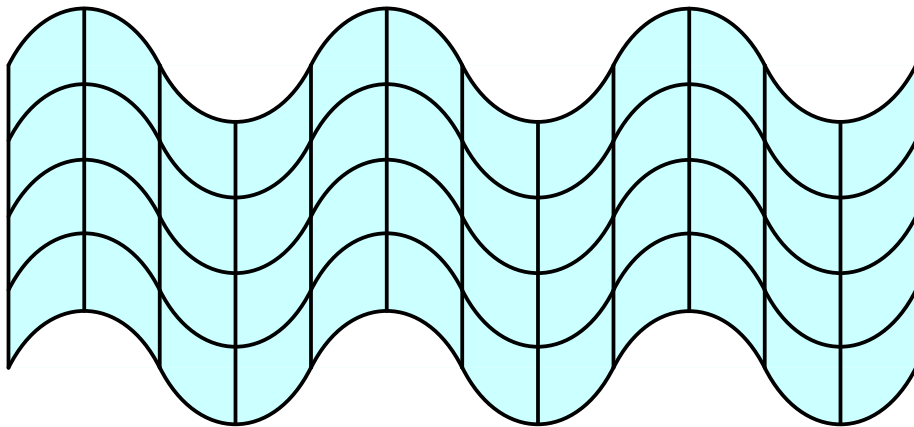
4 – Zgodovina kvarca v elektroniki

5 – Mehanska valovanja

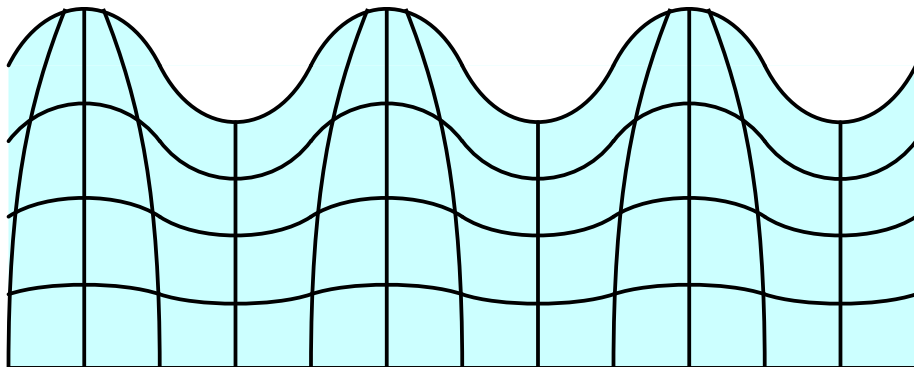
$v \approx 2\text{km/s} \dots 12\text{km/s}$ (*trdne snovi*)





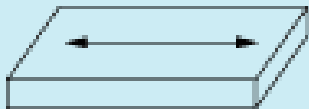
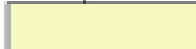

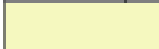
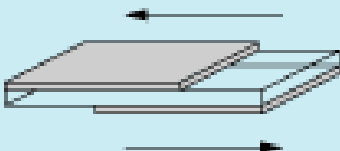
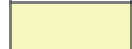
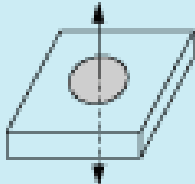
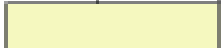
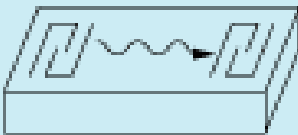
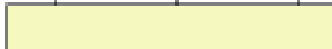
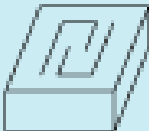
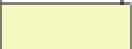
Tlačni val "P" (primary/pressure wave) plini, tekočine, trdne snovi ("BAW" bulk acoustic wave)



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] | 1k | 10k | 100k | 1M | 10M | 100M | 1G | Application |
|---|--|--|---|--|-----|------|----|--|
|  | Flextural mode  | | | | | | | Piezoelectric buzzer |
|  | | Length mode  | | | | | | kHz Ceramic filter |
|  | | | 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
 $Q > 10^6$

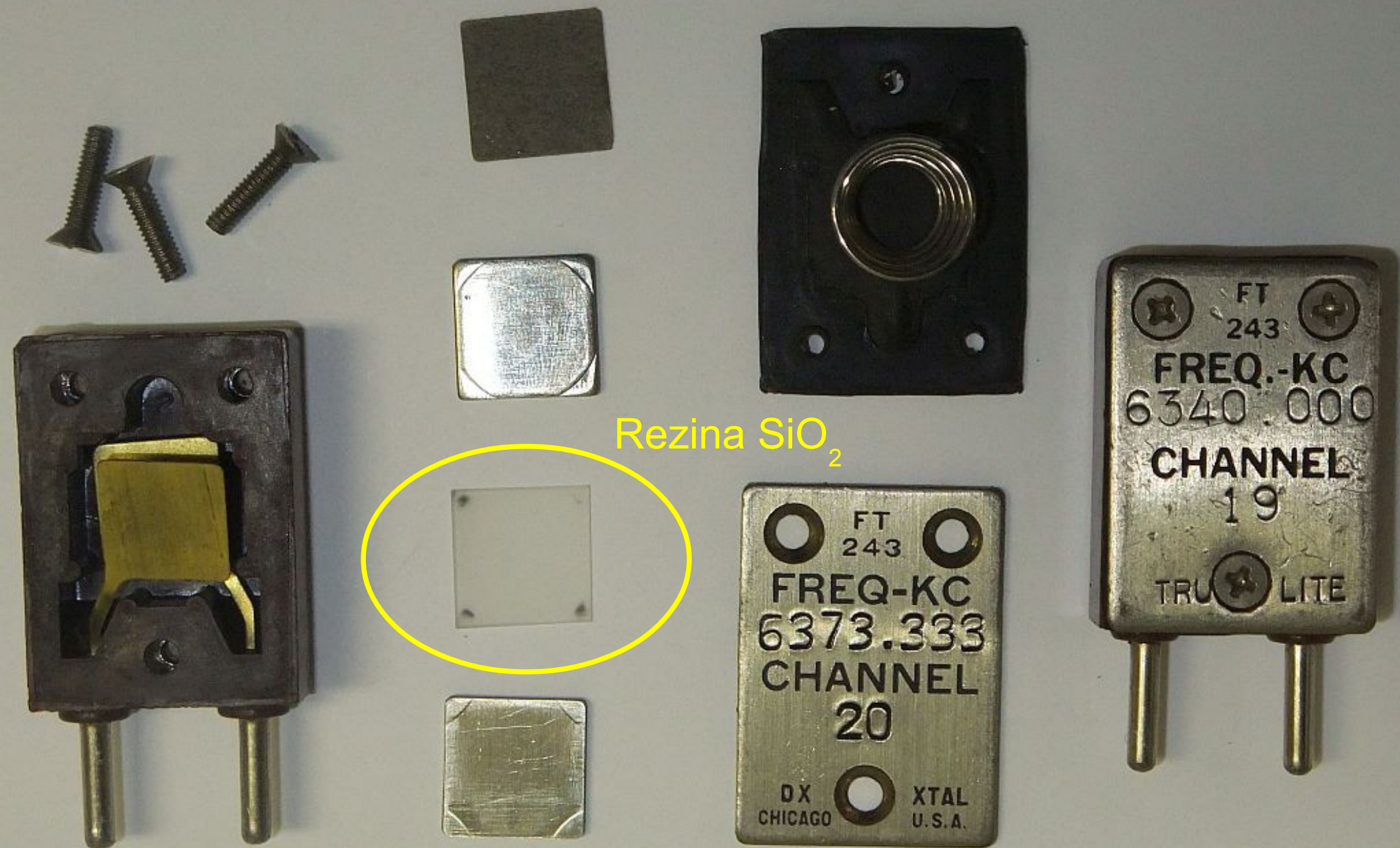
Piezoelektrik



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

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

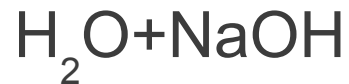
desnosučni α -kvarc



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

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

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

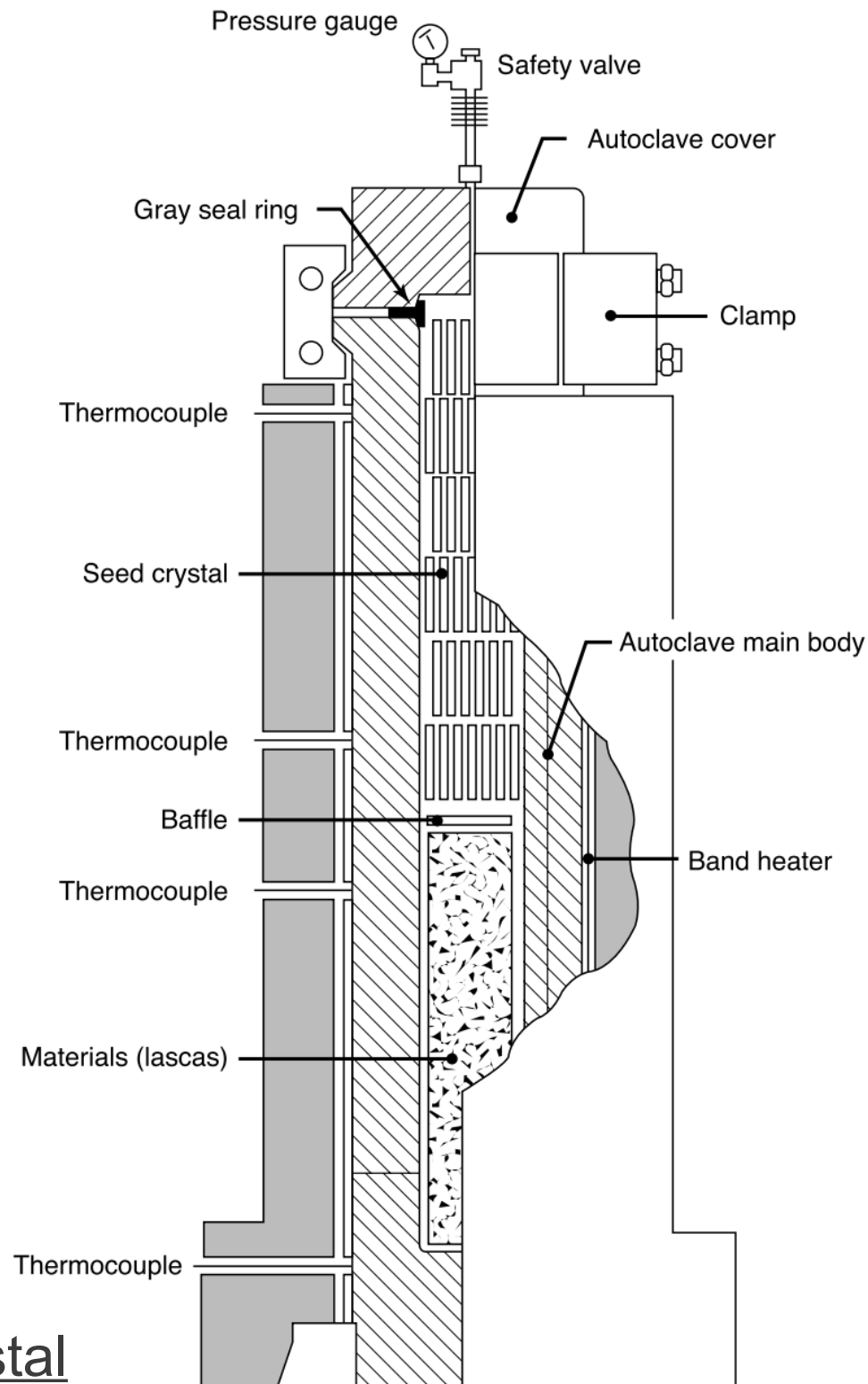


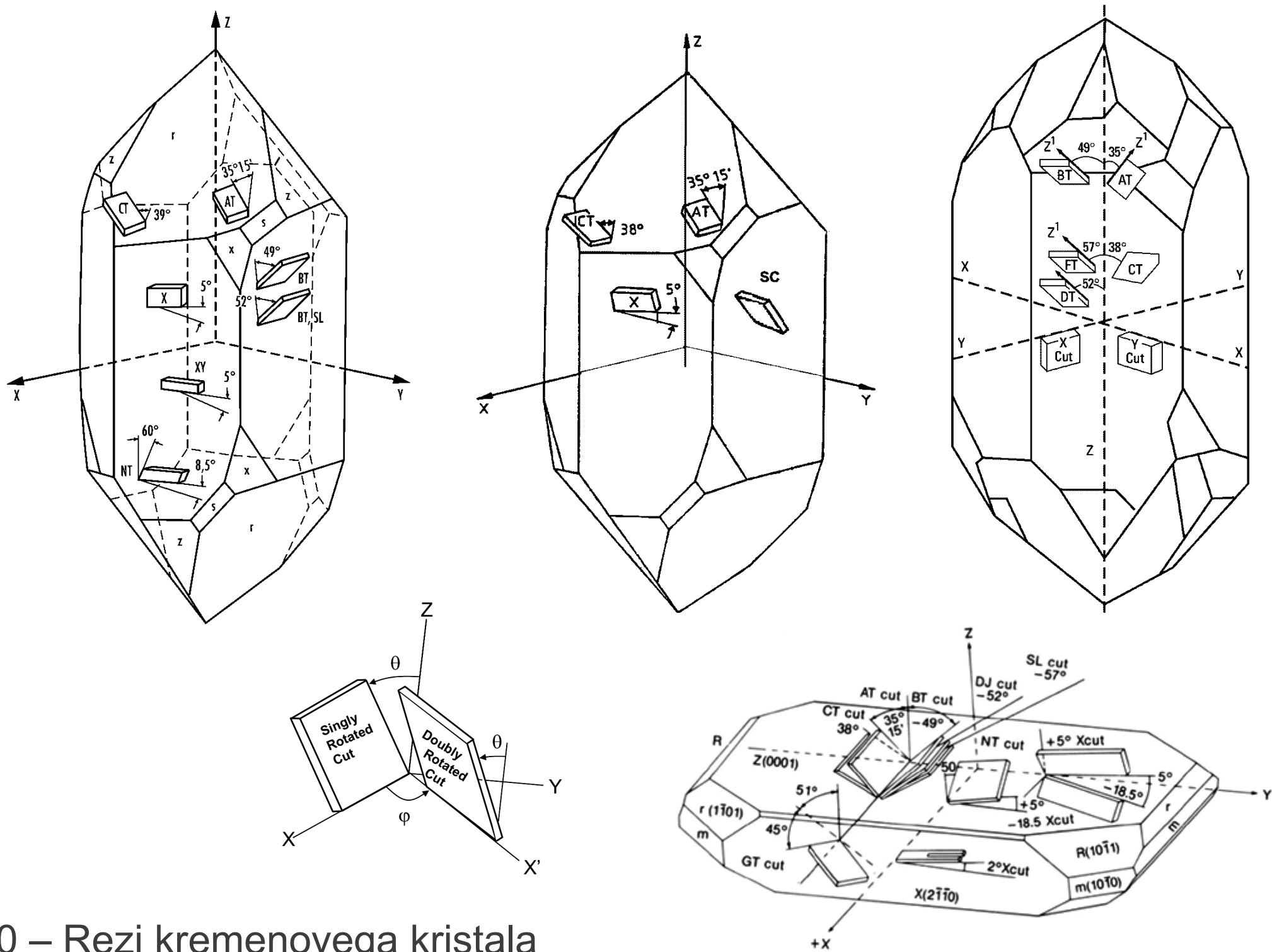
$p \approx 1000\text{--}1500\text{bar}$

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

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

9 – Umetni kremenov kristal





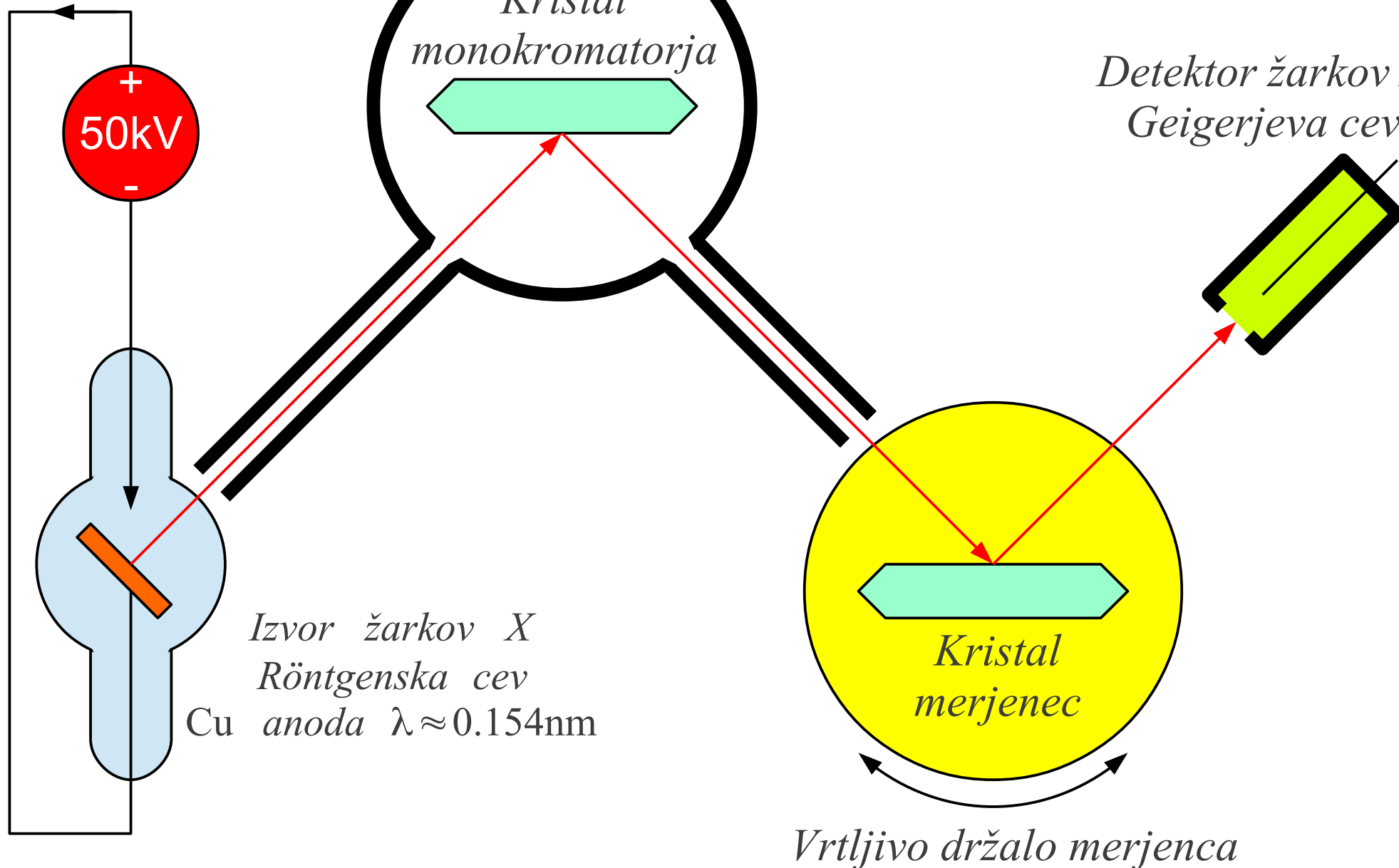
10 – Rezi kremenovega kristala

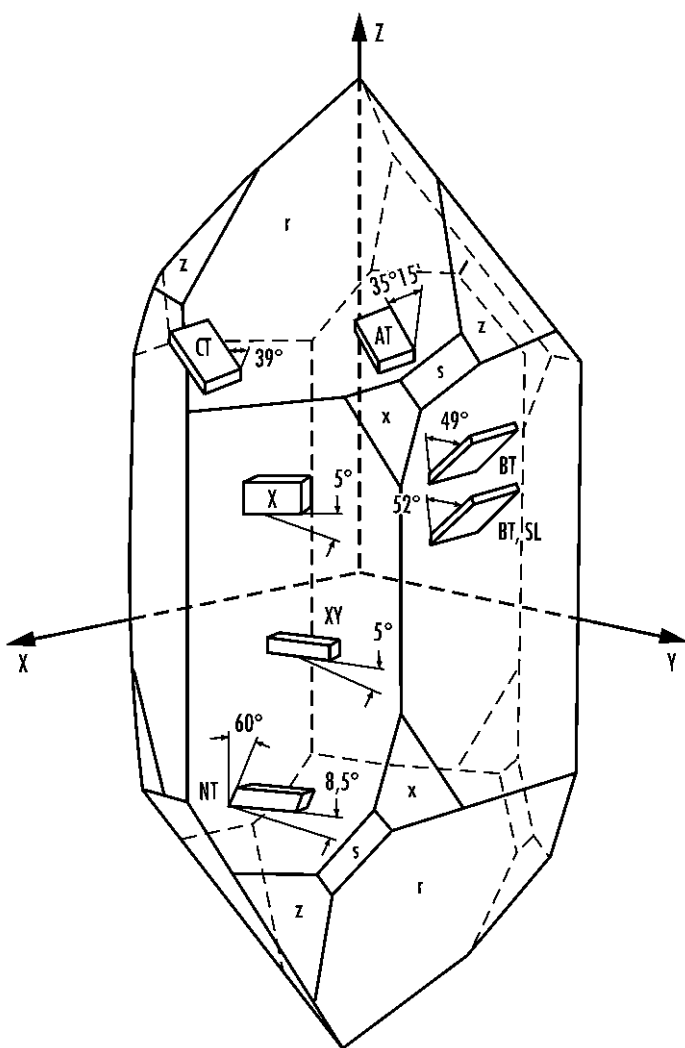
Pb oklop za žarke X

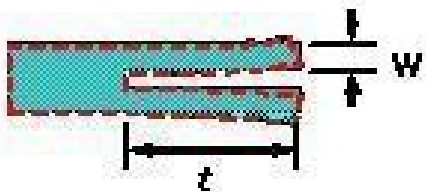
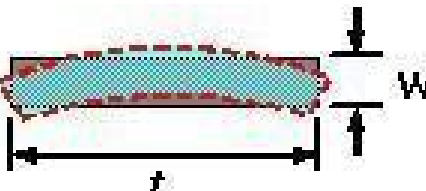
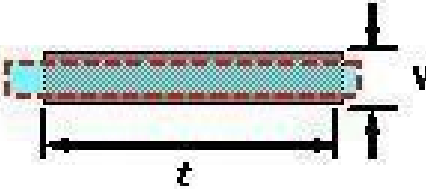
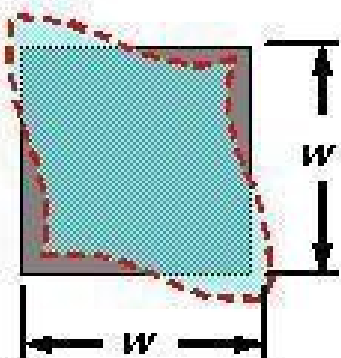

$I \approx 10\text{mA}$

*Kristal
monokromatorja*

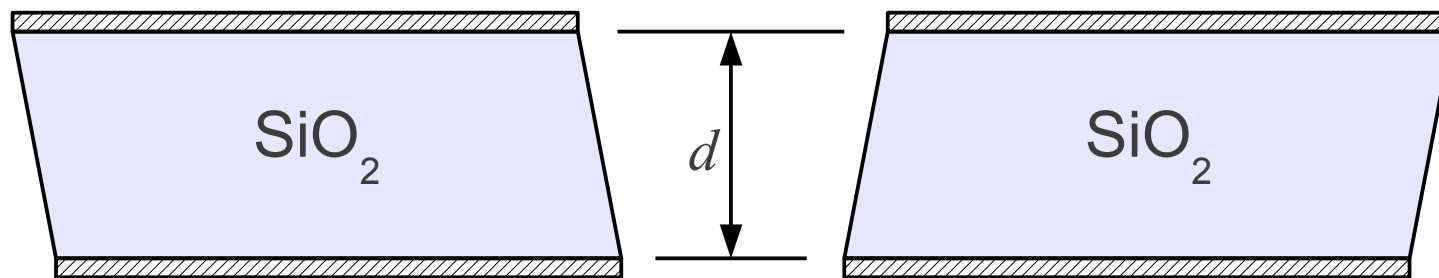
*Detektor žarkov X
Geigerjeva cev*



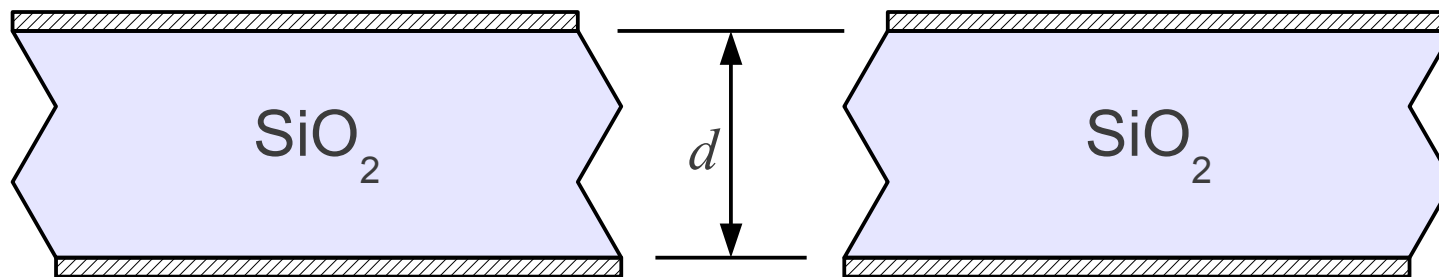


| Vibration Mode | Orientation Angle |
|--|--|
| Tuning Fork  | $+ 2^{\circ} X$ |
| Flexure  | XY NT |
| Extension  | $+ 5^{\circ} X$ $- 18.5^{\circ} X$ |
| Face Shear  Thickness Shear  | DT CT SL AT Fundamental AT 3 rd Overtone AT 5 th Overtone BT Fundamental |

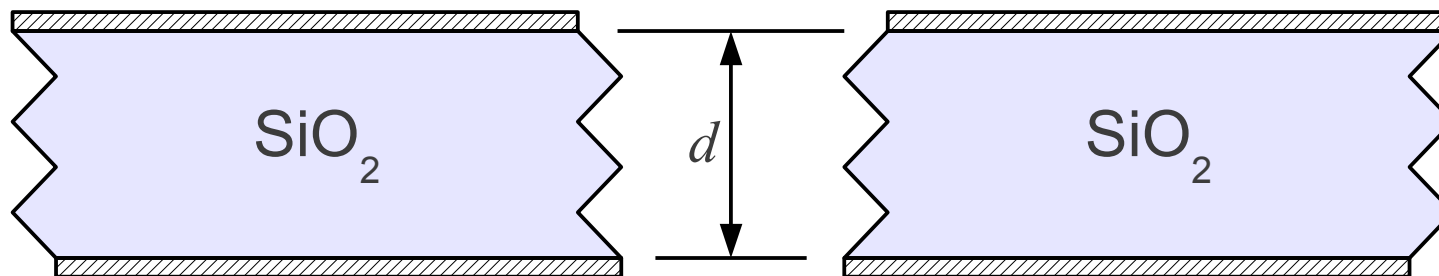




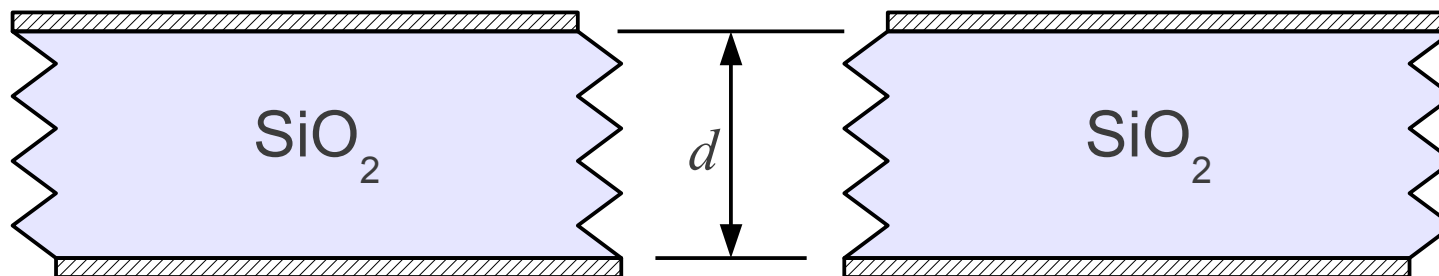
Osnovna
rezonanca
 $f_1 \approx v/2d$



Tretji
overton $\sim 3f_1$

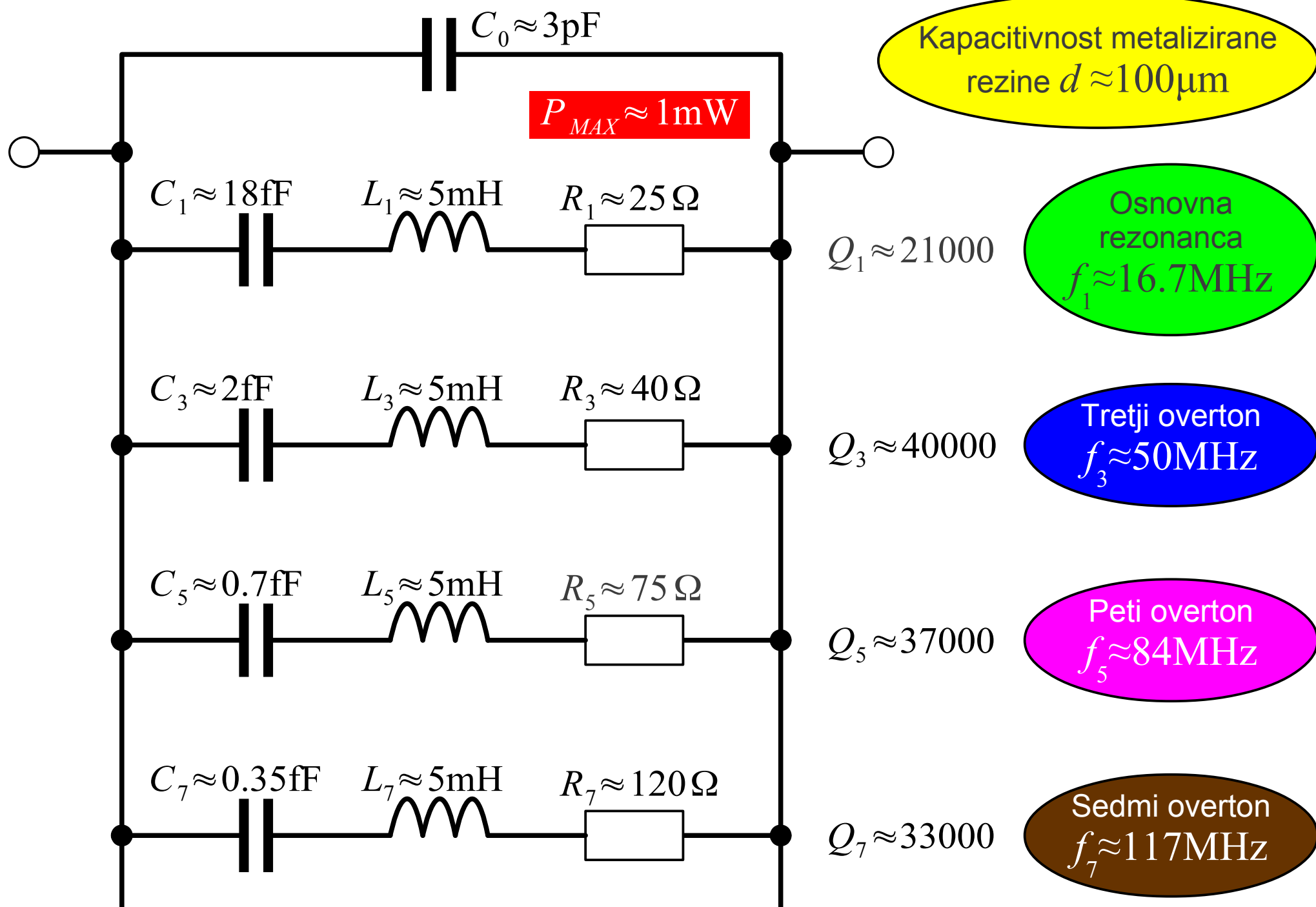


Peti
overton $\sim 5f_1$



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**

$1/R_3$

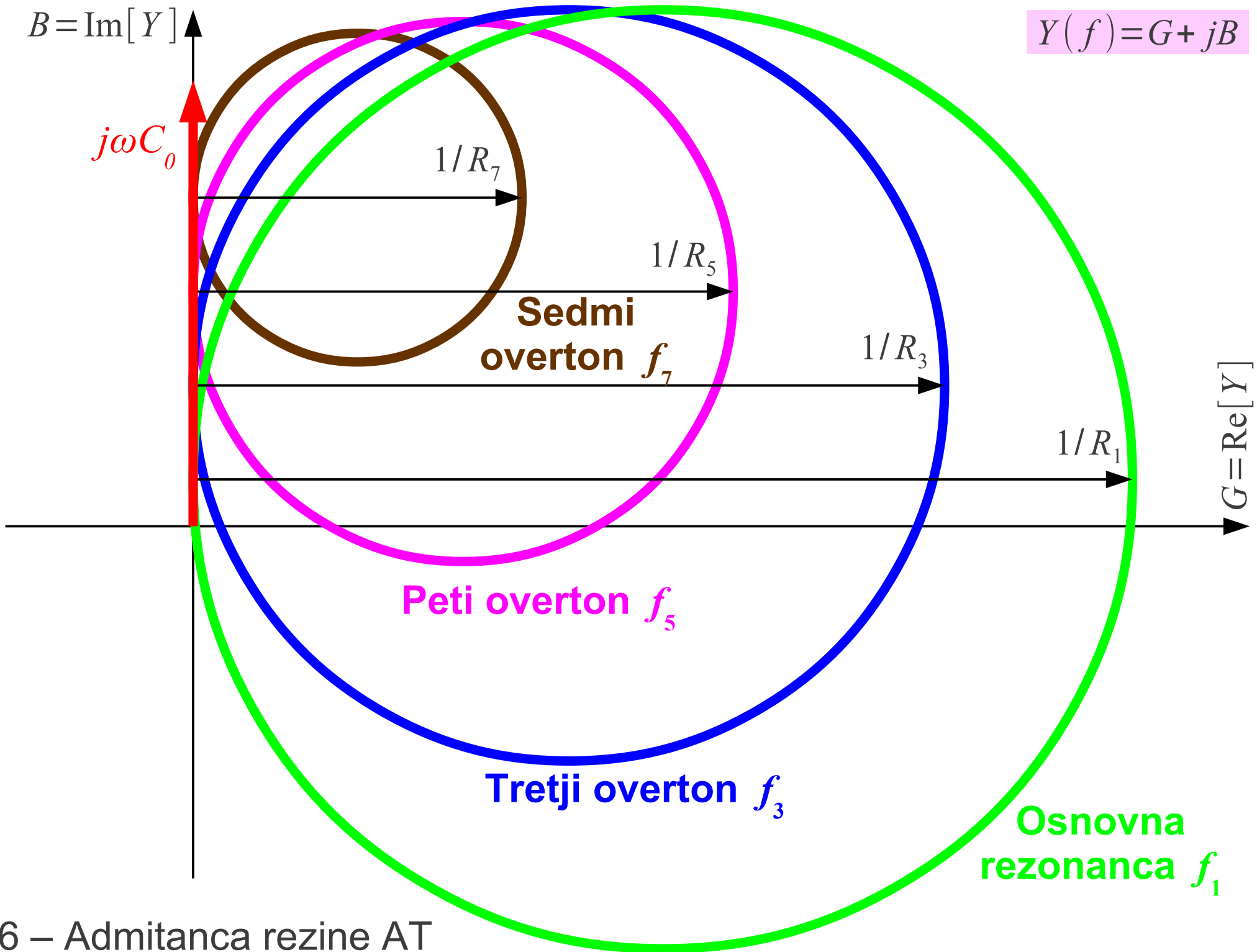
$1/R_1$

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

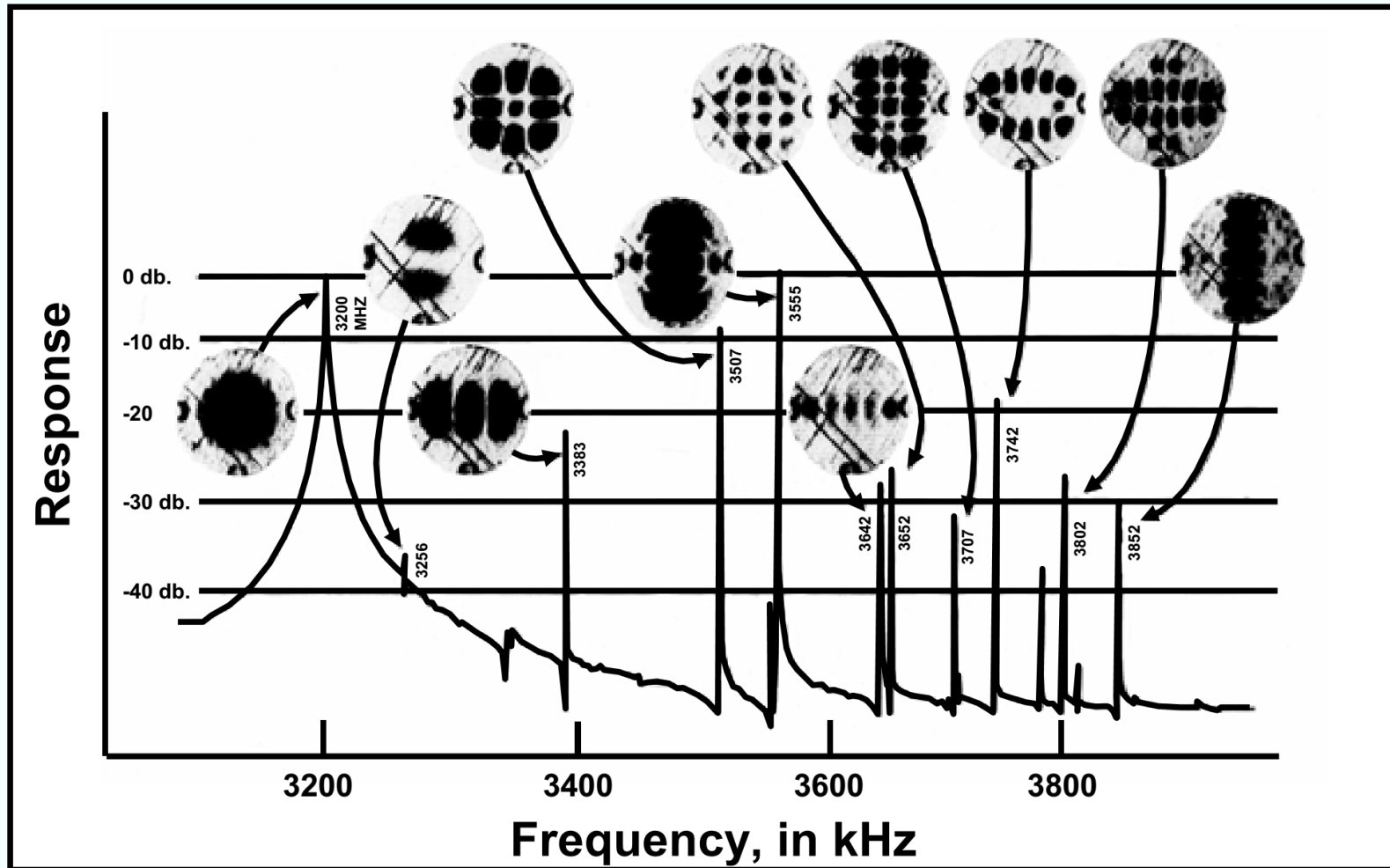
Peti overtone f_5

Tretji overtone f_3

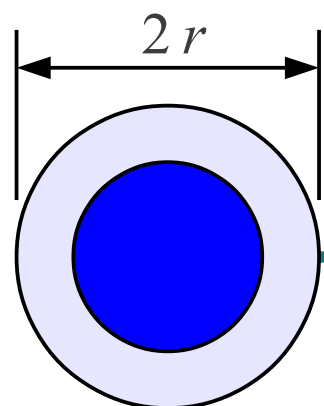
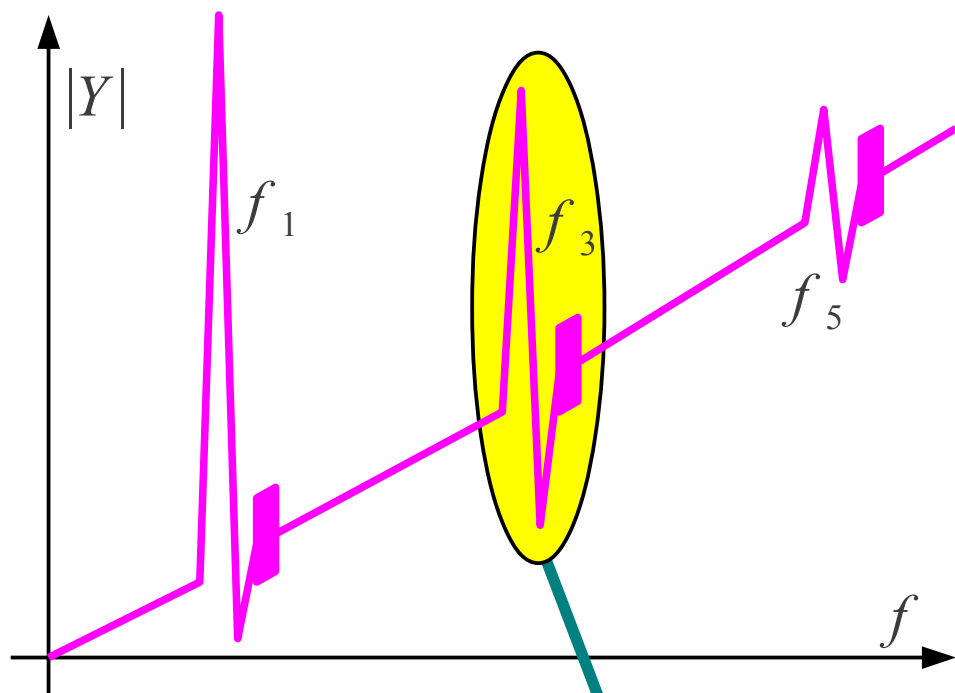
**Osnovna
rezonanca f_1**



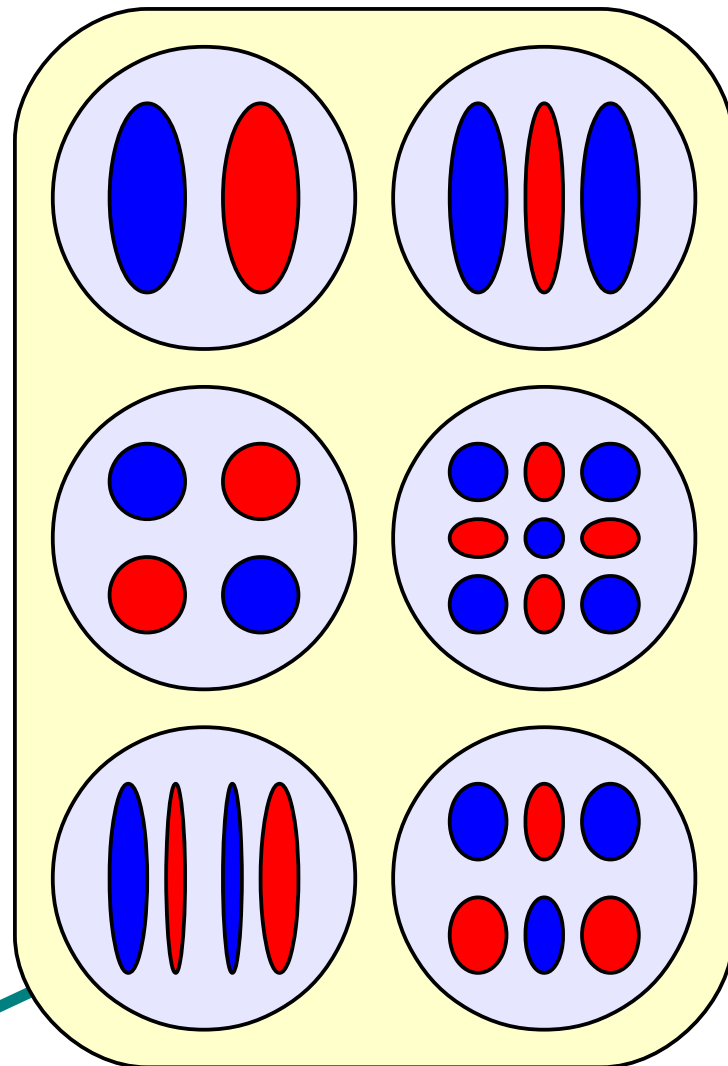
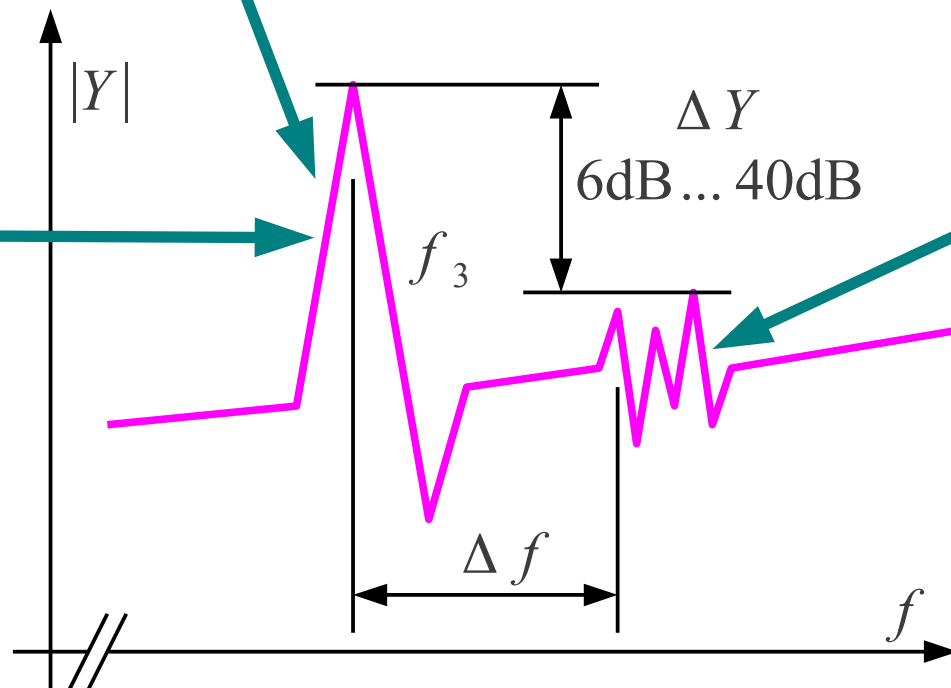
Resonant Vibrations of a Quartz Plate



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.



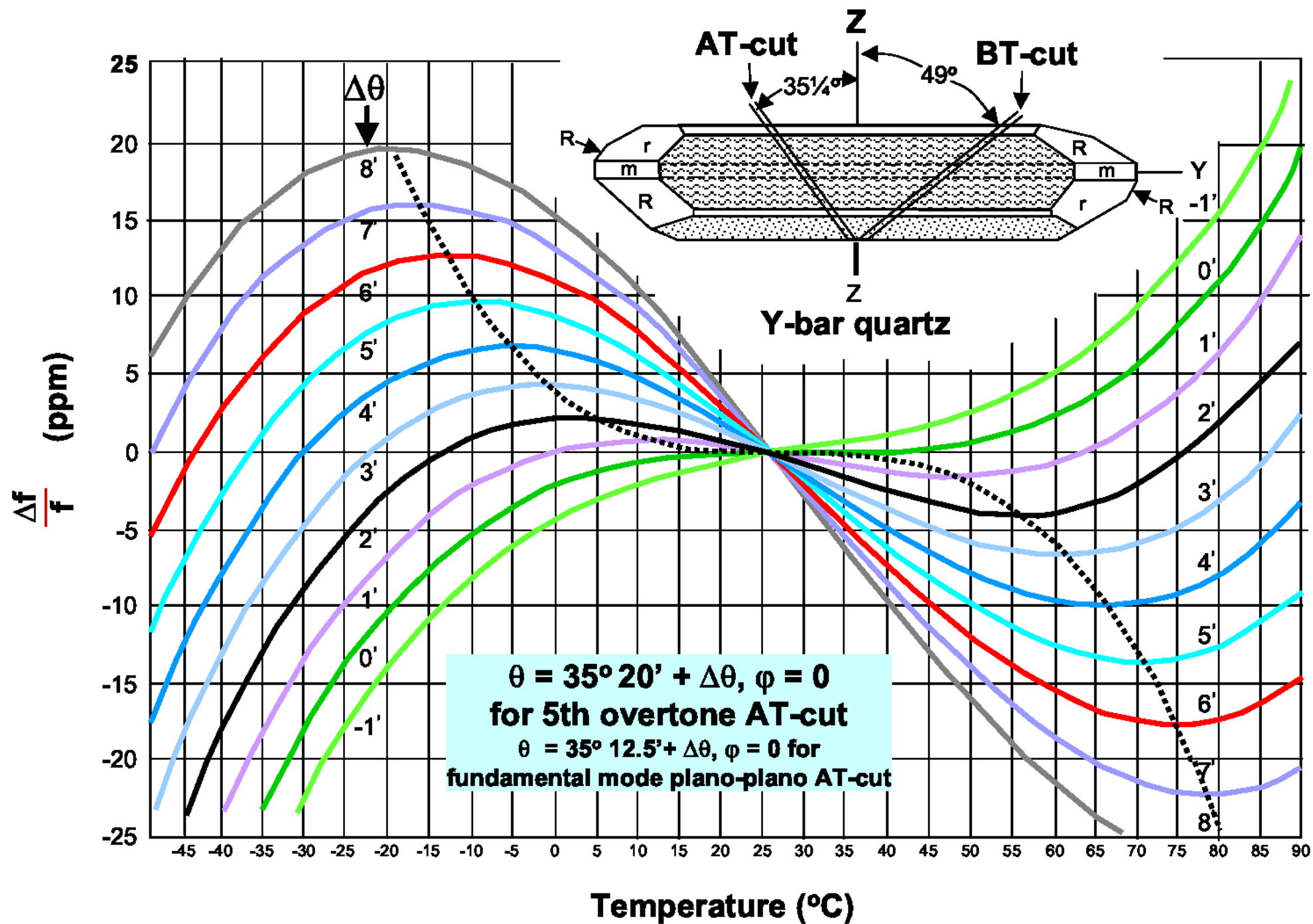
Osnovni prečni rod

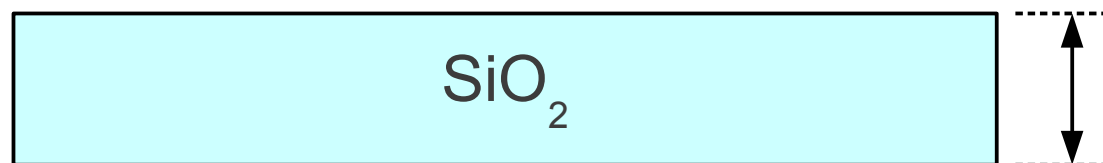


Višji prečni rodovi (anharmonics)

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

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

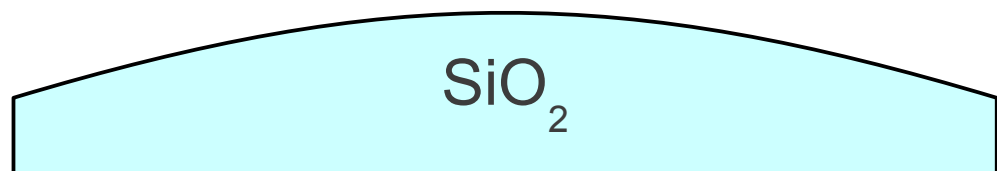




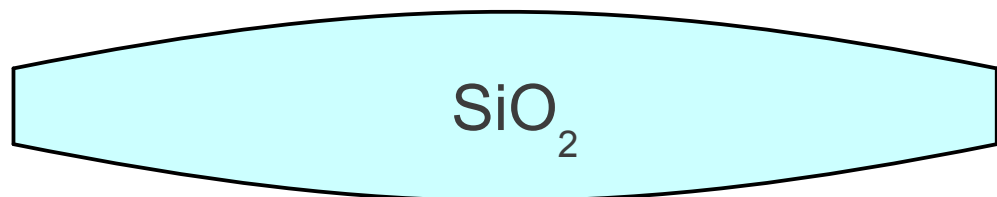
$$d \geq 50 \mu\text{m}$$

Plan-paralelna rezina

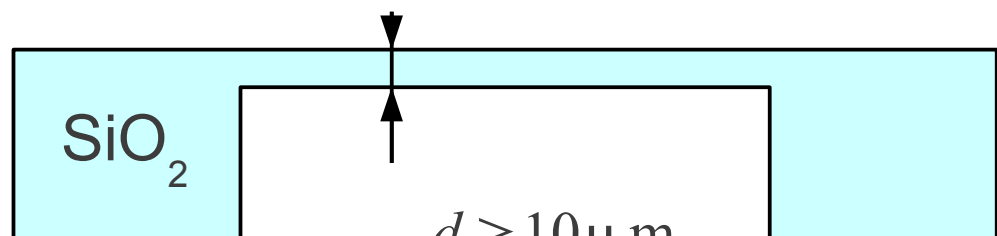
$$f_1 \leq 33\text{MHz}$$



Plan-konveksna rezina



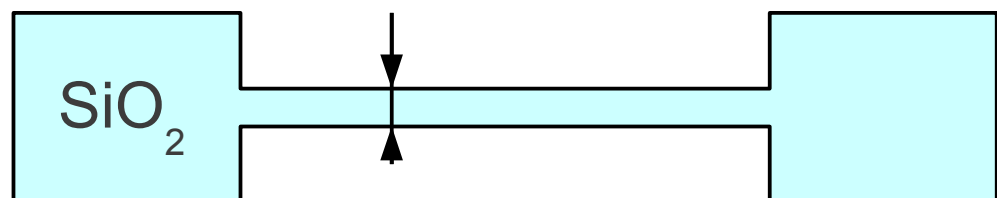
Bi-konveksna rezina



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

Jedkana rezina "inverted mesa"

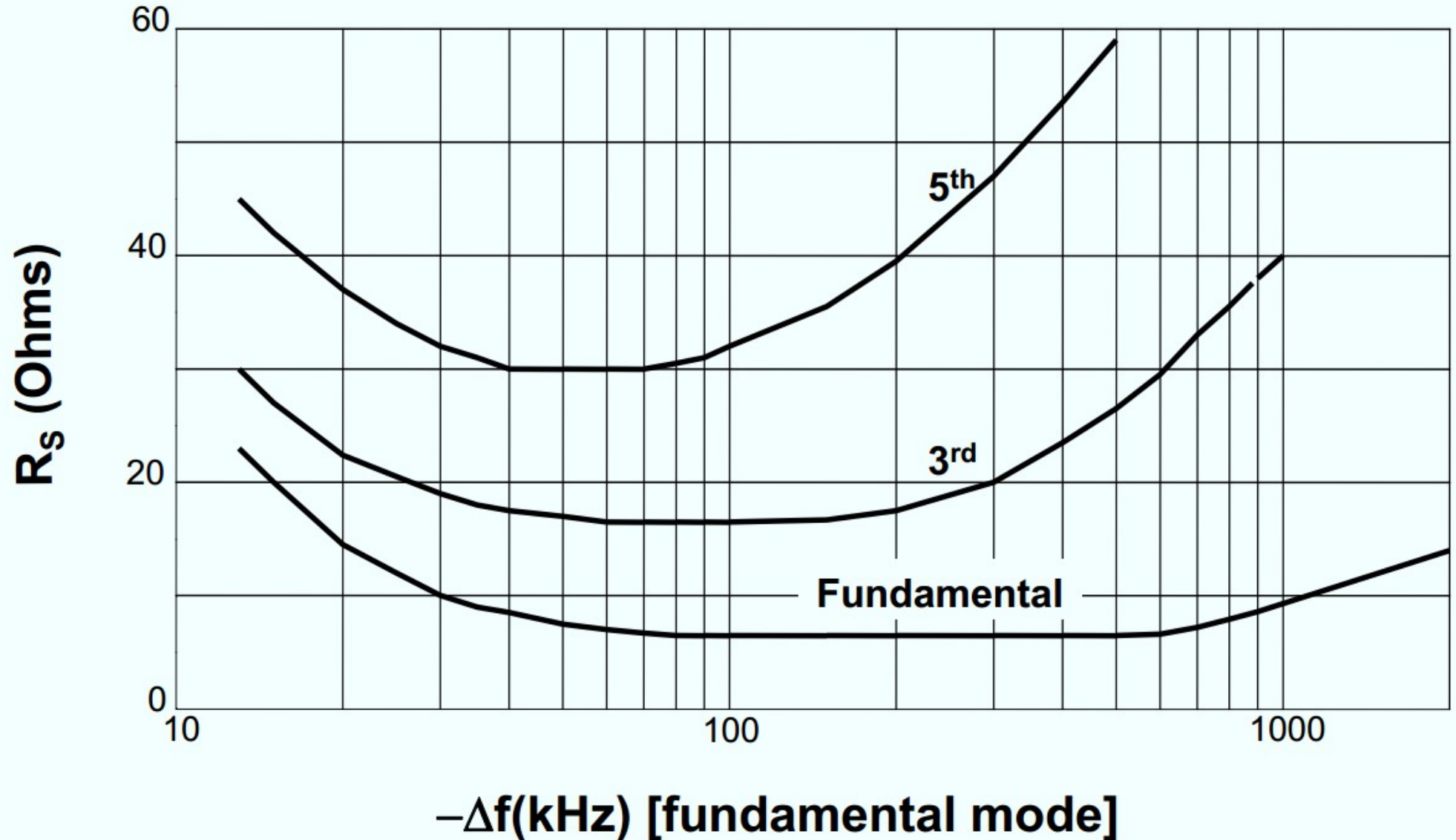
$$f_1 \leq 170\text{MHz}$$



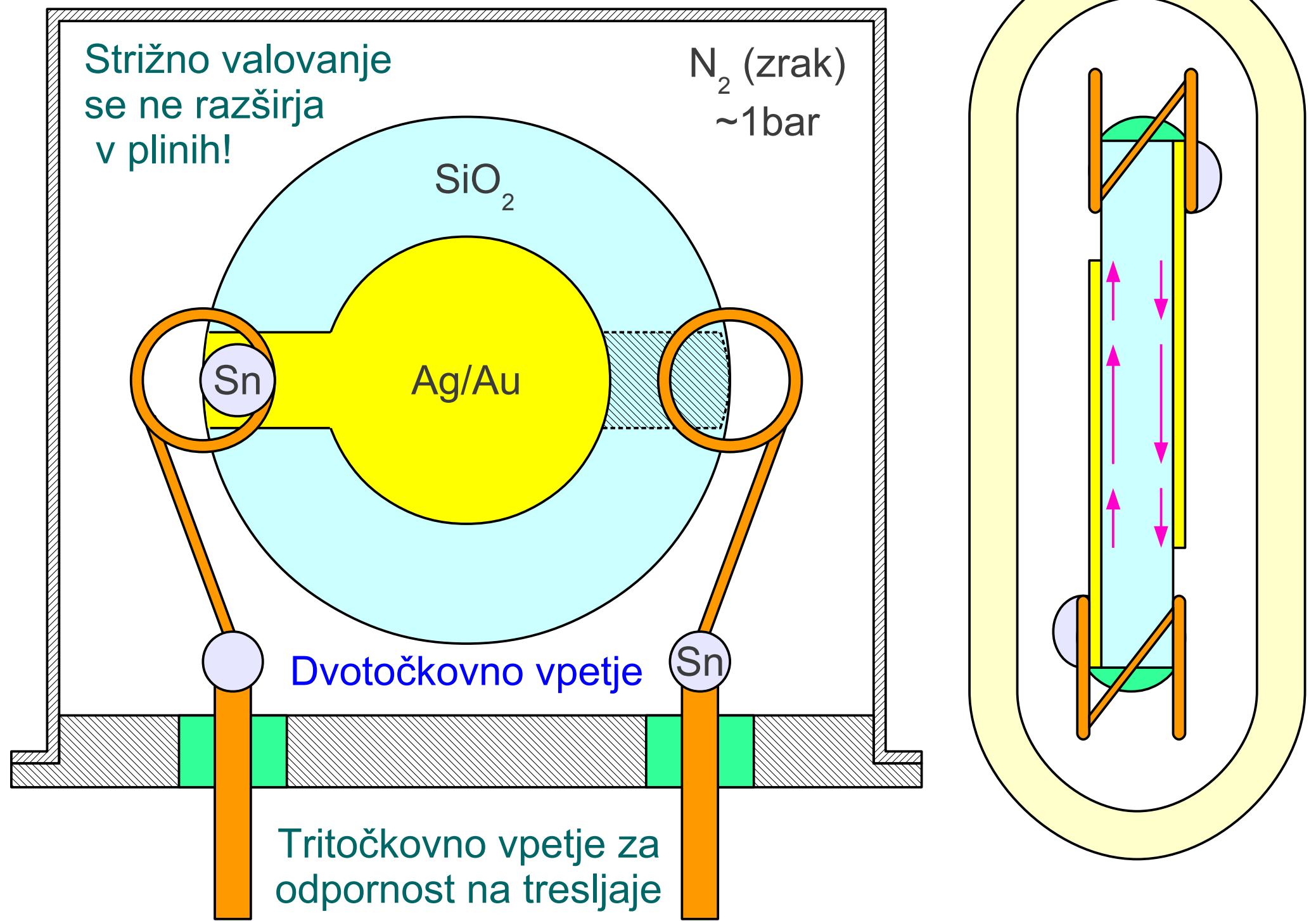
20 – Oblika preseka rezine AT

Resistance vs. Electrode Thickness

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

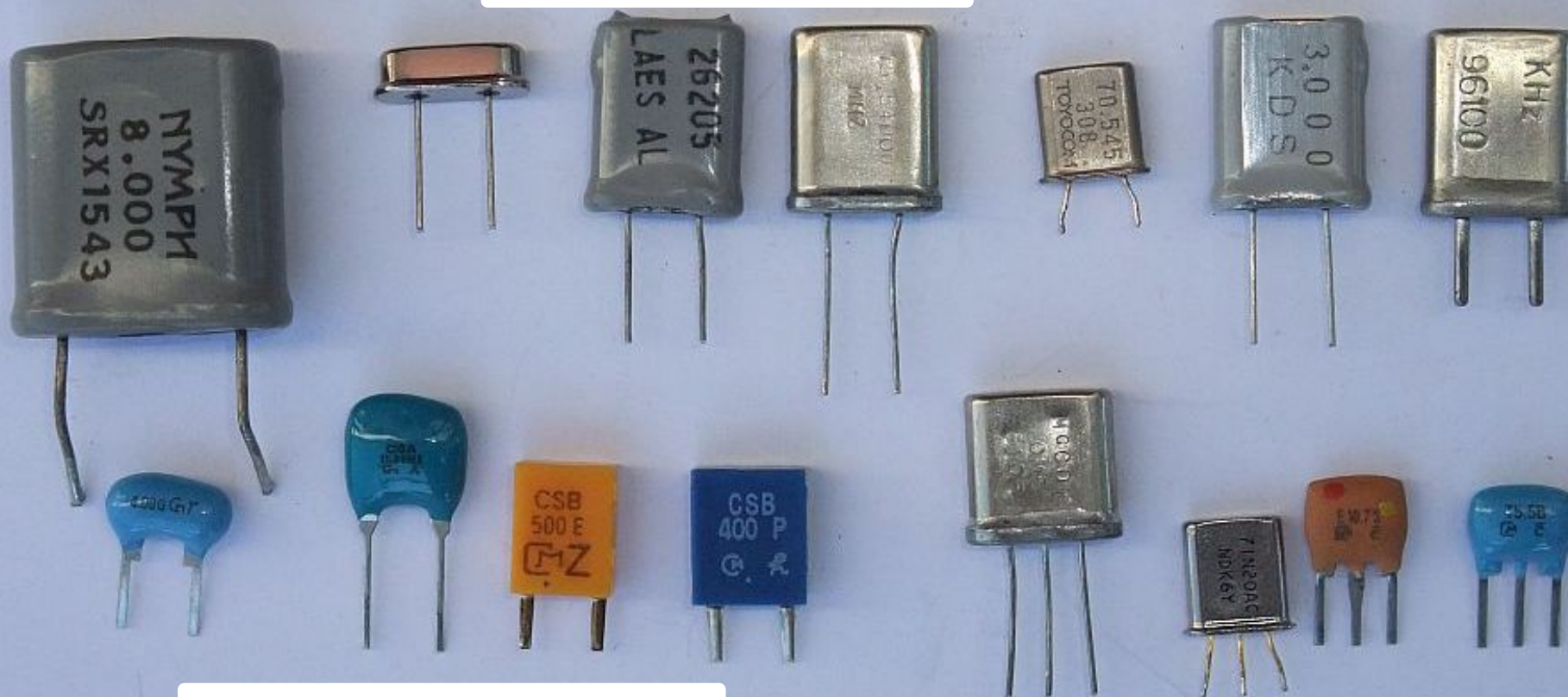


22 – Vgradnja rezine AT v ohišje



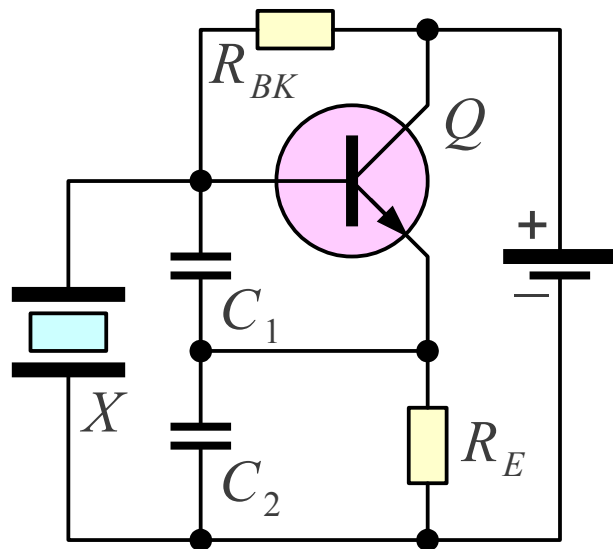


Kremenčevi kristali

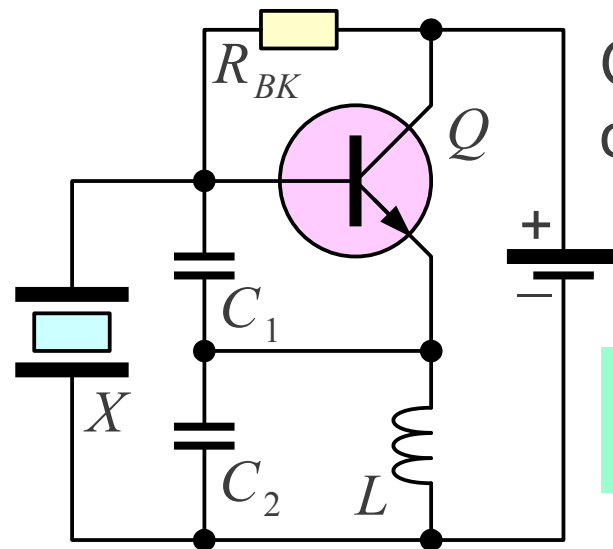


Keramični rezonatorji

Večkratni rezonatorji

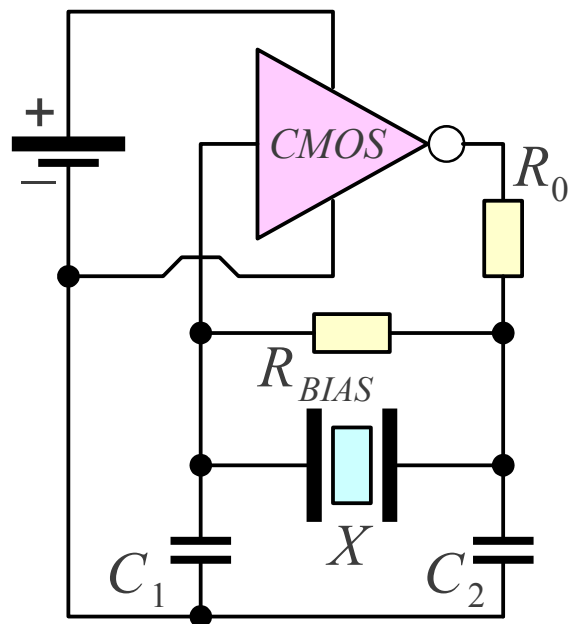


Pierce (Colpitts) na osnovni frekvenci f_1



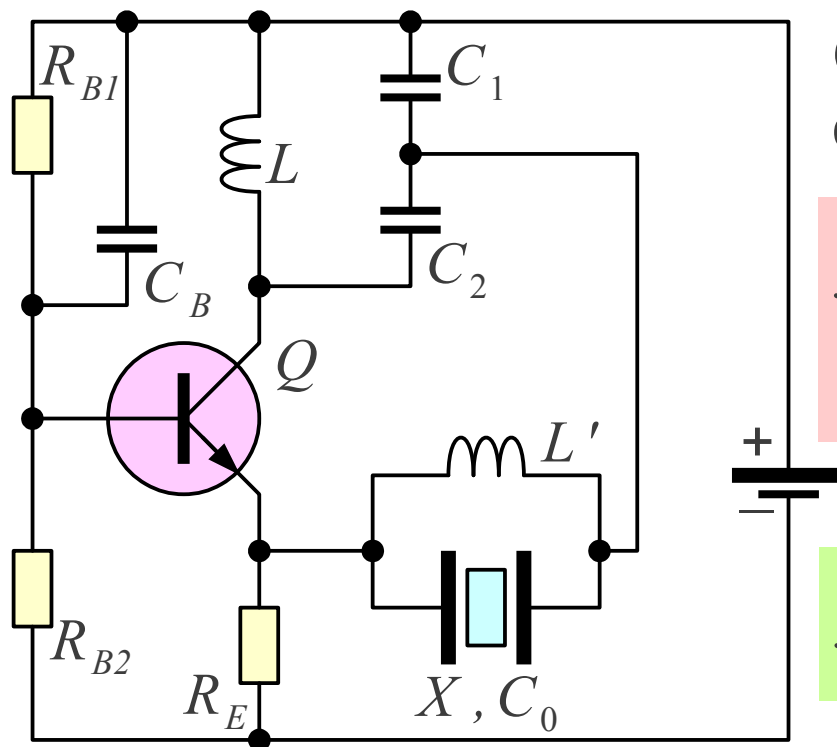
Overtonski oscilator f_3

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



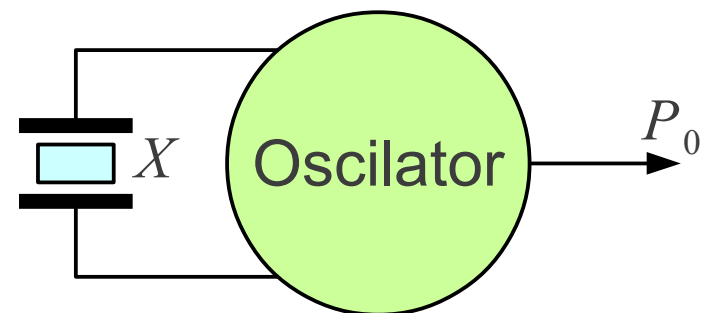
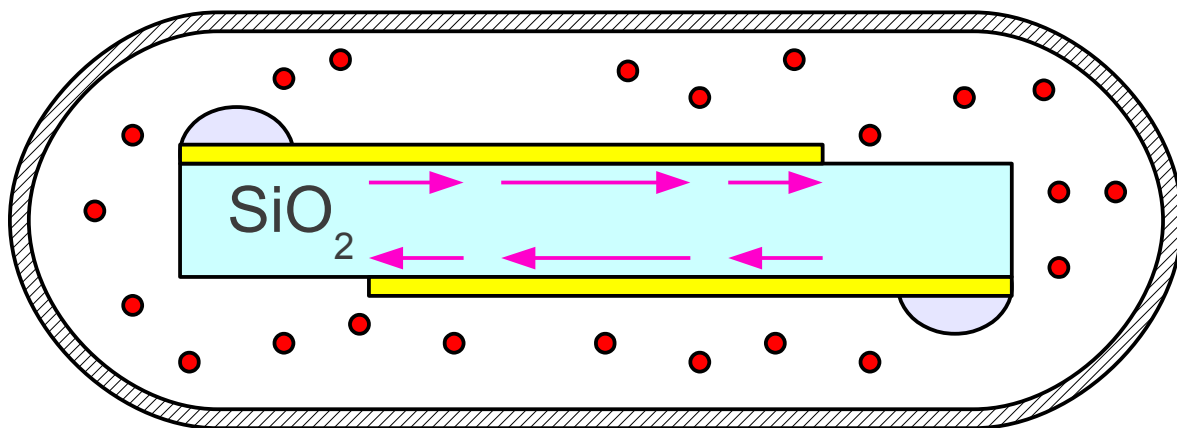
Overtonski oscilator f_5

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



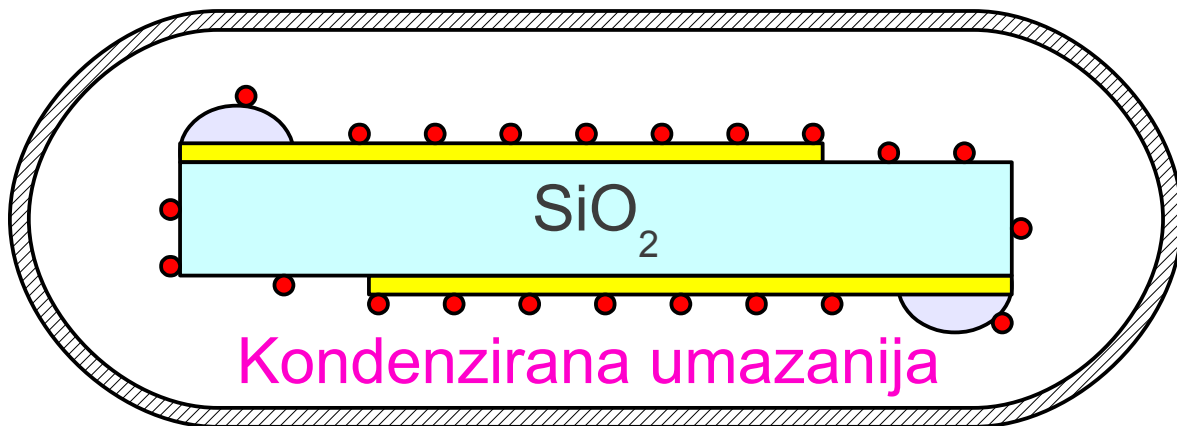
$$f_5 = \frac{1}{\sqrt{L' C_0}}$$

TOPLO

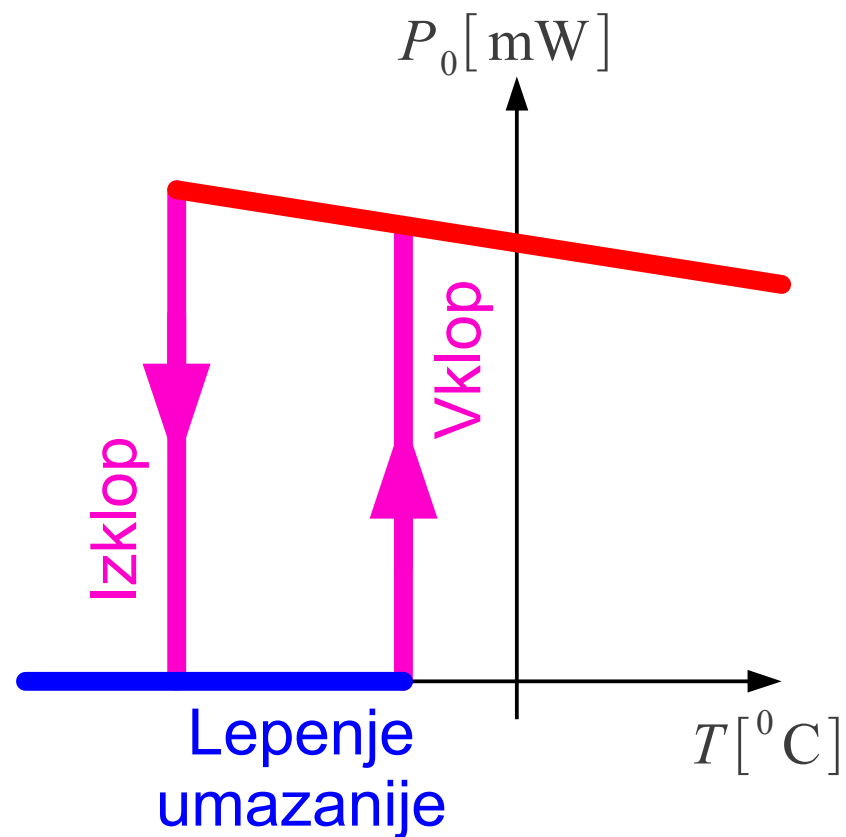


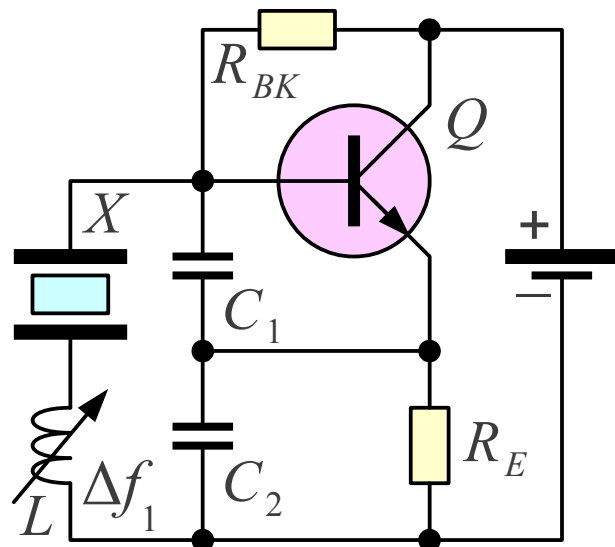
Ogrevanje

Ohlajanje

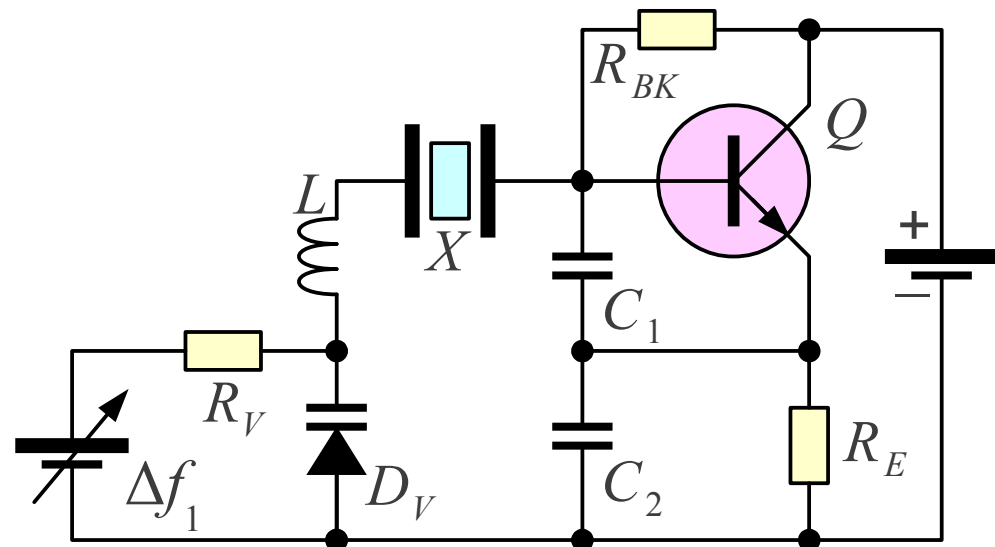
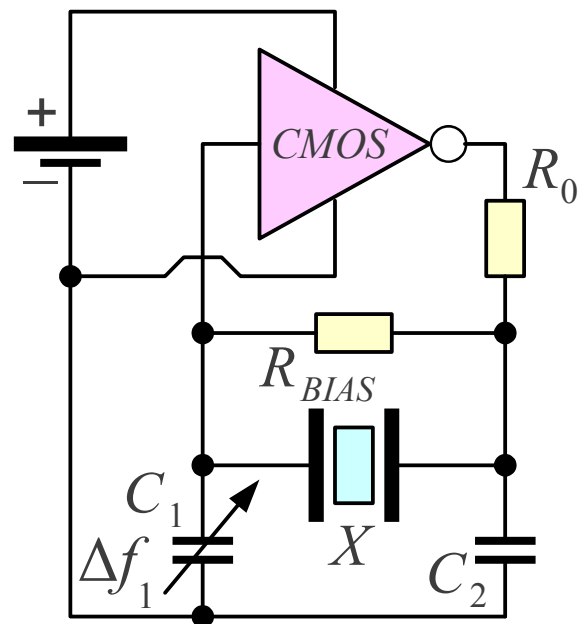


HLADNO



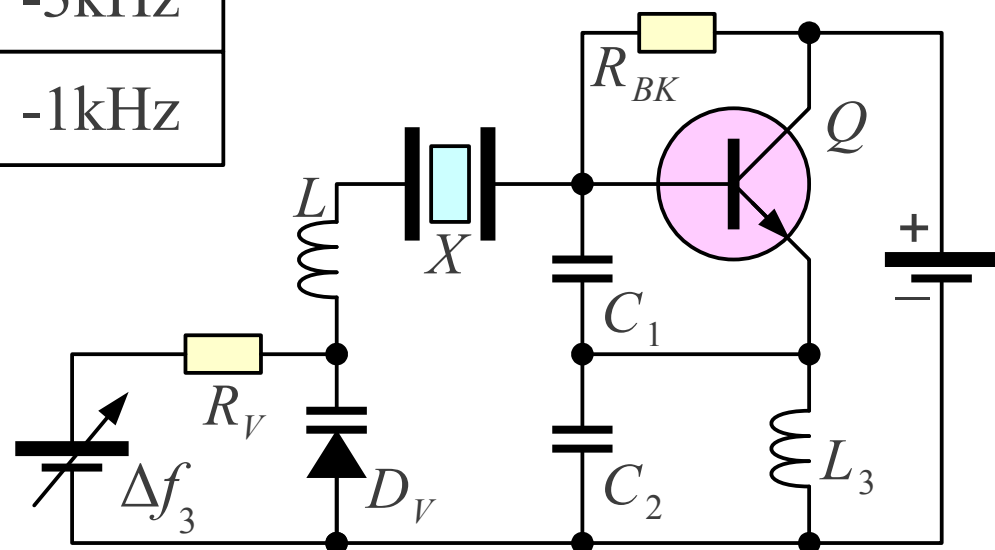


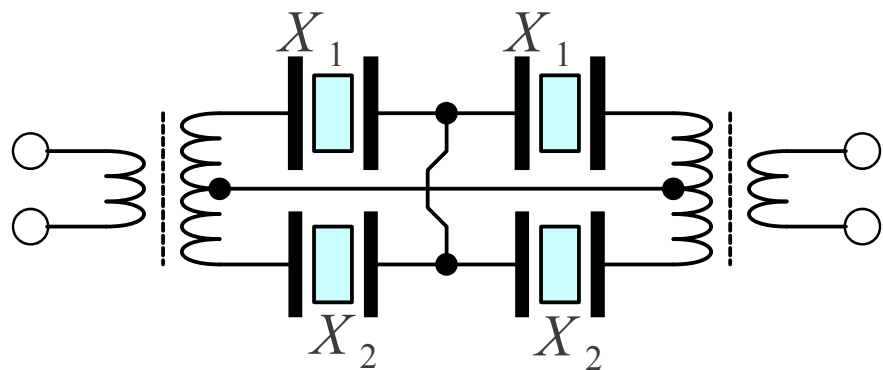
Nastavljivi kristalni oscilator VXO



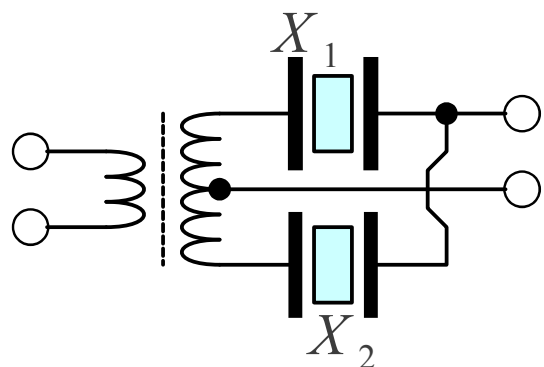
Napetostno nastavljivi kristalni oscilator VCXO

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

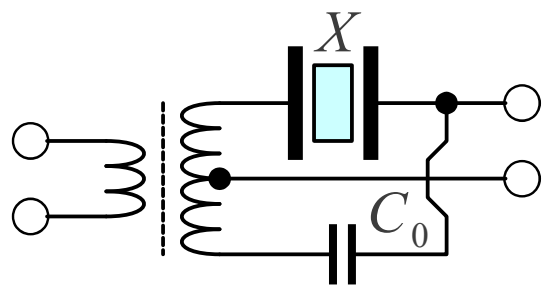




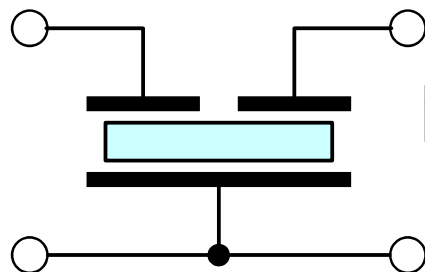
Dvojno mostično pasovno sito



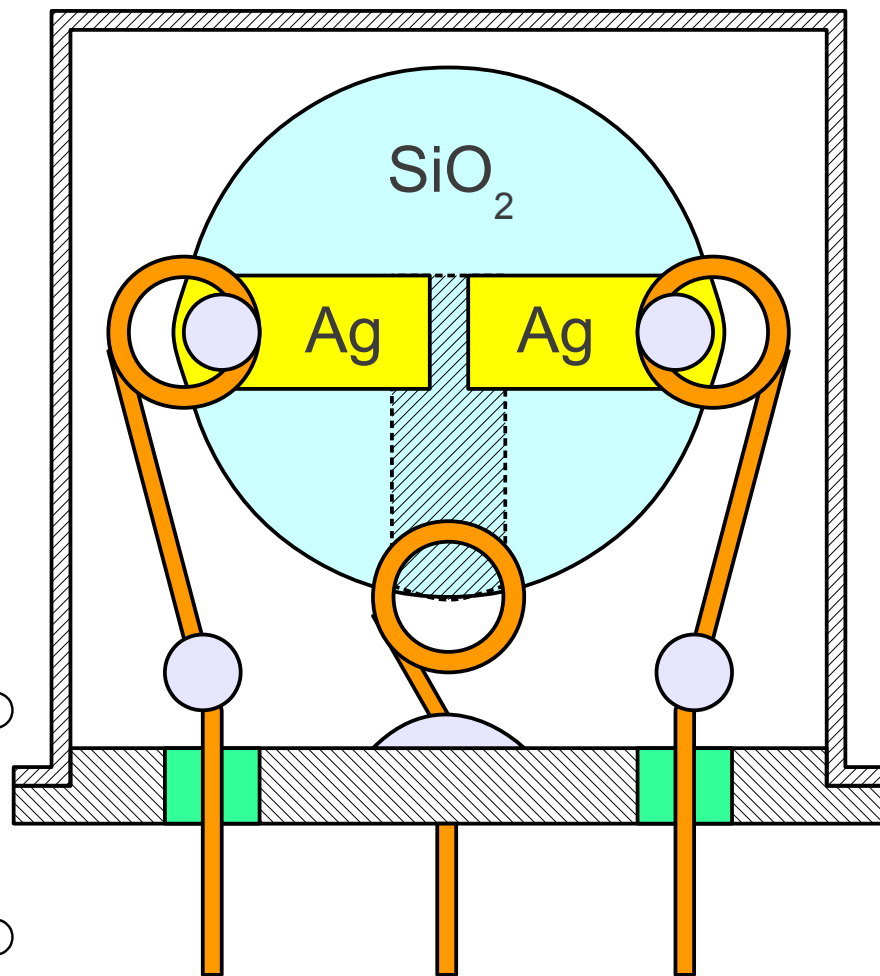
Mostično pasovno sito



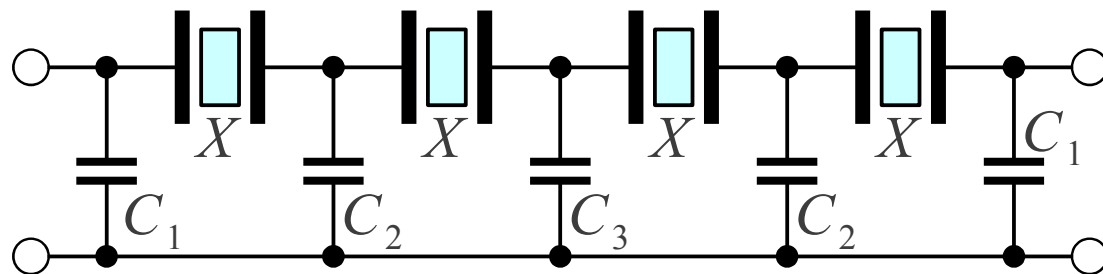
Preprosto pasovno sito



Monolitno pasovno sito

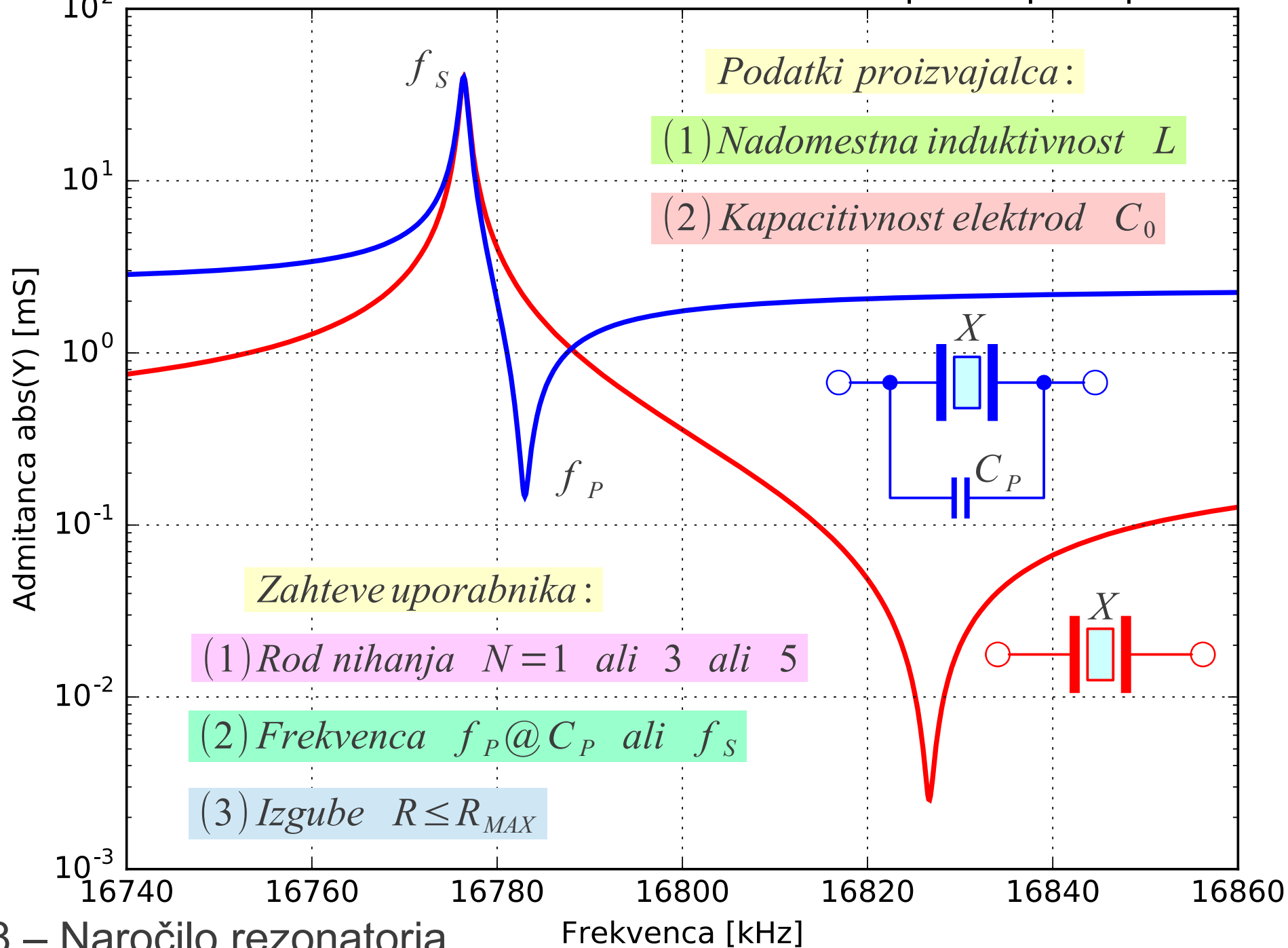


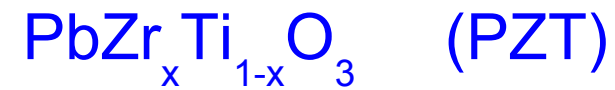
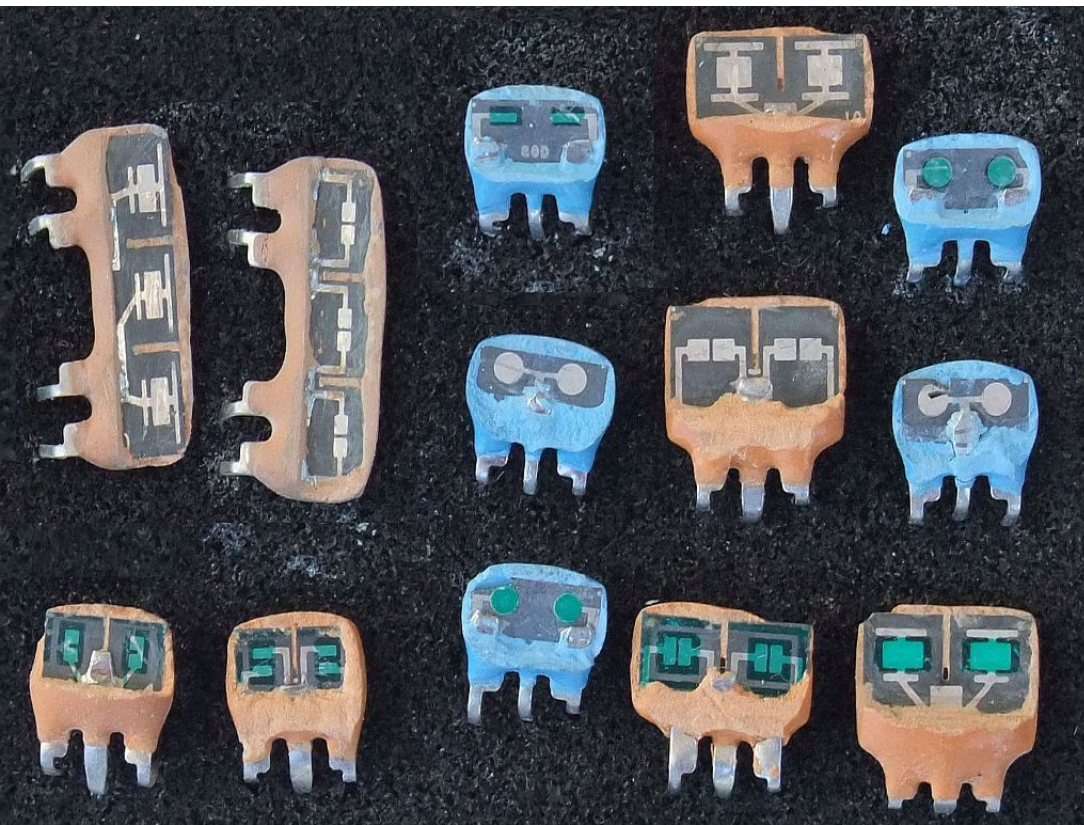
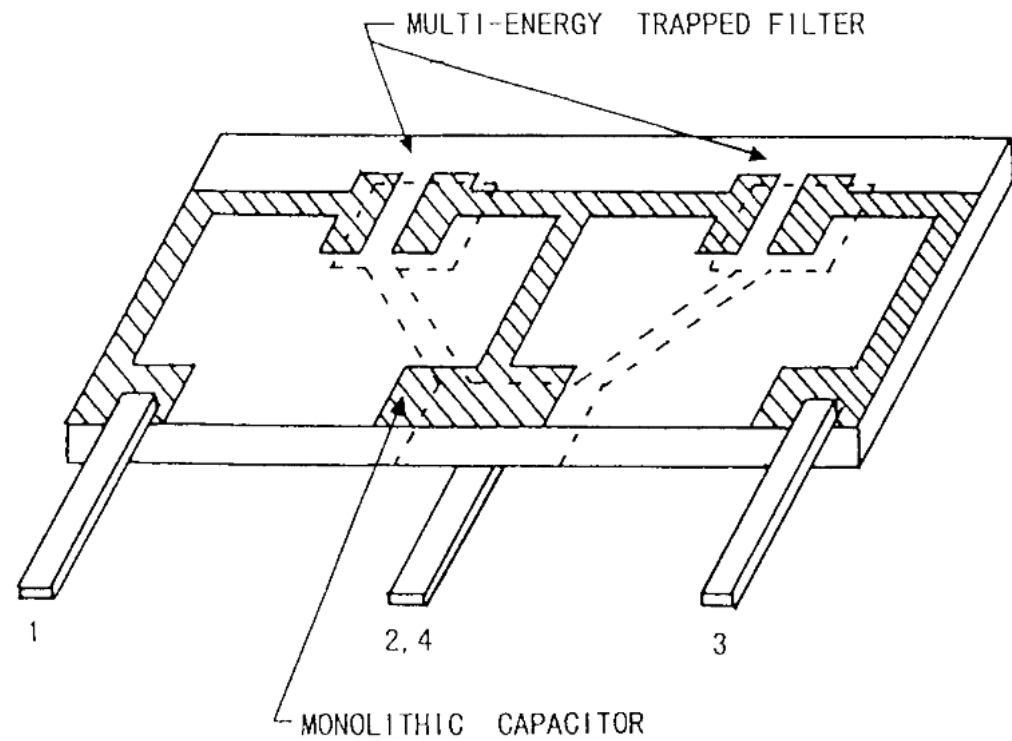
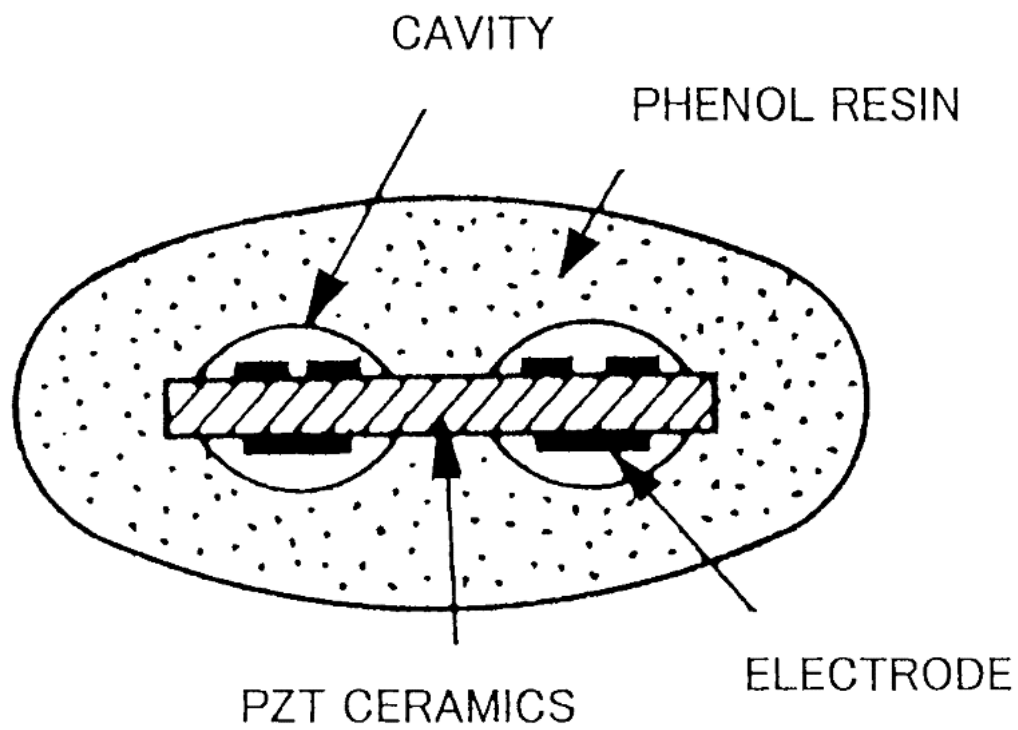
$$200\text{Hz} \leq B \leq 50\text{kHz}$$



Lestvičasto pasovno sito

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





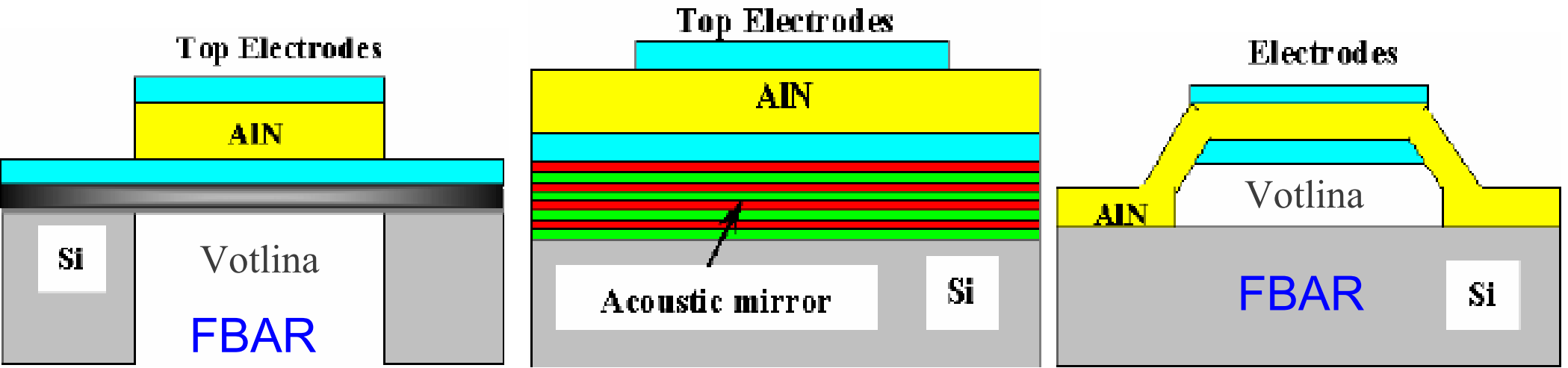
$$x \approx 0.52$$

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

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

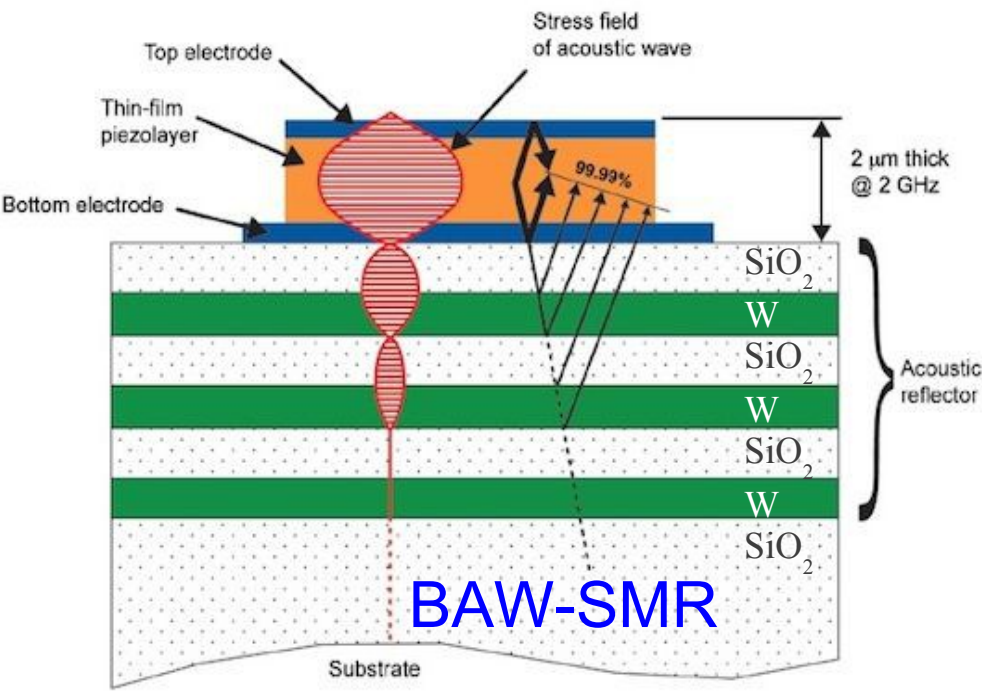
Film Bulk Acoustic Resonator (FBAR)

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



BAW-SMR

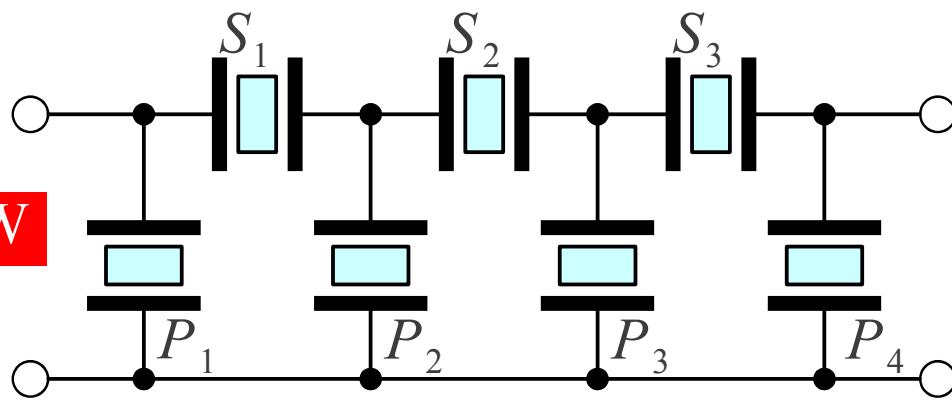
$v \approx 6\text{km/s} \dots 11\text{km/s}$ *tlačni val P*



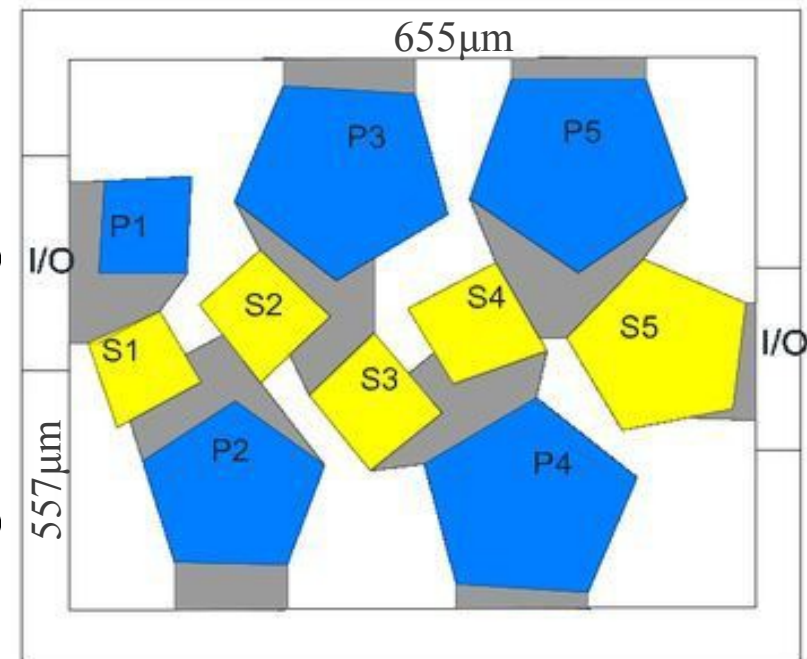
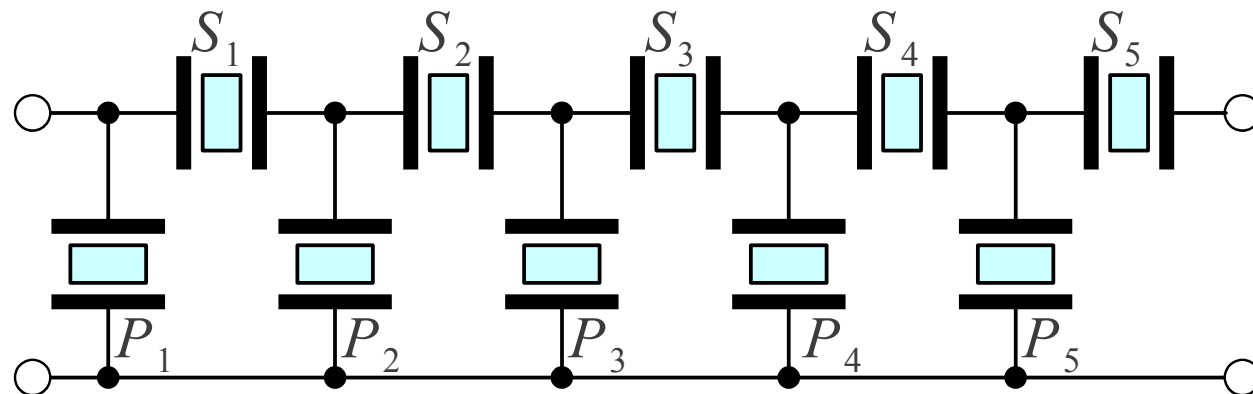
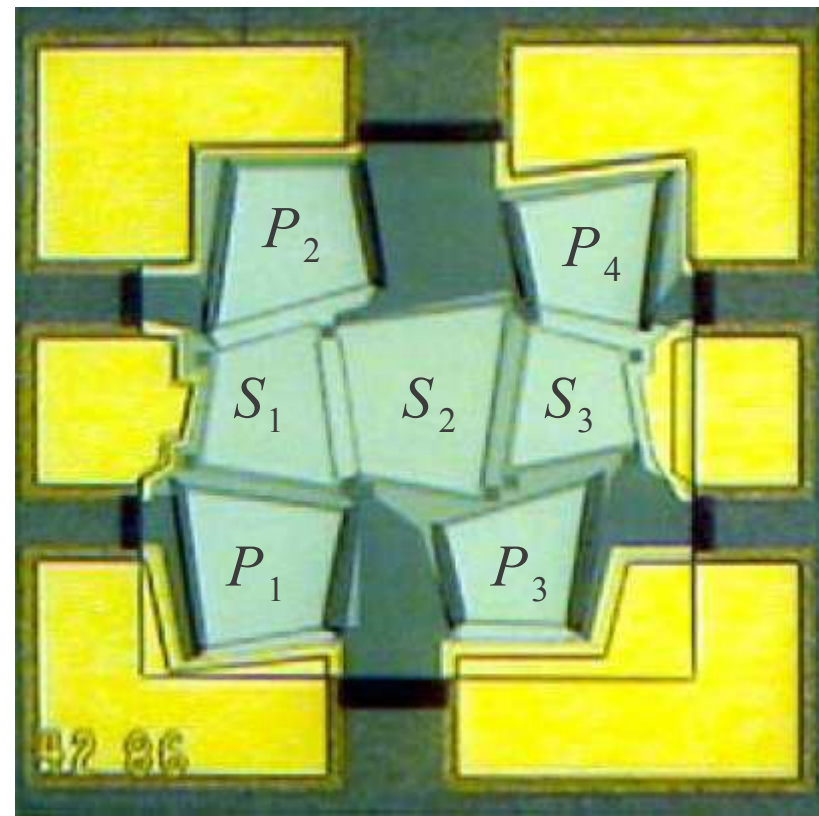
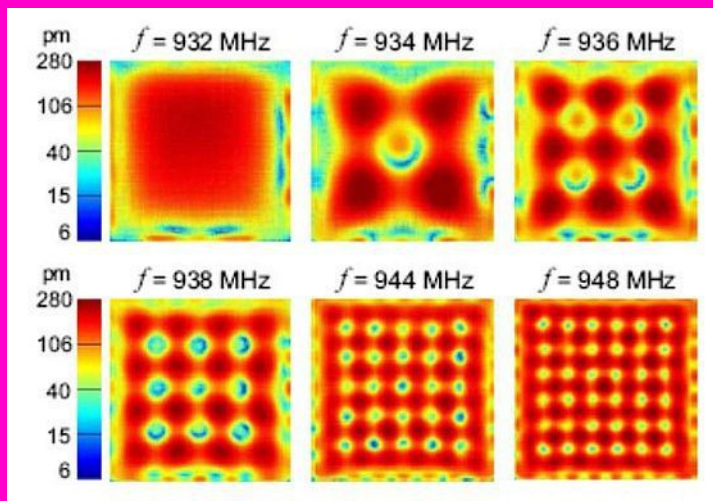
BAW-SMR

| 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 |

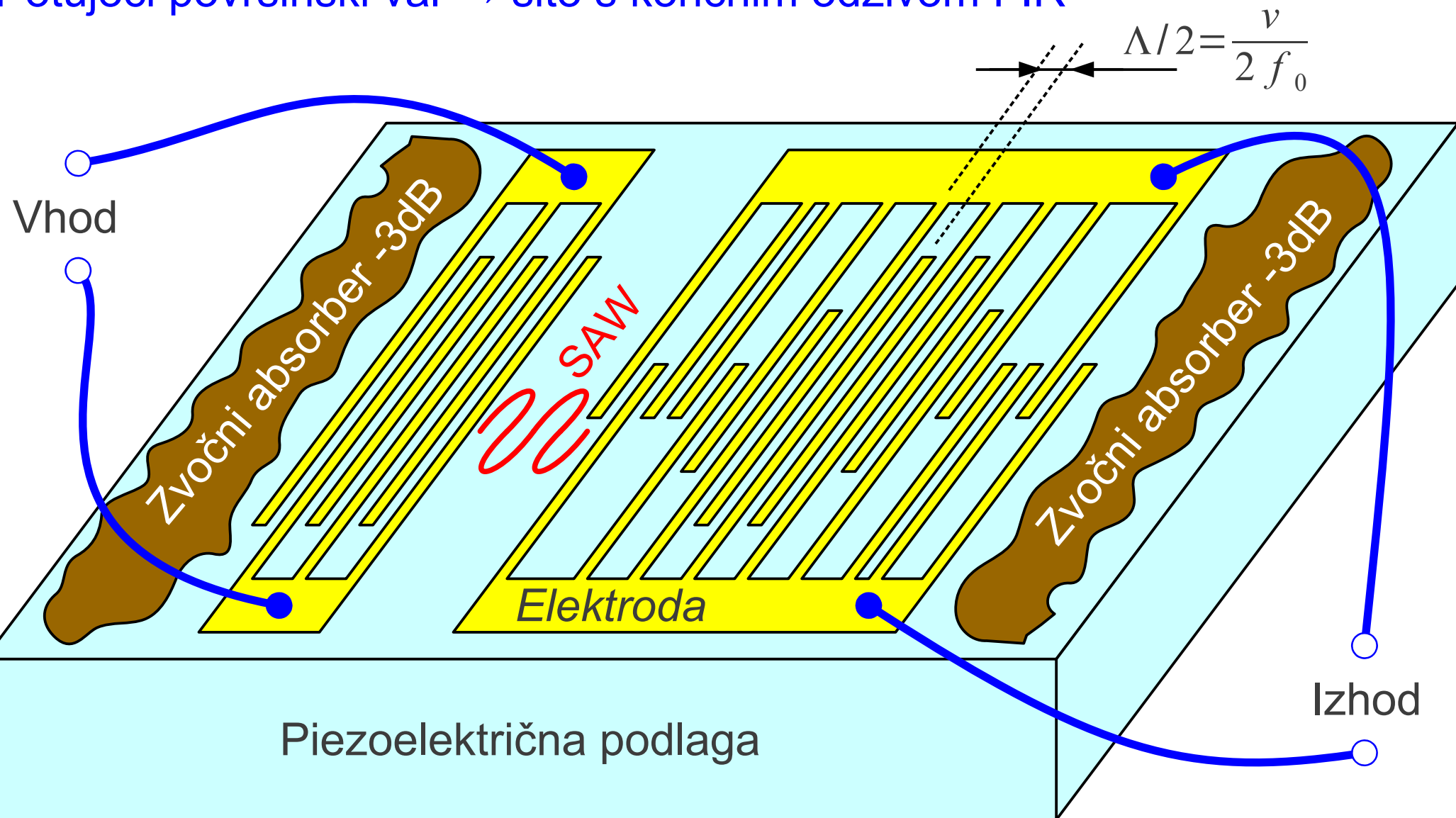
$$P_{MAX} \approx 1W$$



Prečni rodovi
v kvadratnem
rezonatorju
FBAR



Potujoči površinski val → sito s končnim odzivom FIR

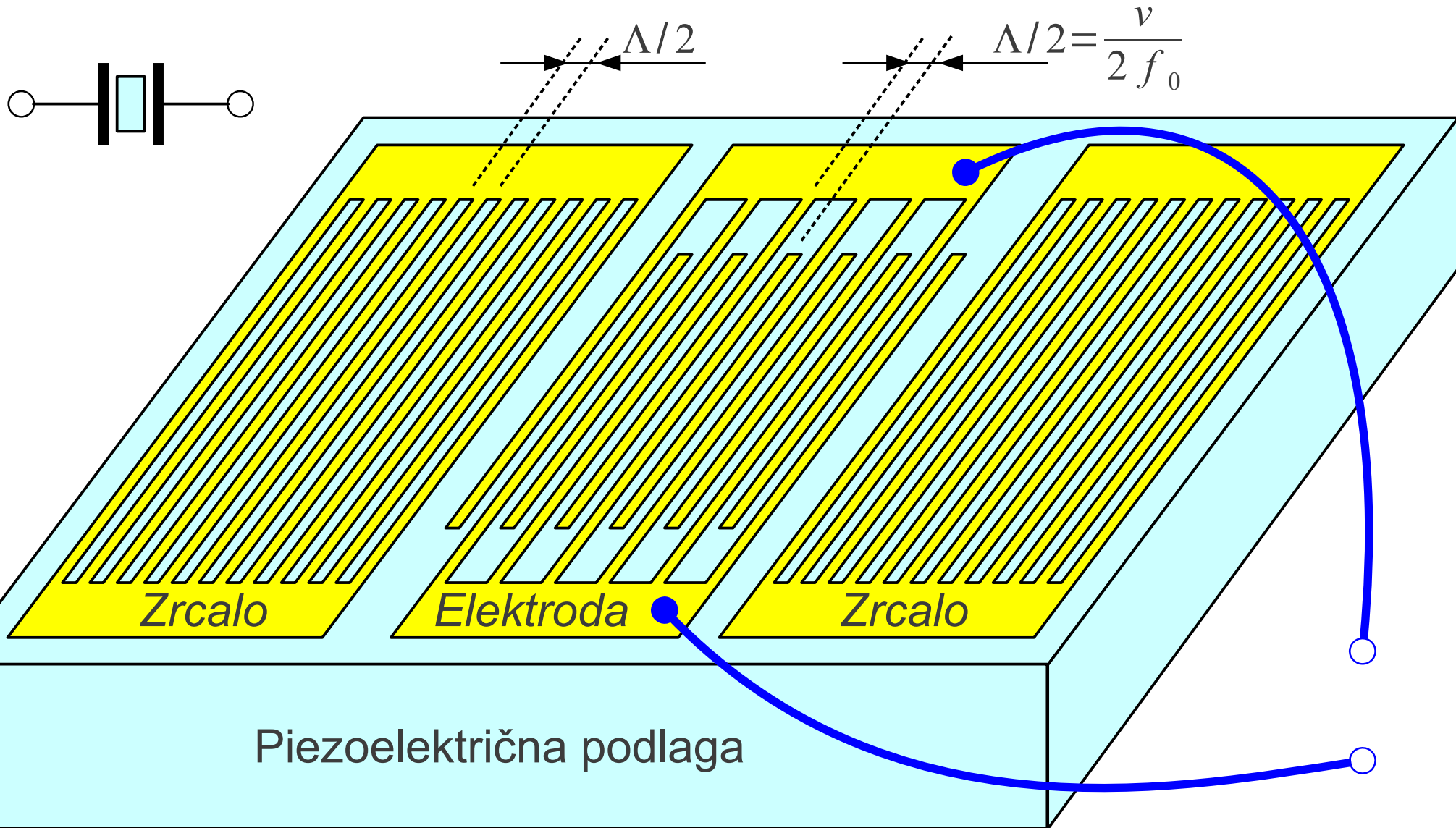


Kristalna podlaga: SiO_2 ali LiNbO_3 ali LiTaO_3 ali $\text{La}_3\text{Ga}_5\text{SiO}_{14}$
(kvarc) (langasite)



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)