

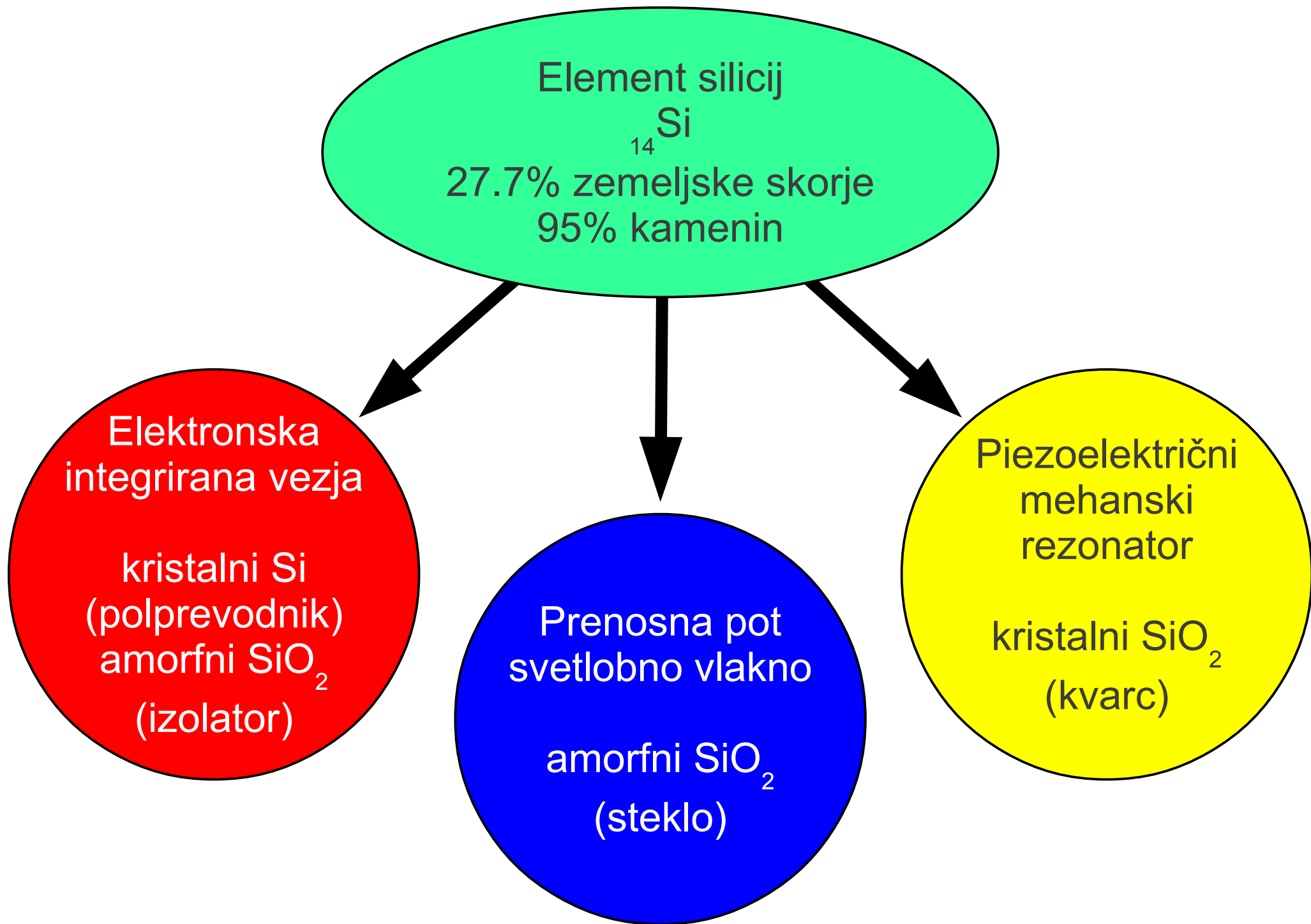
# Piezoelektrični rezonatorji v radijski tehniki

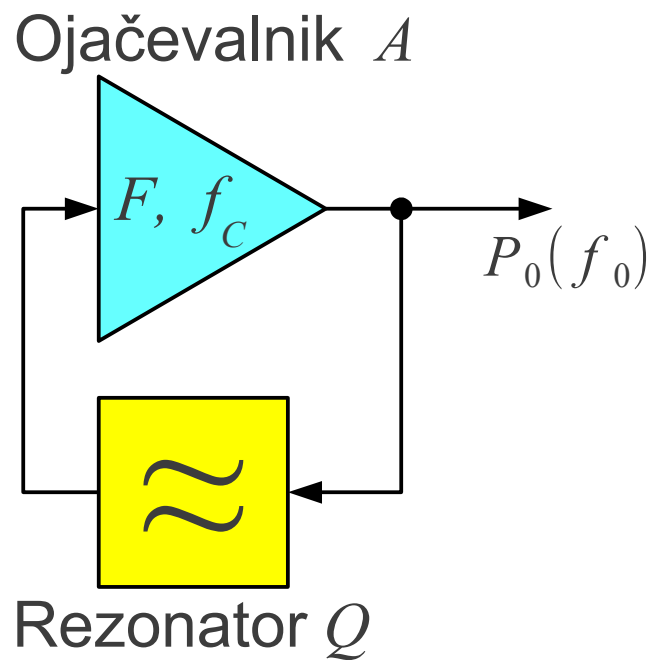
Matjaž Vidmar

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 – Rezone kremenovega kristala
- 11 – Določanje kristalnih osi z žarki X
- 12 – Rodovi nihanja rezin kremena
- 13 – Rezone 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 – Naročilo rezonatorja
- 28 – Piezokeramika
- 29 – Tehnologije FBAR
- 30 – FBAR pasovna sita
- 31 – SAW pasovno sito FIR
- 32 – SAW pasovno sito za 36MHz
- 33 – SAW rezonator





*Leesonova enačba: spektralna gostota faznega šuma*

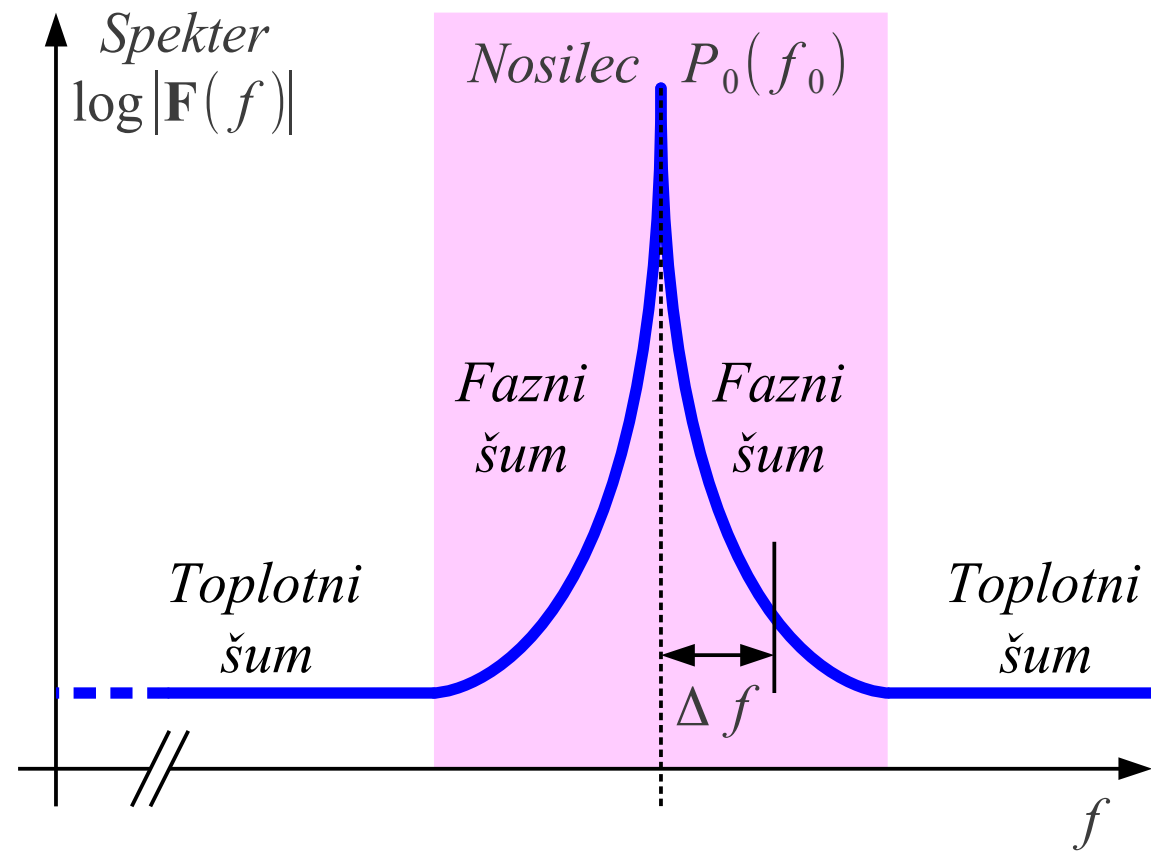
$$L(\Delta f) = \frac{1}{2} \cdot \left[ 1 + \left( \frac{f_0}{2Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left( 1 + \frac{f_c}{|\Delta f|} \right)$$

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

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

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

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



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

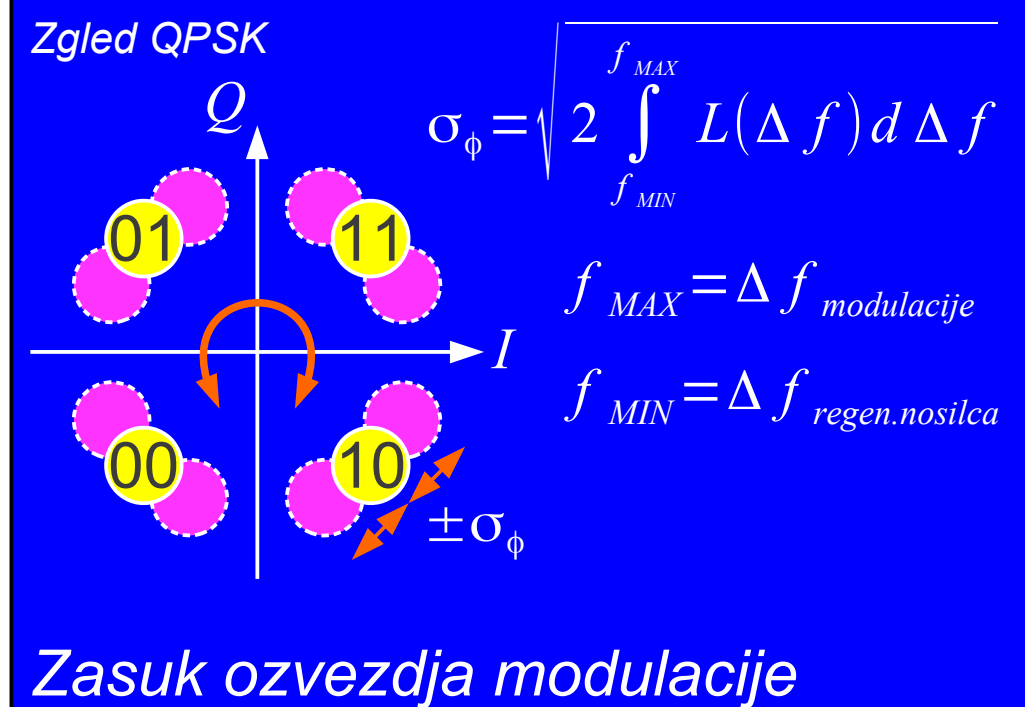
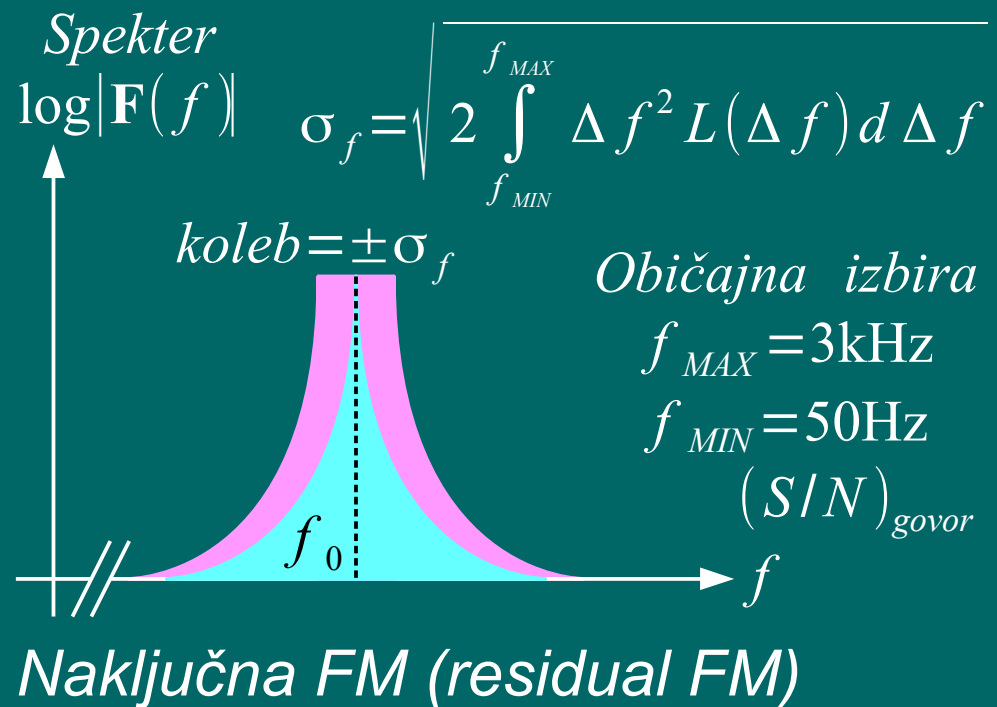
$Q_L \approx 30 \text{ (LC nihajni krog)}$

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

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

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

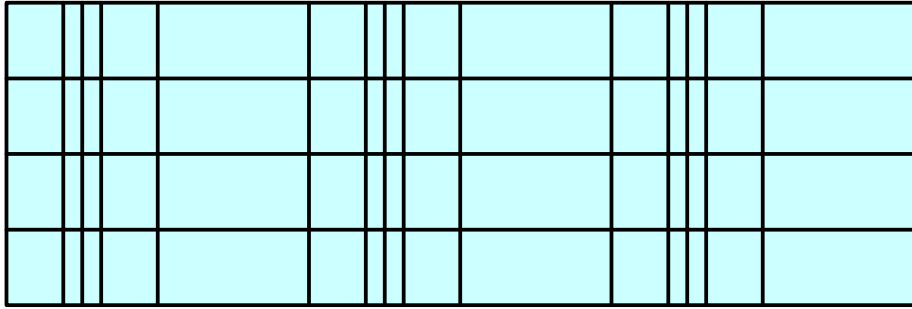
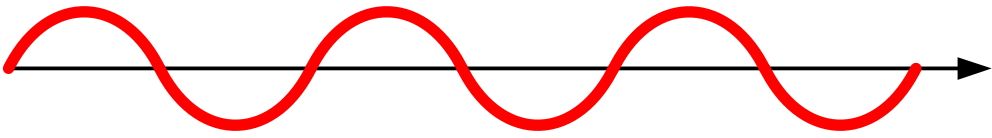
3 – Omejitve faznega šuma

- 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

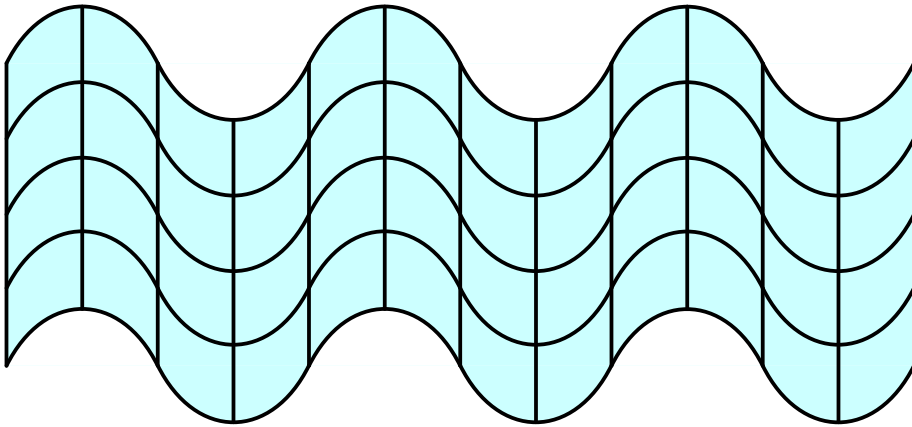
#### 4 – Zgodovina kvarca v elektroniki

## 5 – Mehanska valovanja

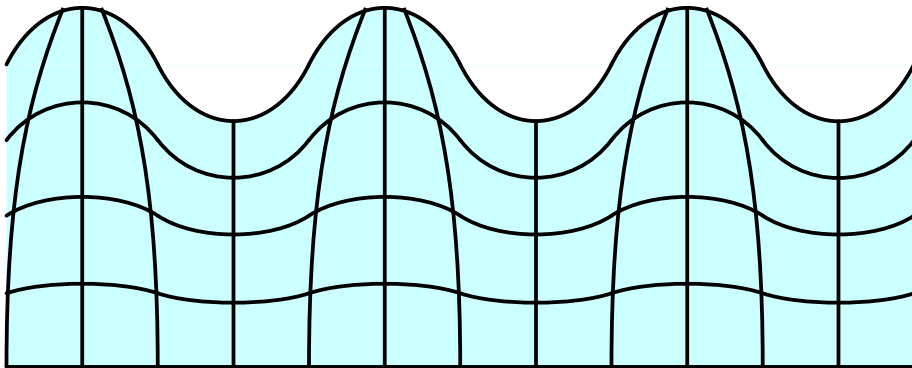
$v \approx 2\text{km/s} \dots 12\text{km/s}$  (*trdne snovi*)



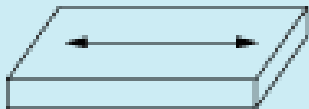
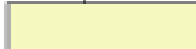
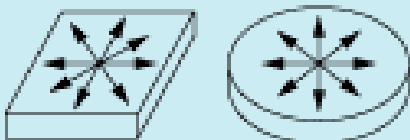
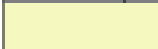
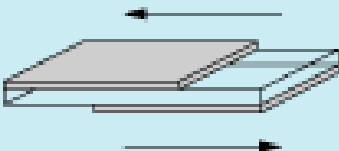
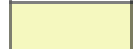
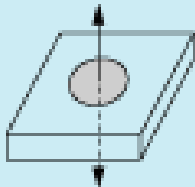
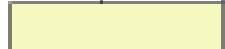
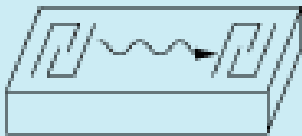
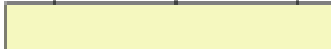
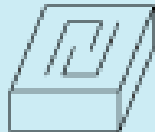
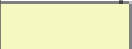
Tlačni val "P" (pressure wave)  
plini, tekočine, trdne snovi  
("BAW" bulk acoustic wave)



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                                          |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-----|------|----|------------------------------------------------------|
|    | <b>Flextural mode</b><br> |                                                                                                          |                                                                                                                   |                                                                                                                        |     |      |    | Piezoelectric buzzer                                 |
|    |                                                                                                            | <b>Length mode</b><br> |                                                                                                                   |                                                                                                                        |     |      |    | kHz Ceramic filter                                   |
|    |                                                                                                            |                                                                                                          | <b>Area expansion mode</b><br> |                                                                                                                        |     |      |    | kHz Ceramic resonator                                |
|    |                                                                                                            |                                                                                                          |                                                                                                                   | <b>Thickness shear mode</b><br>     |     |      |    | MHz Ceramic filter                                   |
|   |                                                                                                            |                                                                                                          |                                                                                                                   | <b>Thickness expansion mode</b><br> |     |      |    | MHz Ceramic resonator                                |
|  |                                                                                                            |                                                                                                          |                                                                                                                   | <b>Surface Acoustic Wave</b><br>  |     |      |    | SAW filter<br>SAW resonator                          |
|  |                                                                                                            |                                                                                                          |                                                                                                                   | <b>BGS Wave/SH Wave</b><br>       |     |      |    | HF trap<br>HF Ceramic resonator<br>HF Ceramic filter |

↔ Vibration Modes

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

Tališče  
1670°C

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

$T > 573^\circ\text{C}$   
 $\beta$ -kvarc

Mehanski  
 $Q > 10^6$

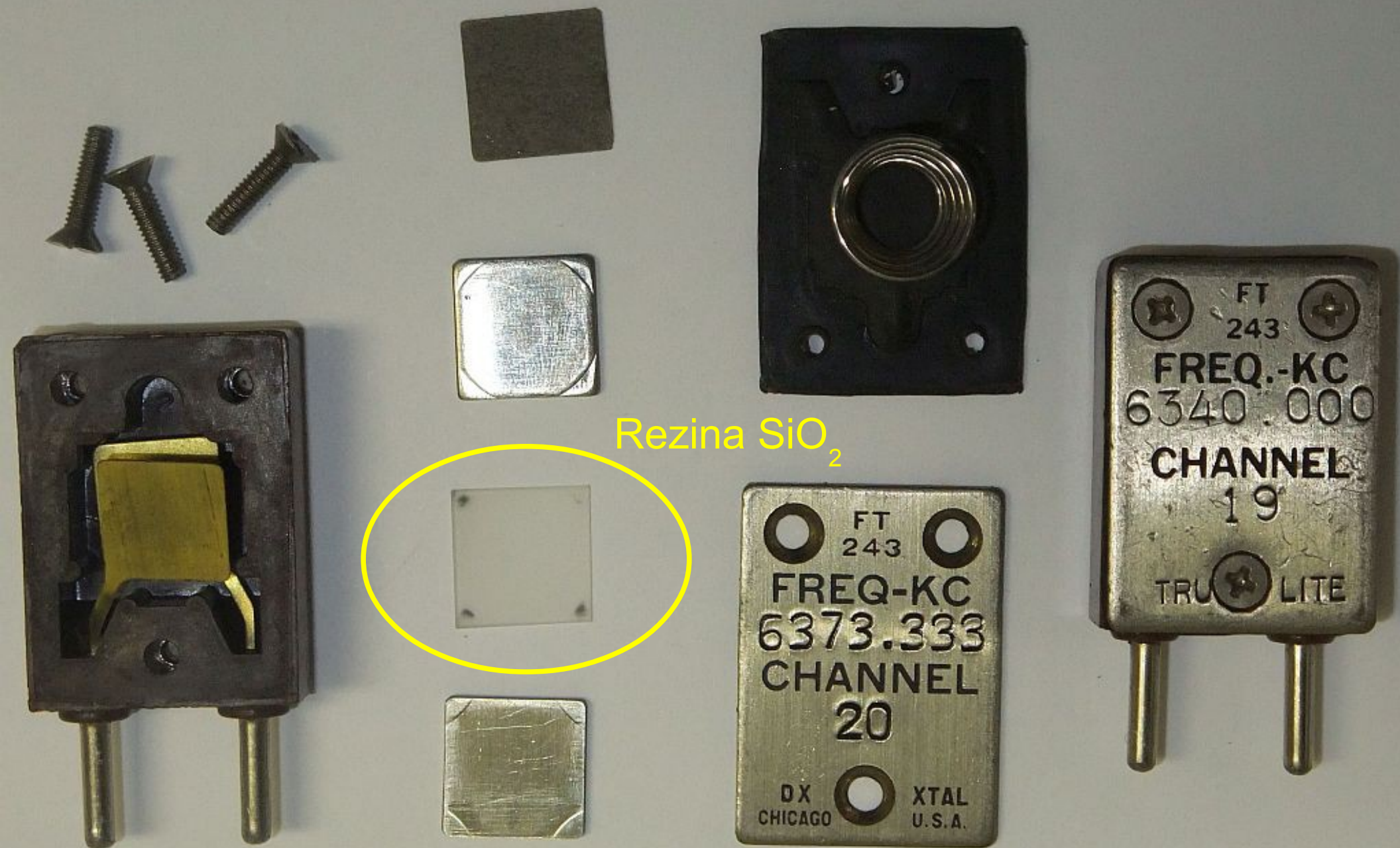
Piezoelektrik



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  $\alpha$ -kvarc



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

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

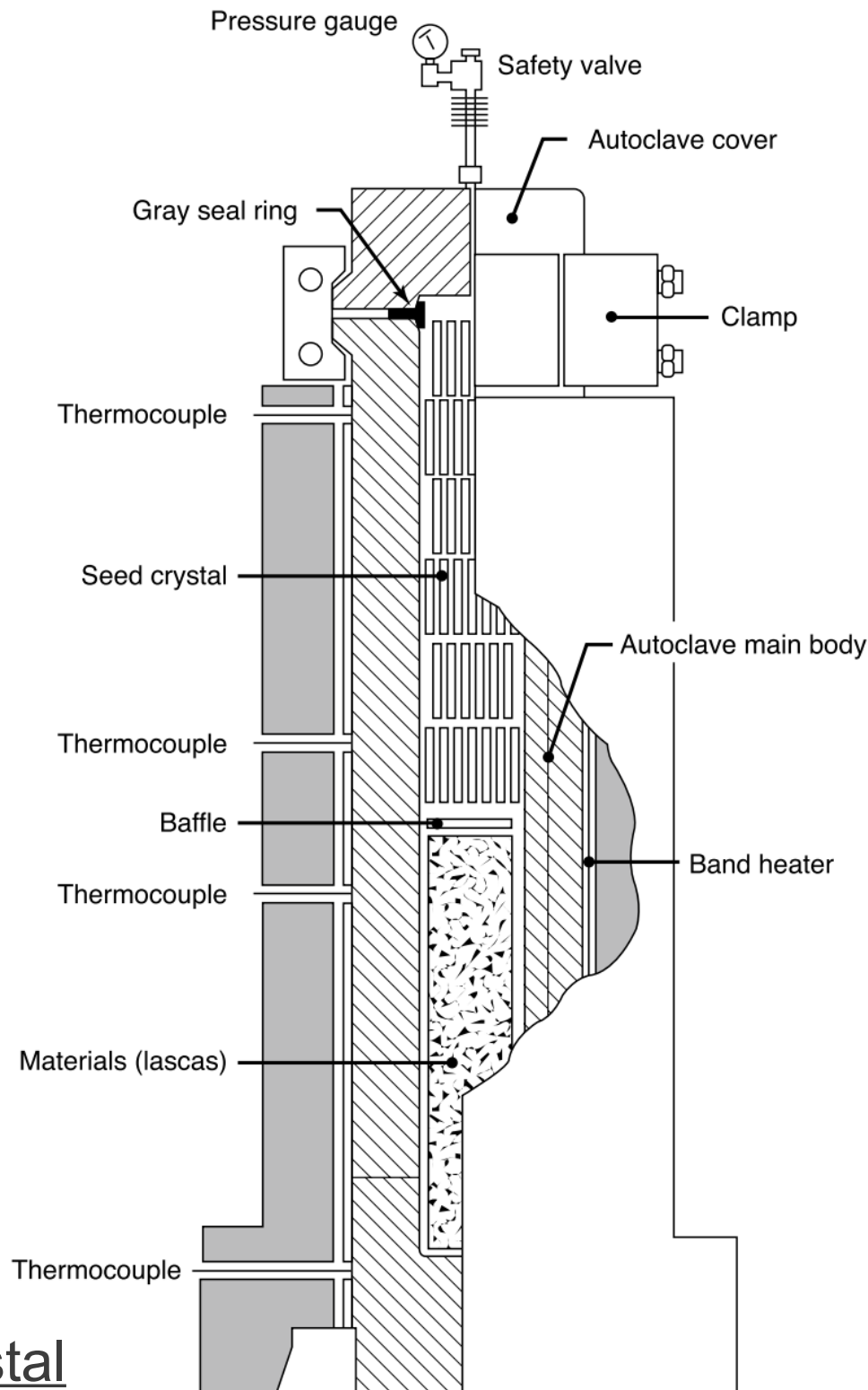
$$v_{\text{rast}}(z) \approx 0.4\text{mm/dan}$$

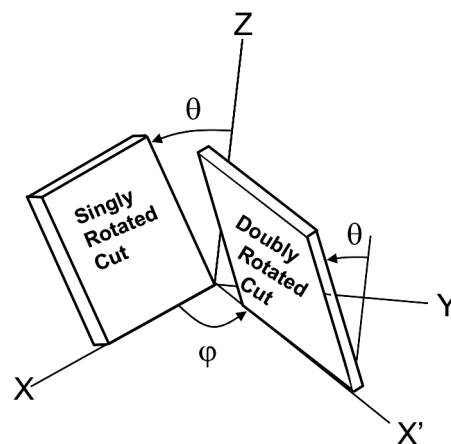
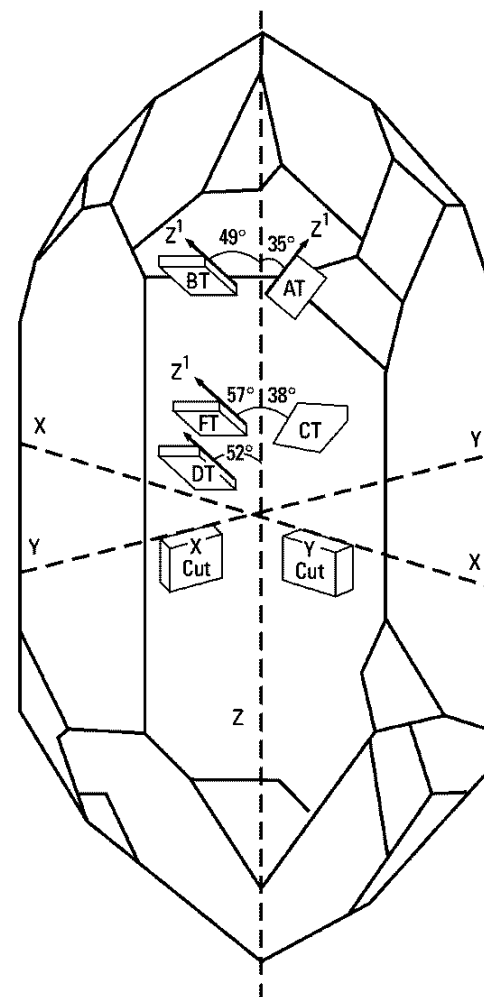
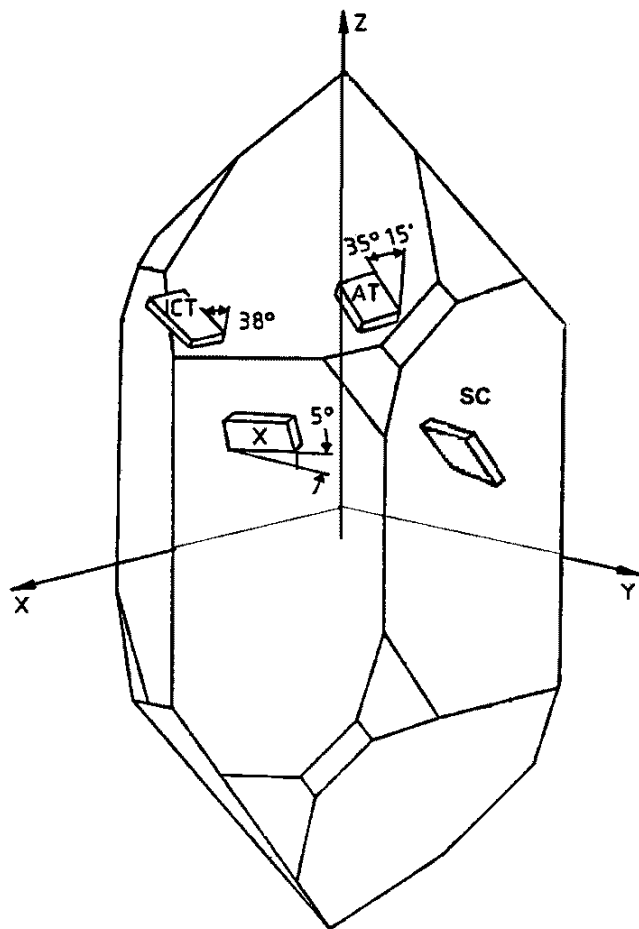
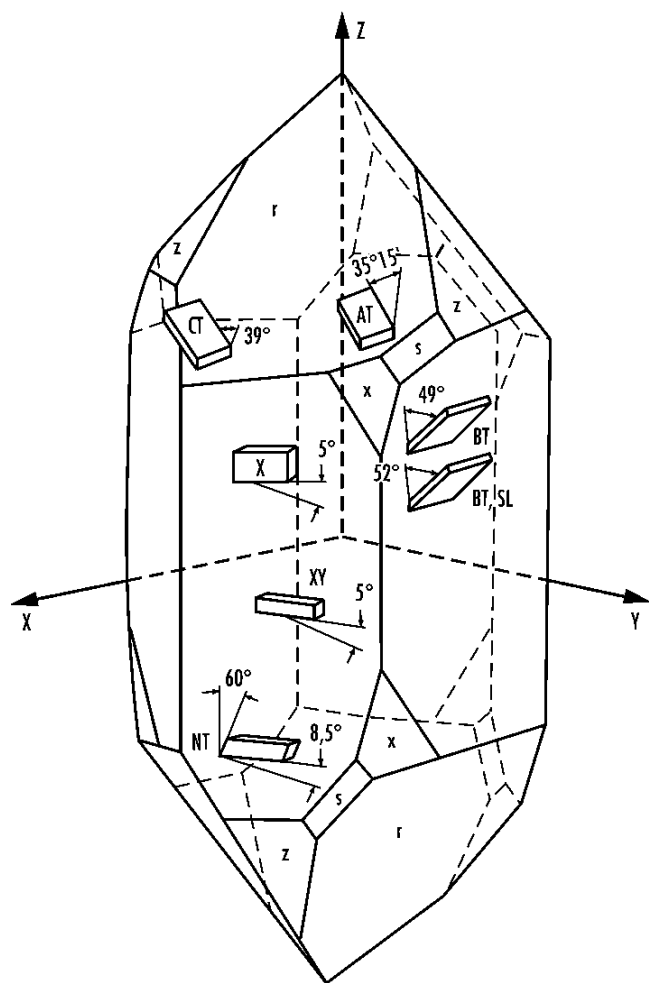


$p \approx 1000\text{--}1500\text{bar}$

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

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



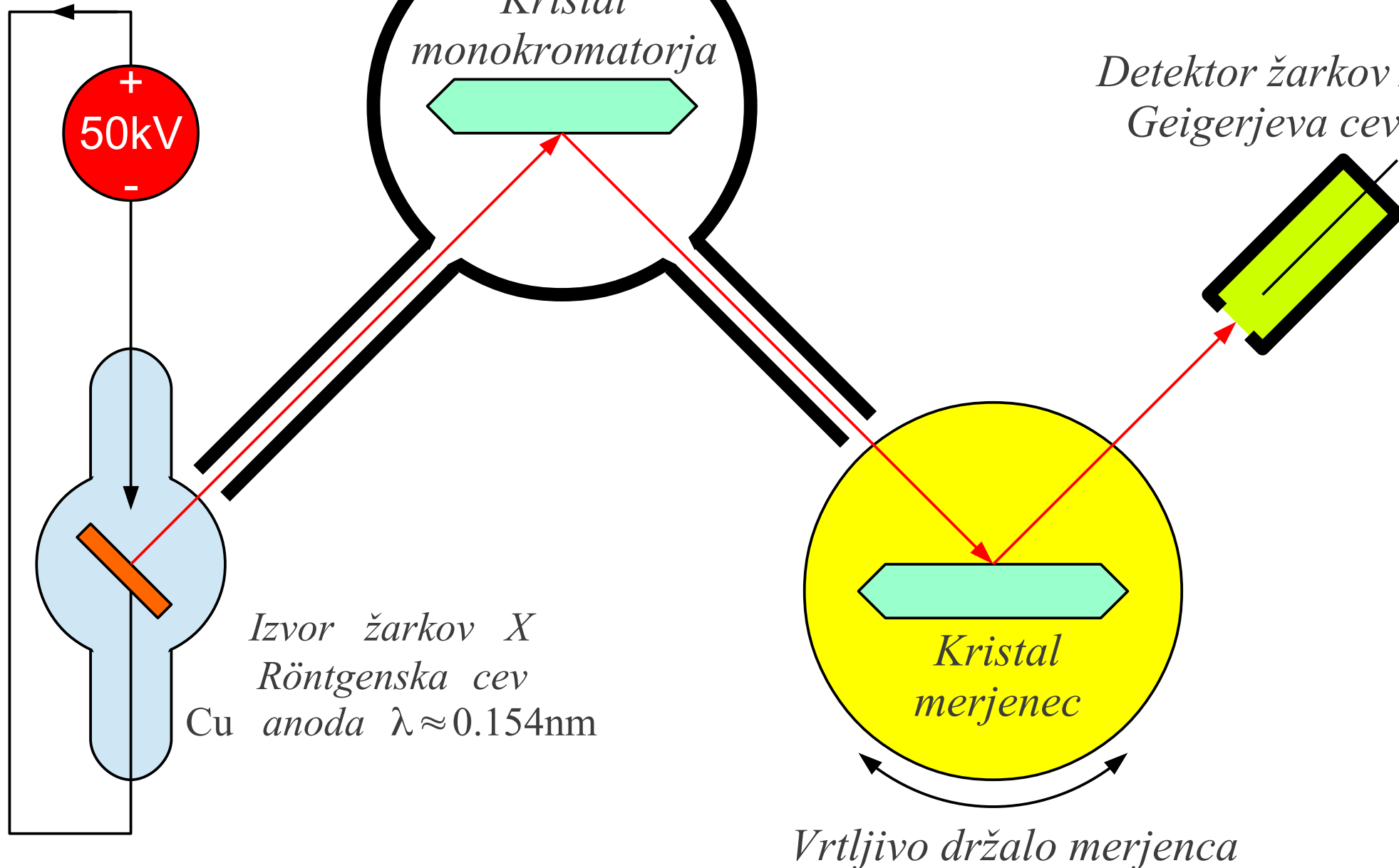


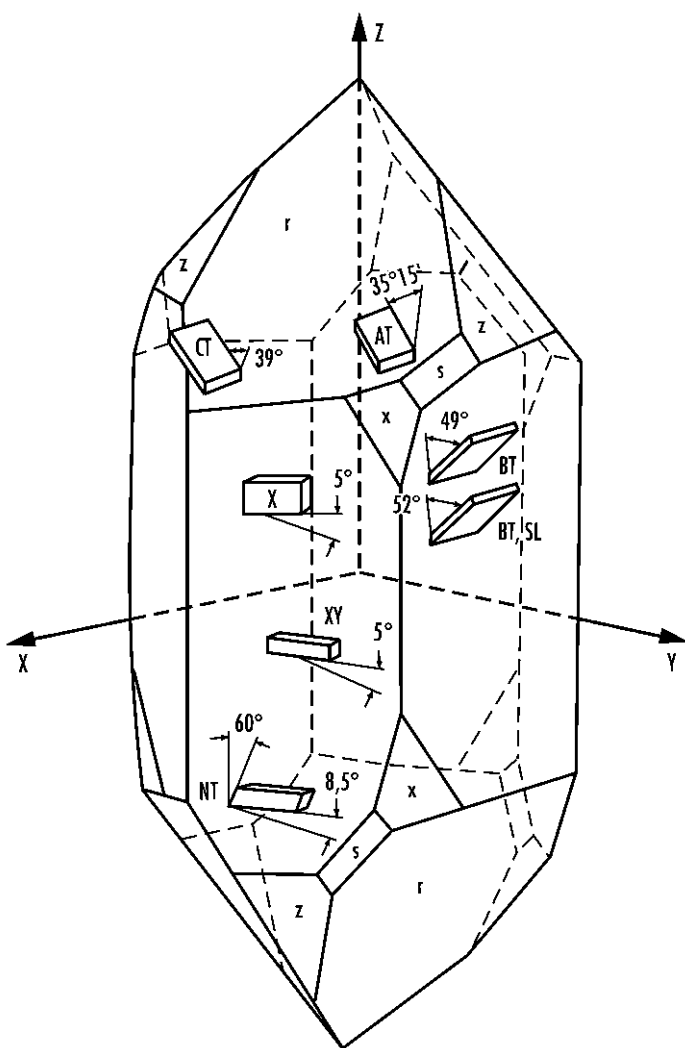
*Pb oklop za žarke X*

$I \approx 10\text{mA}$

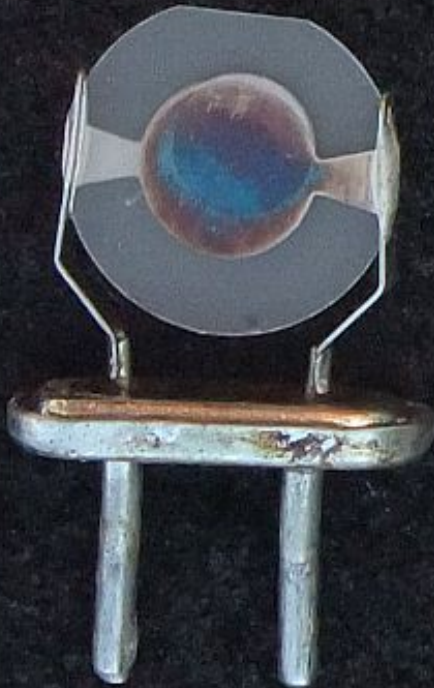
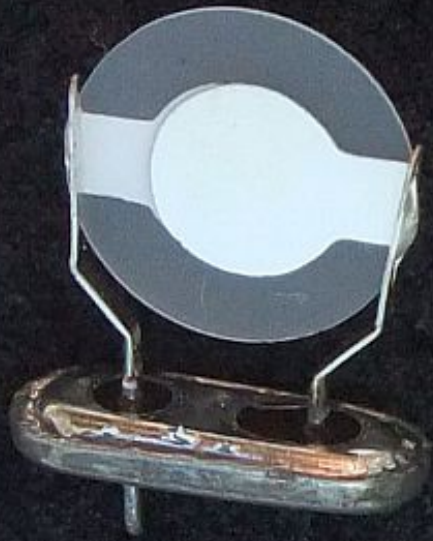
*Kristal  
monokromatorja*

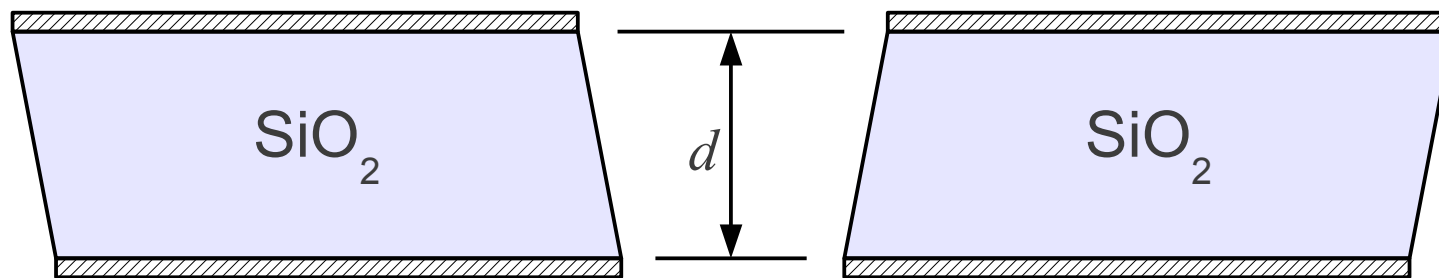
*Detektor žarkov X  
Geigerjeva cev*



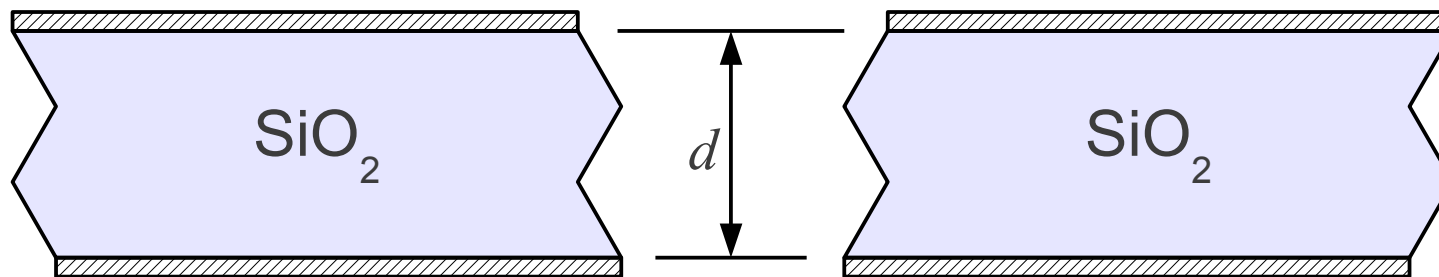


| Vibration Mode  | Orientation Angle                                                                              |
|-----------------|------------------------------------------------------------------------------------------------|
| Tuning Fork     | $+ 2^{\circ} X$                               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

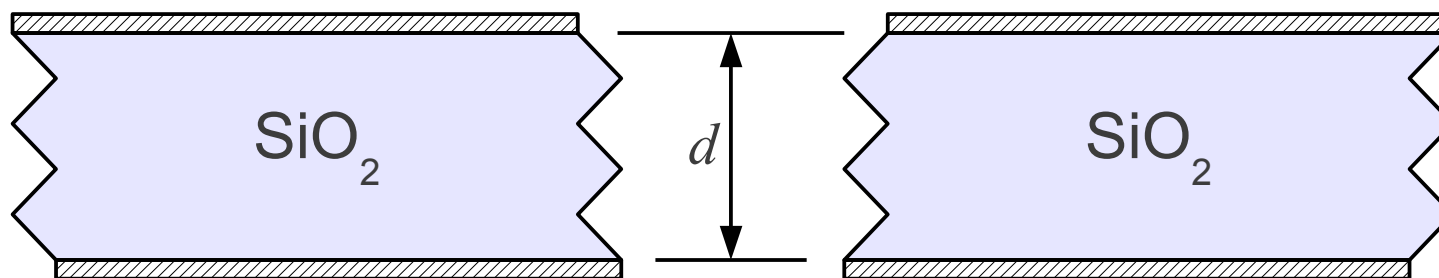




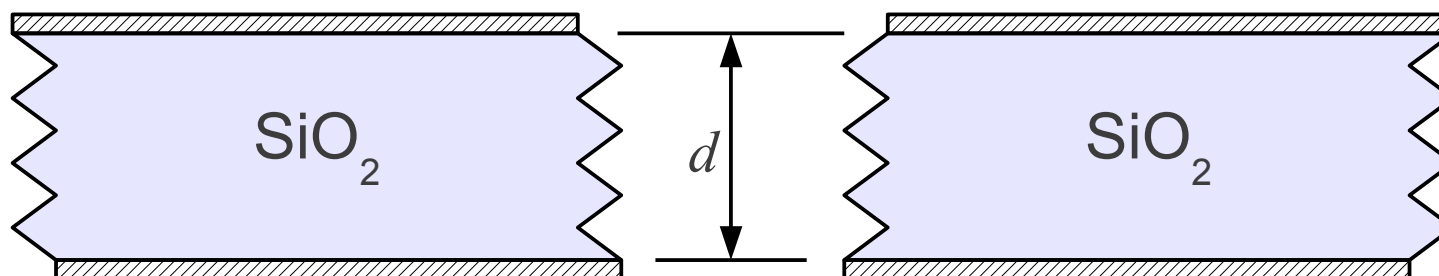
Osnovna  
rezonanca  
 $f_1 \approx v/2d$



Tretji  
overton  $\sim 3f_1$

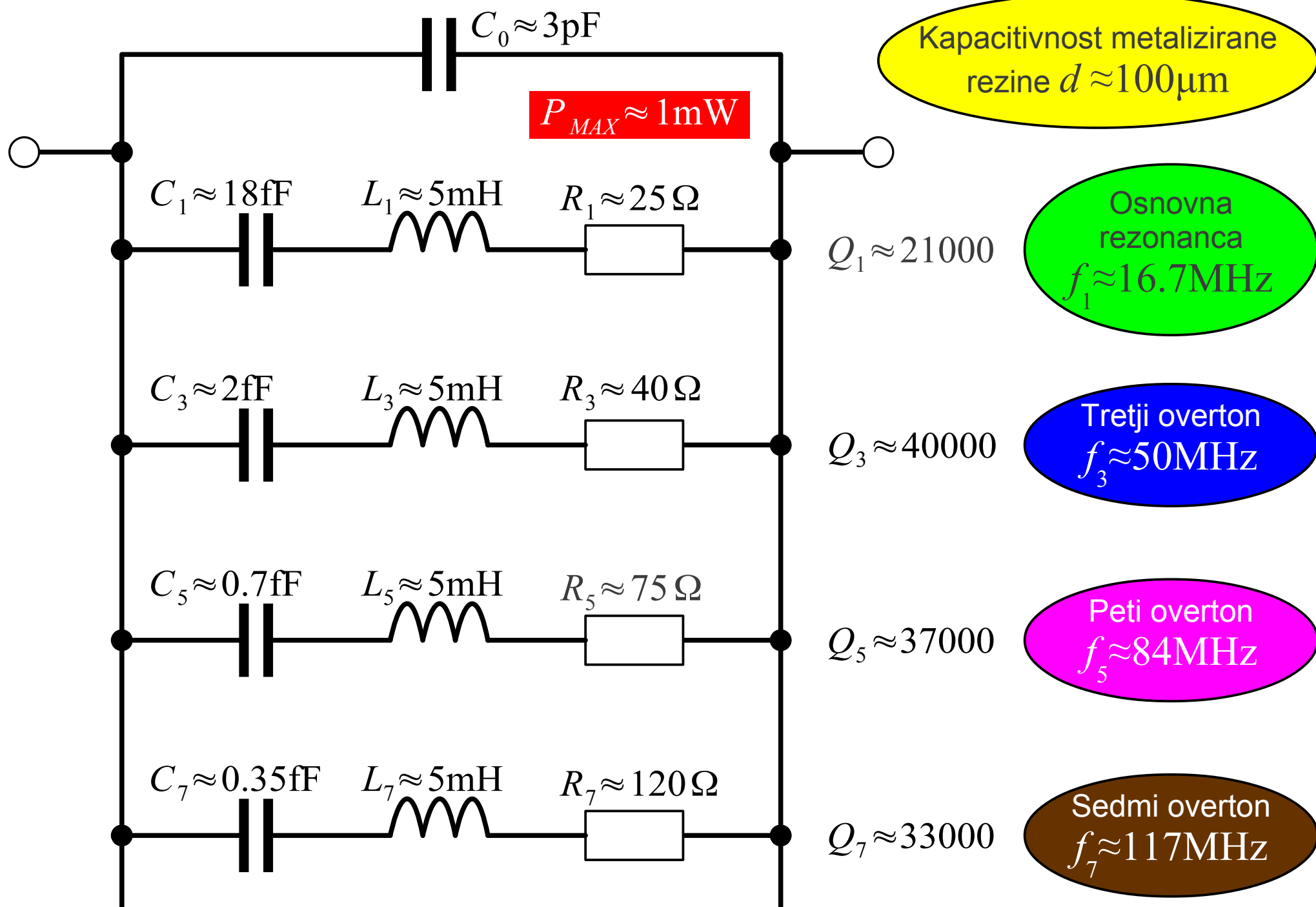


Peti  
overton  $\sim 5f_1$



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  $f_7$**

$1/R_3$

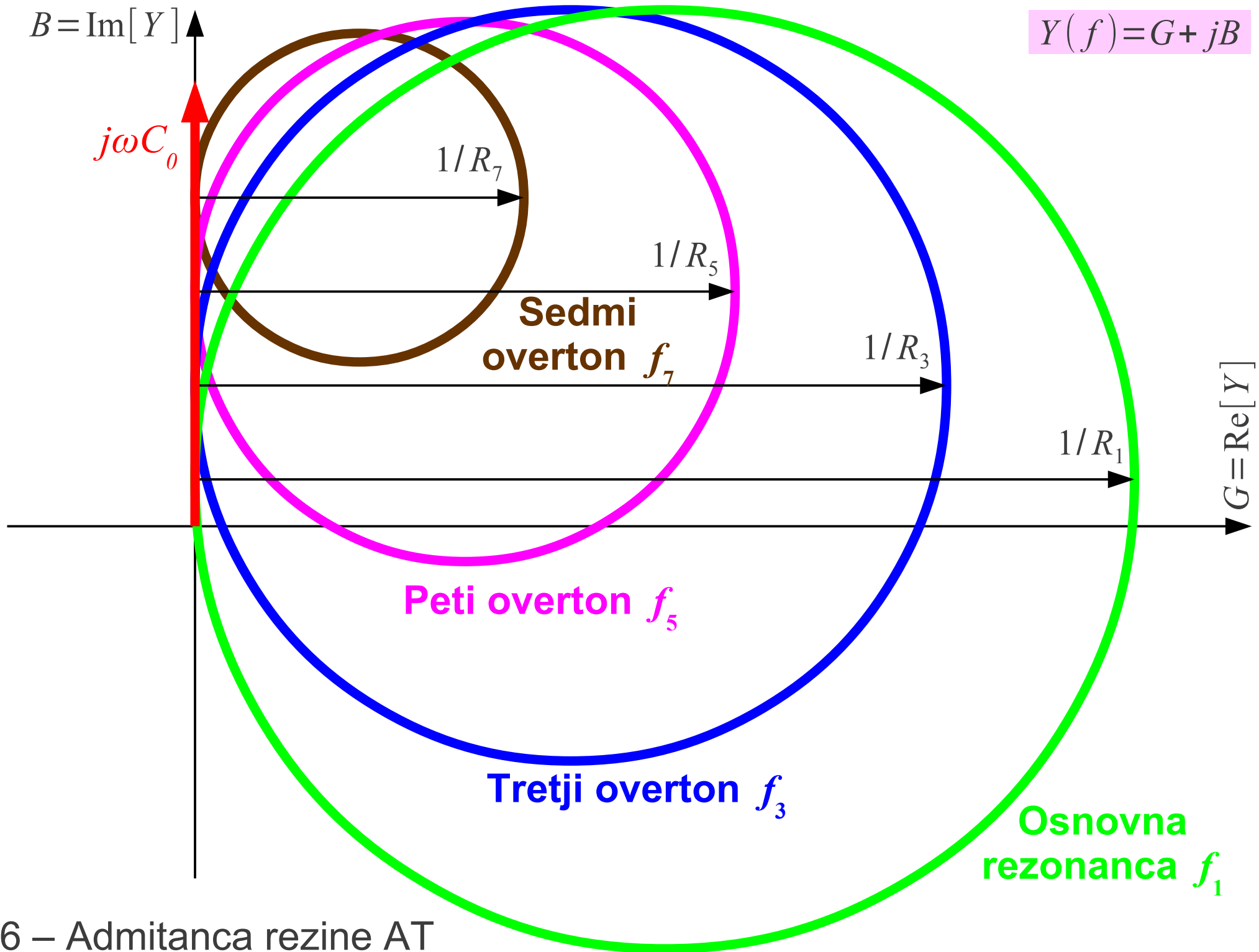
$1/R_1$

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

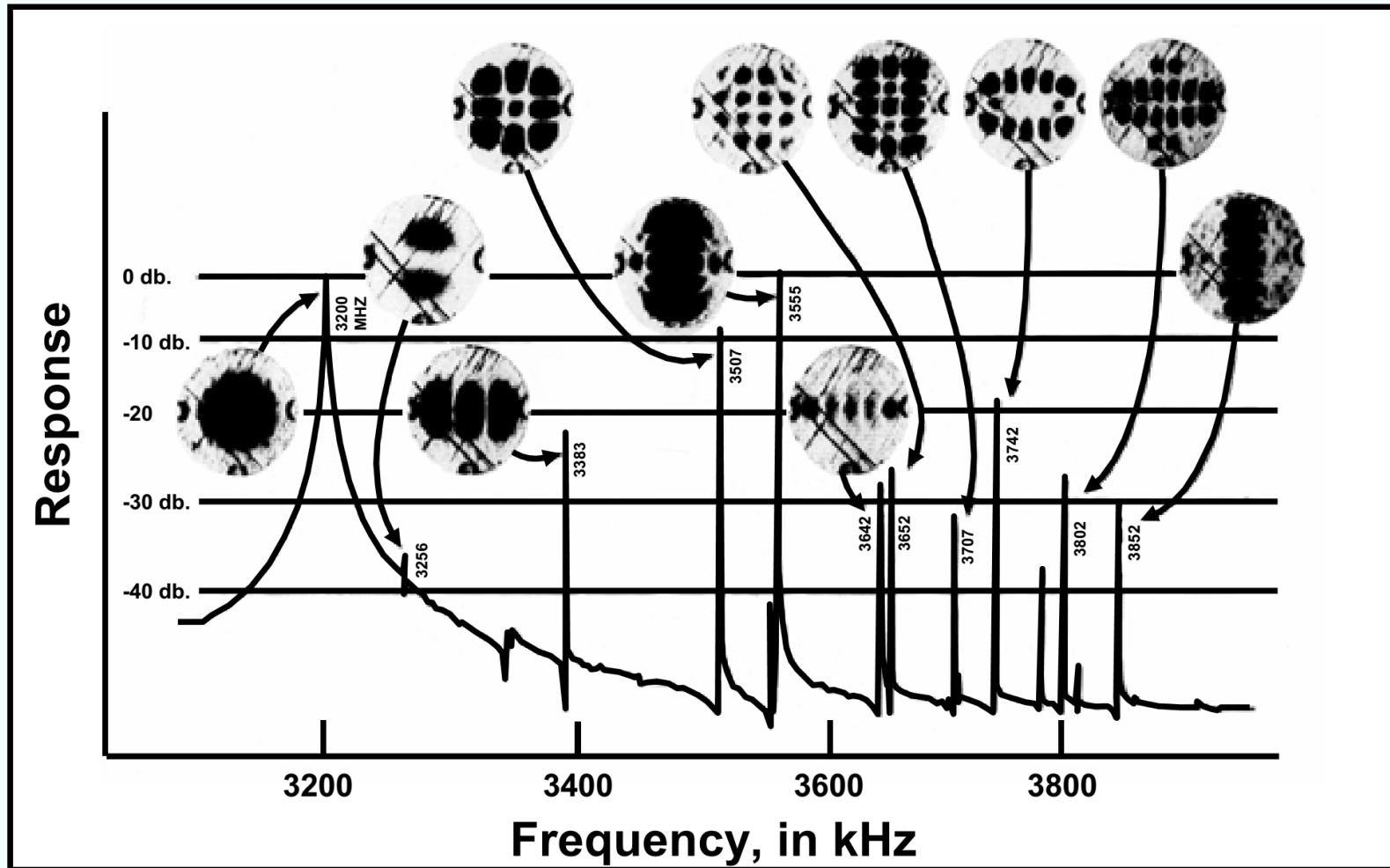
**Peti overtone  $f_5$**

**Tretji overtone  $f_3$**

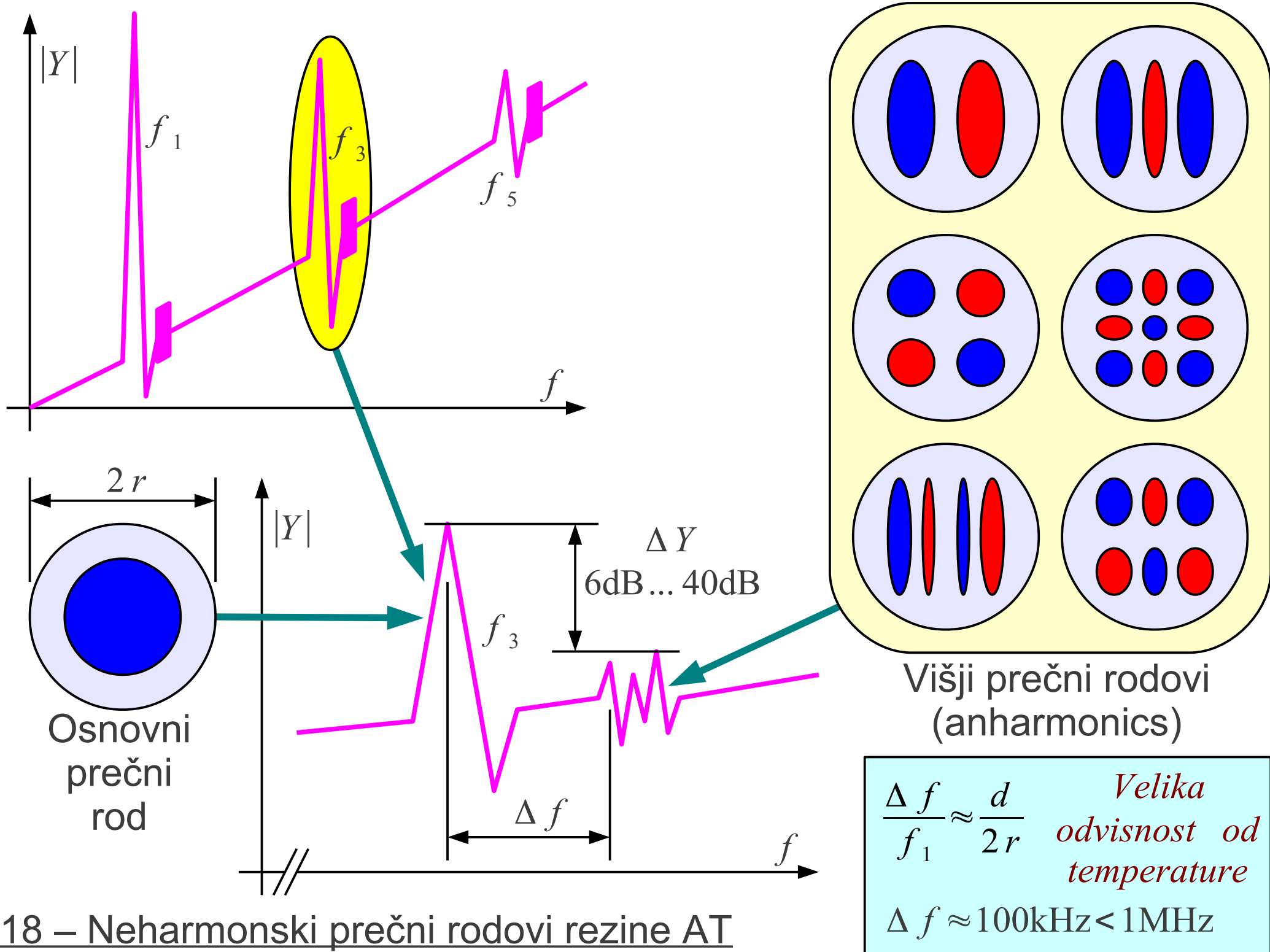
**Osnovna  
rezonanca  $f_1$**



# 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.

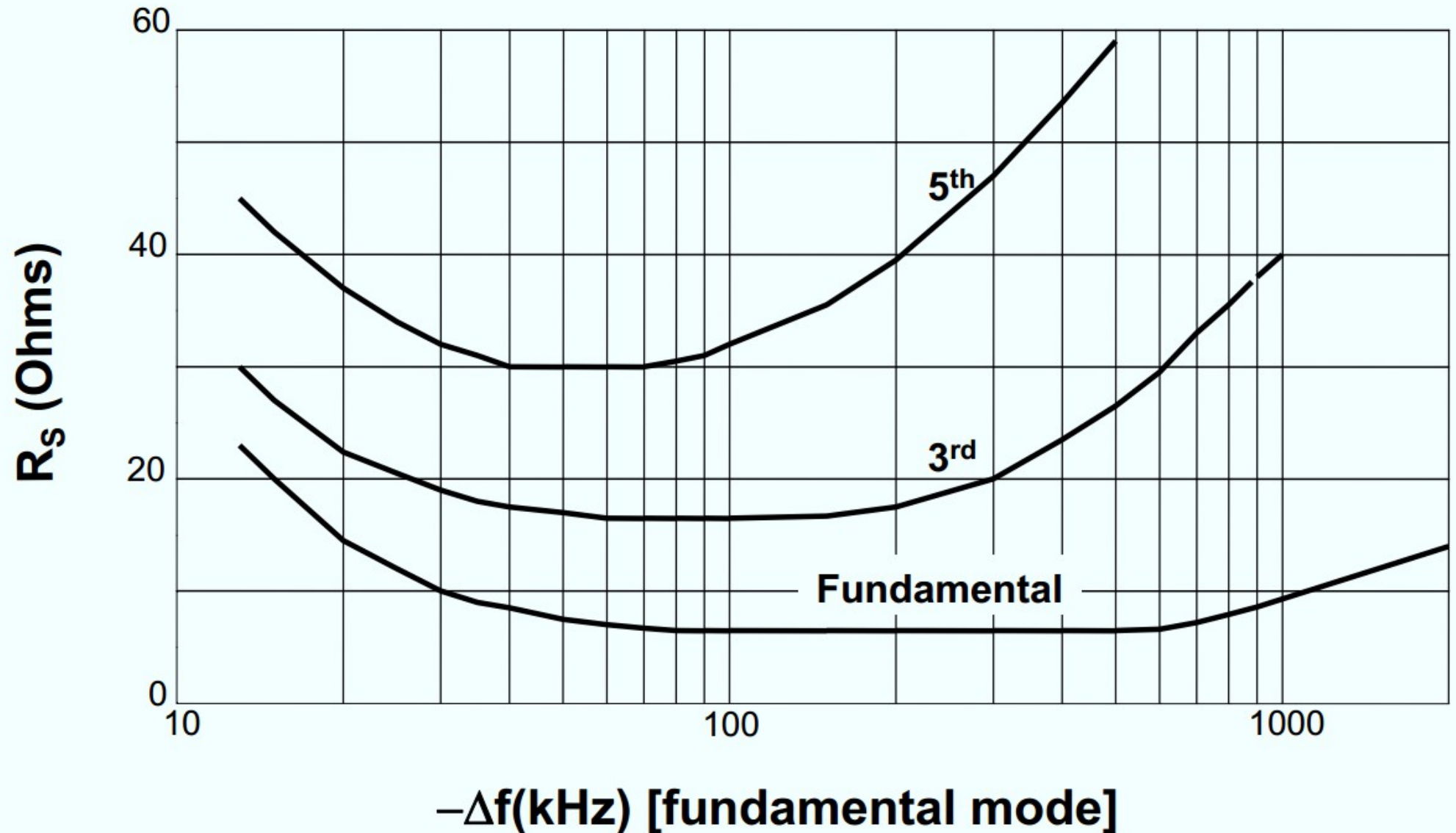


18 – Neharmonski prečni rodovi rezine AT

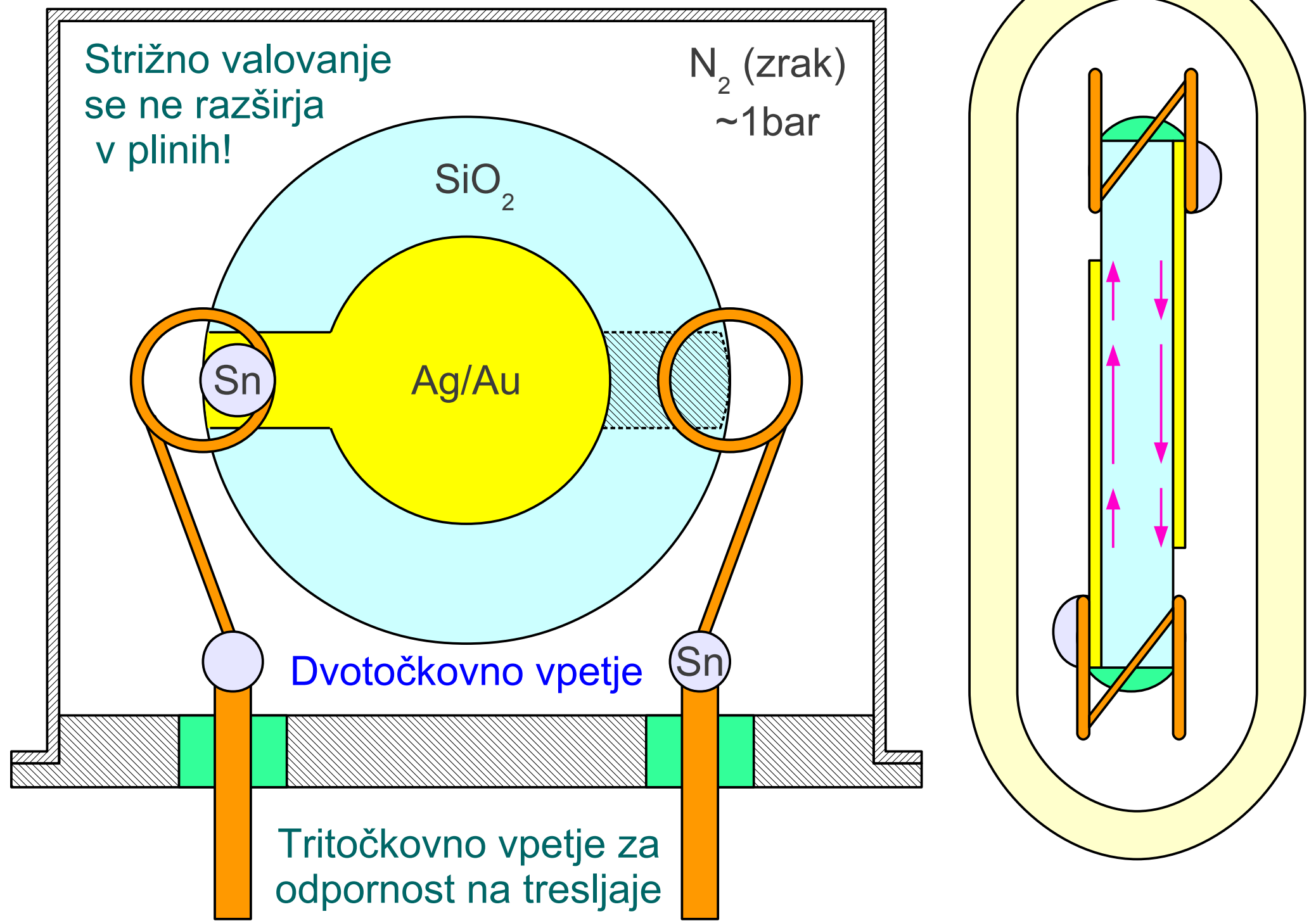


# Resistance vs. Electrode Thickness

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

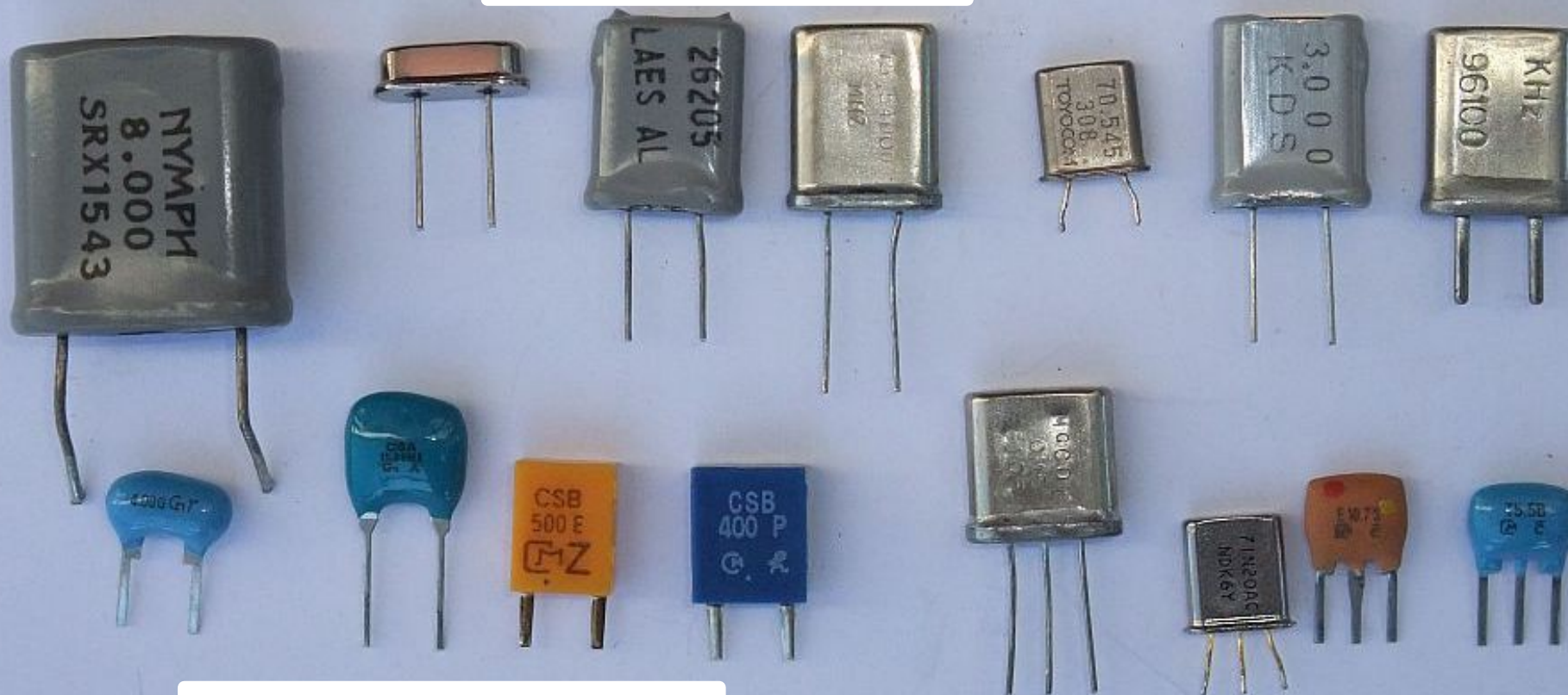


21 – Vgradnja rezine AT v ohišje



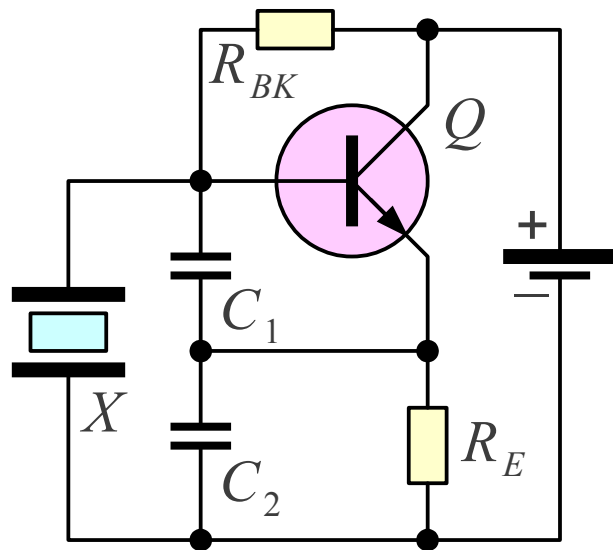


Kremenčevi kristali

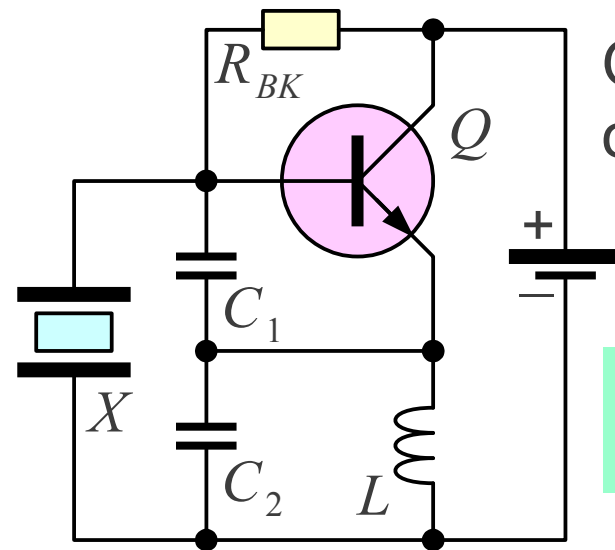


Keramični rezonatorji

Večkratni rezonatorji

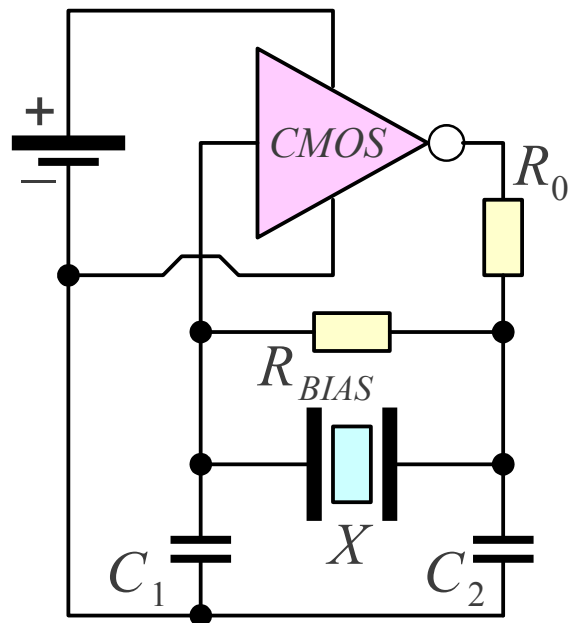


Pierce (Colpitts) na osnovni frekvenci  $f_1$



Overtonski oscilator  $f_3$

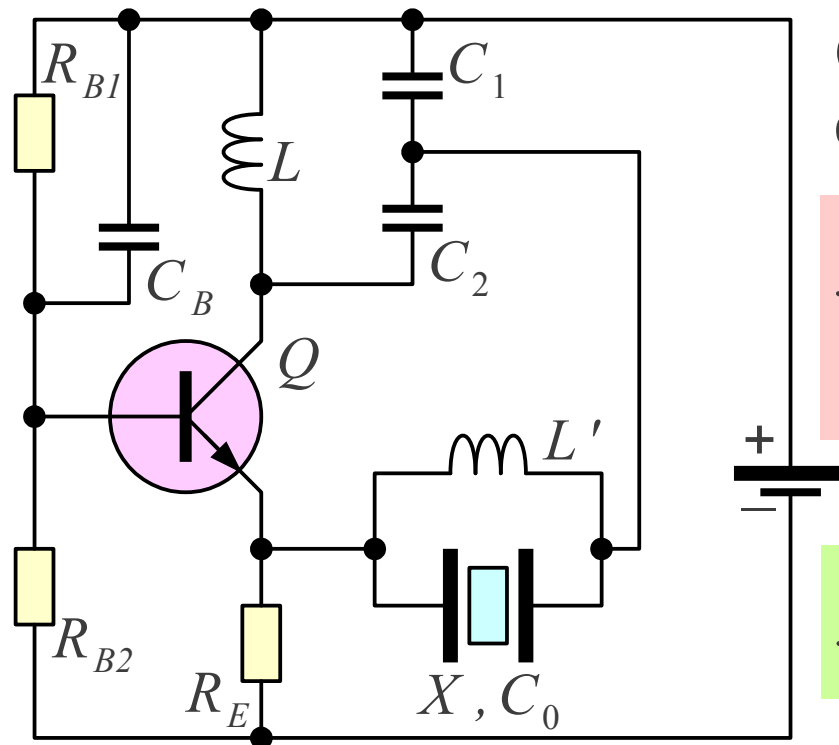
$$f_1 < \frac{1}{\sqrt{LC}} < f_3$$



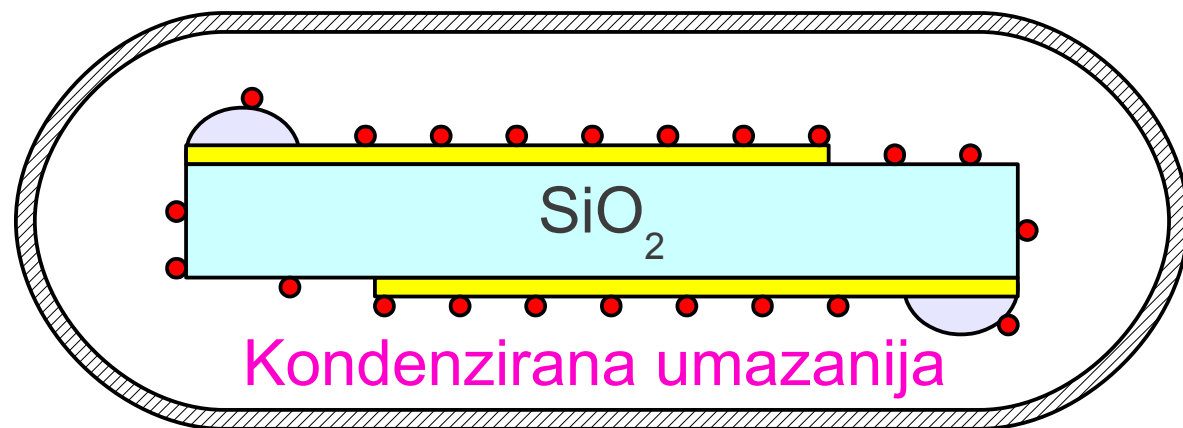
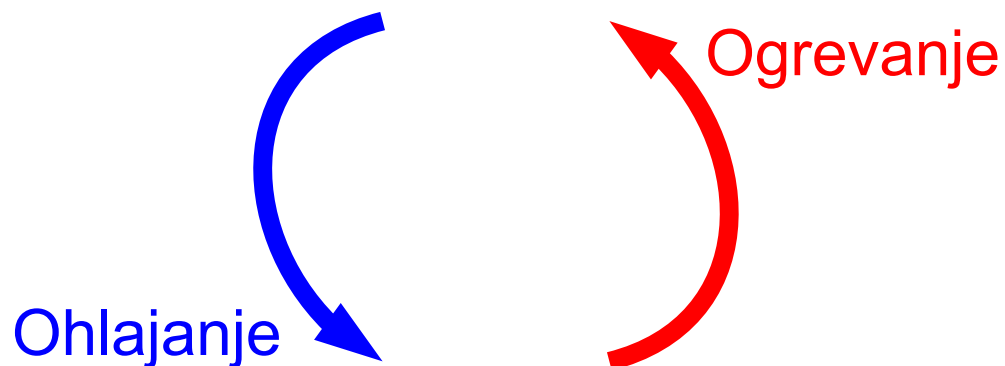
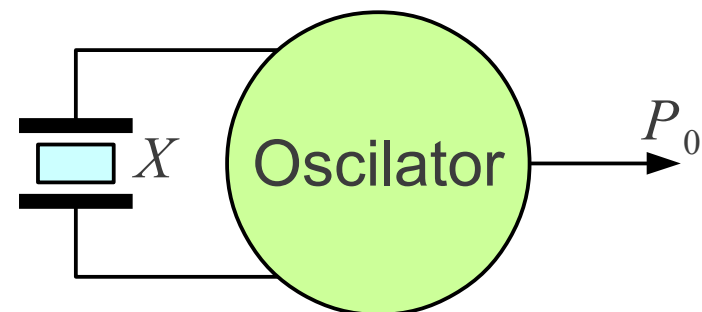
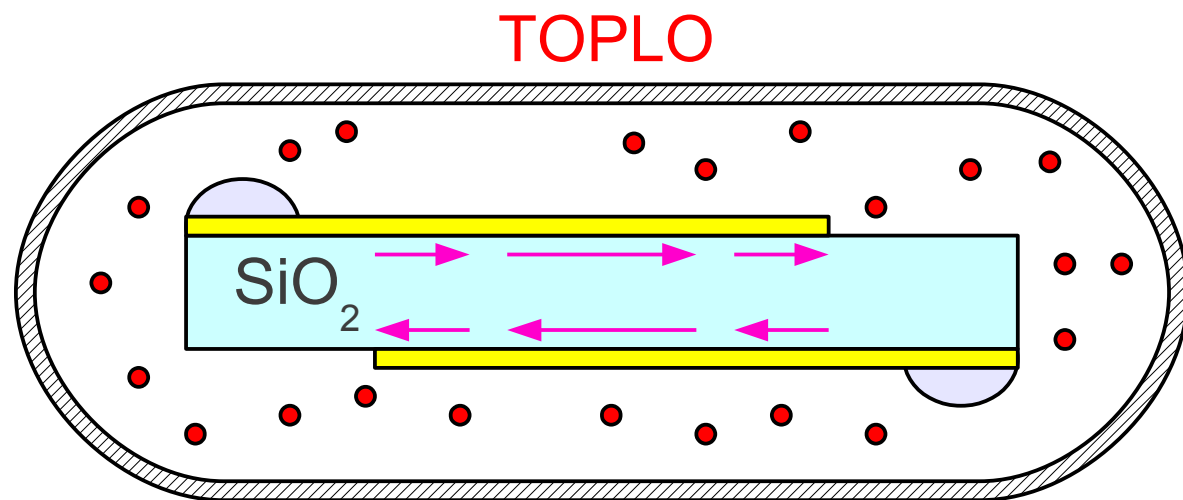
Overtonski oscilator  $f_5$

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

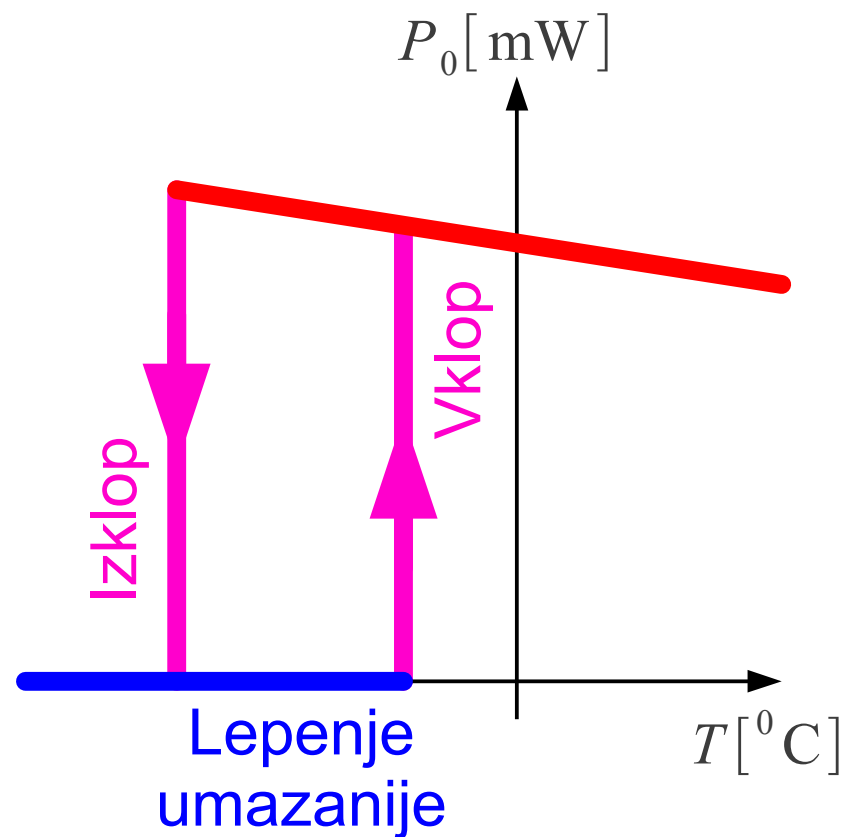
$$f_5 = \frac{1}{\sqrt{L' C_0}}$$

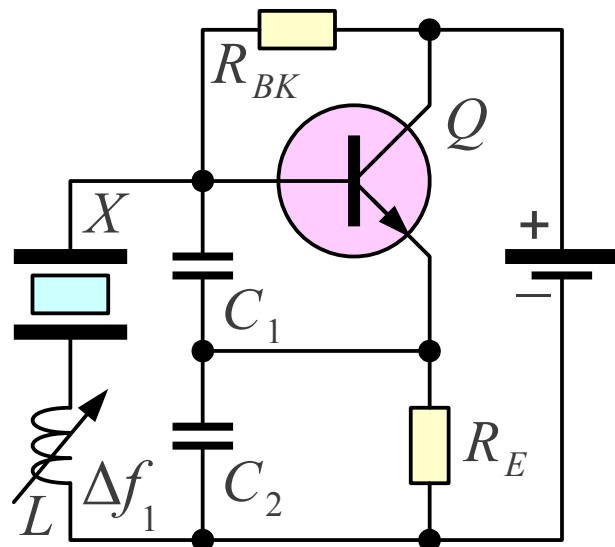


$$f_5 = \frac{1}{\sqrt{L' C_0}}$$

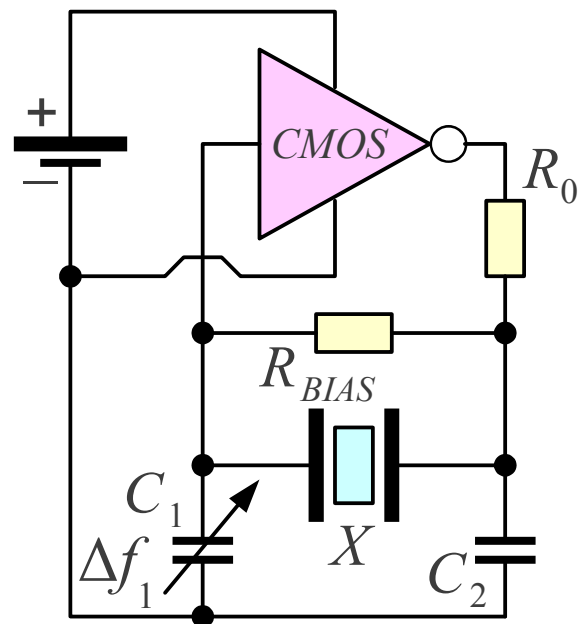


**HLADNO**

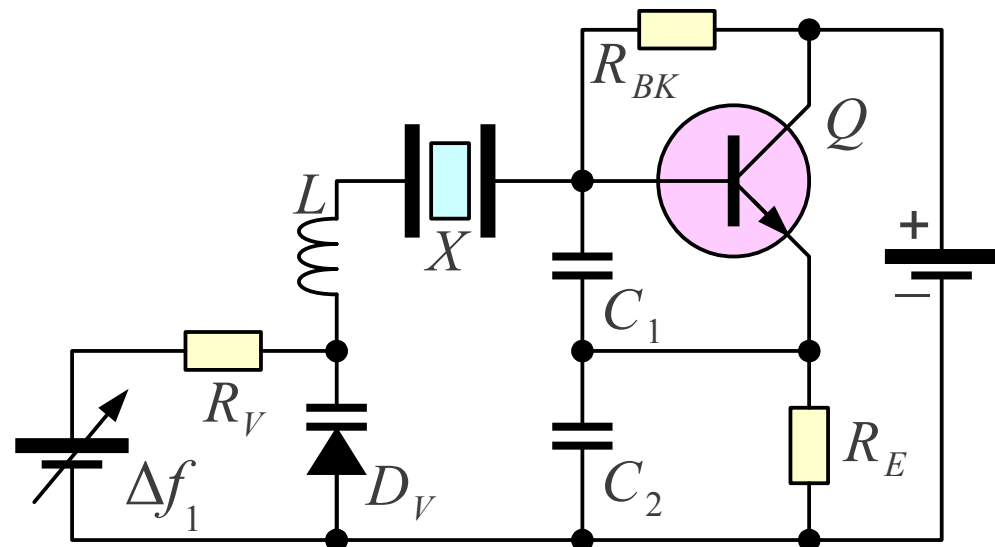




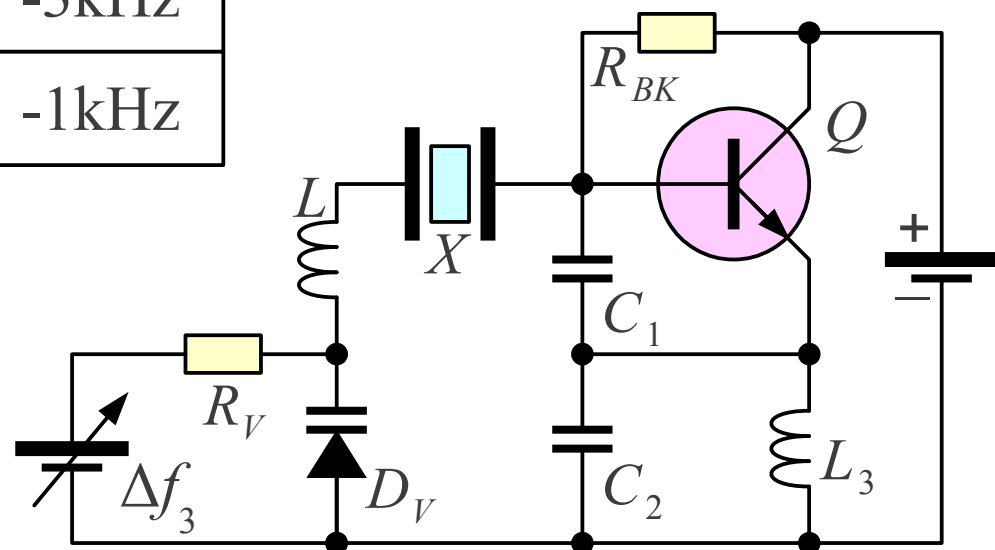
Nastavljivi kristalni oscilator VXO

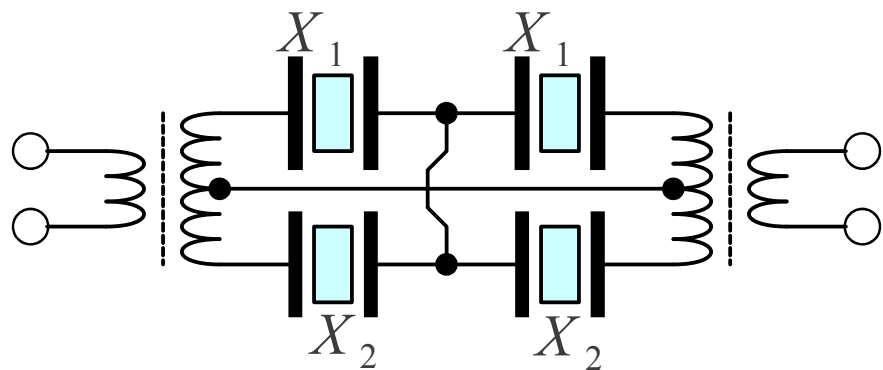


|              | $\epsilon$ | $L$    |
|--------------|------------|--------|
| $\Delta f_1$ | +10kHz     | -30kHz |
| $\Delta f_3$ | +1kHz      | -3kHz  |
| $\Delta f_5$ | +300Hz     | -1kHz  |

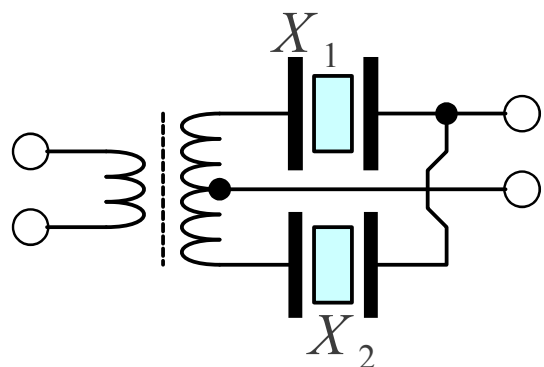


Napetostno nastavljivi kristalni oscilator VCXO

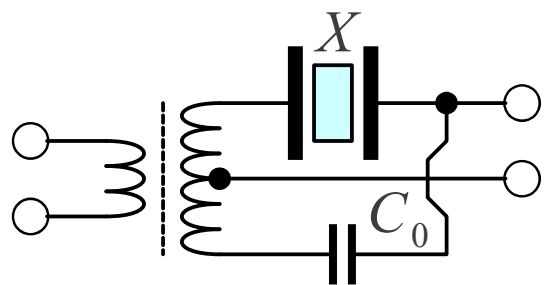




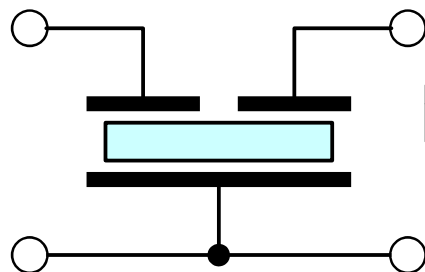
Dvojno mostično pasovno sito



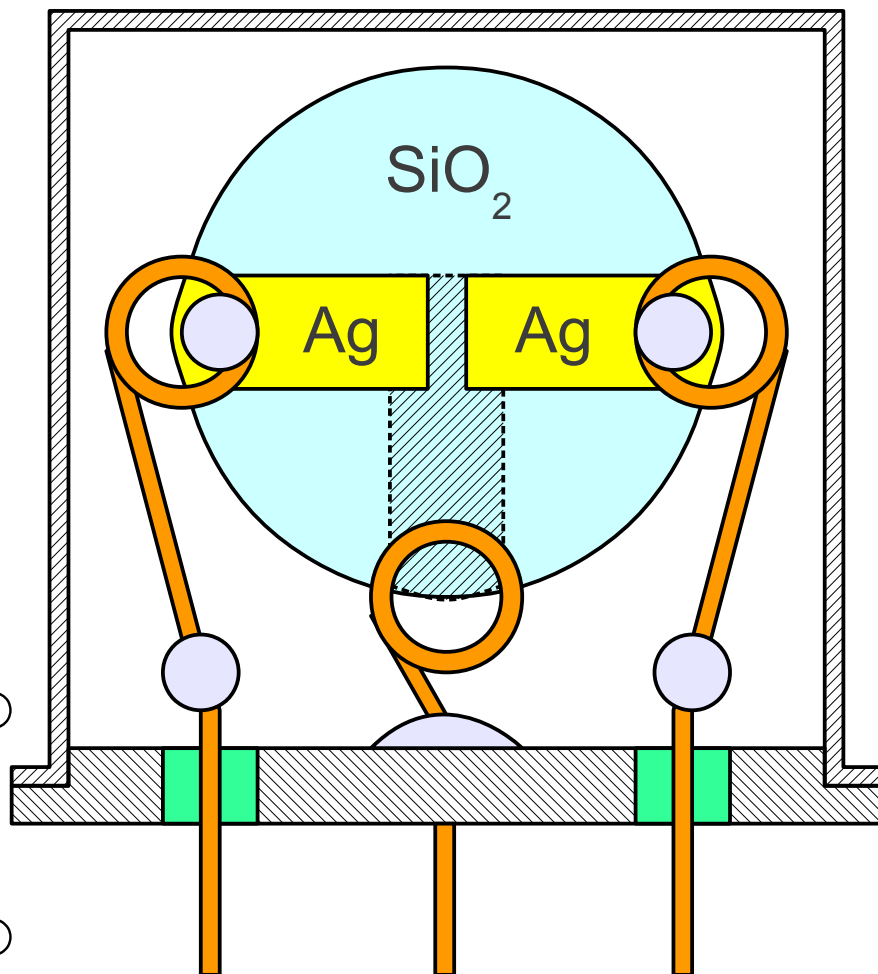
Mostično pasovno sito



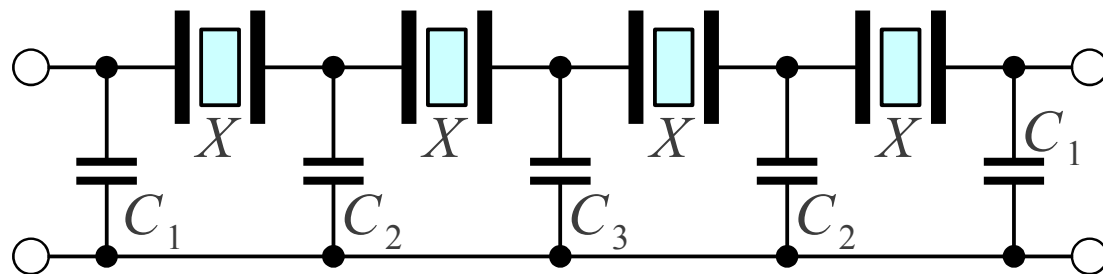
Preprosto pasovno sito



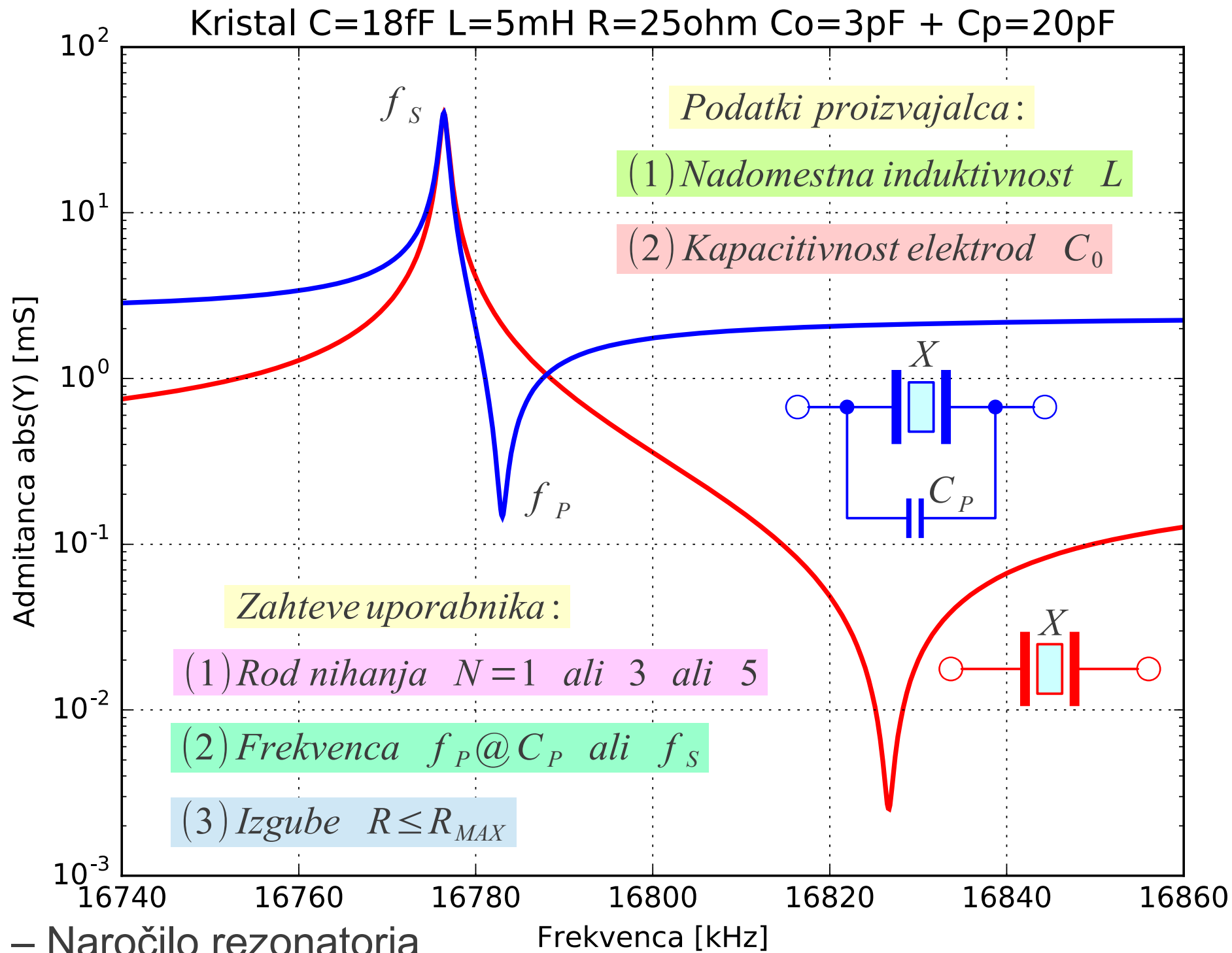
Monolitno pasovno sito

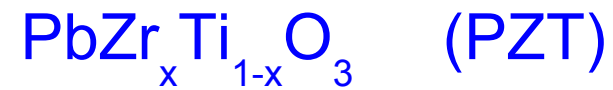
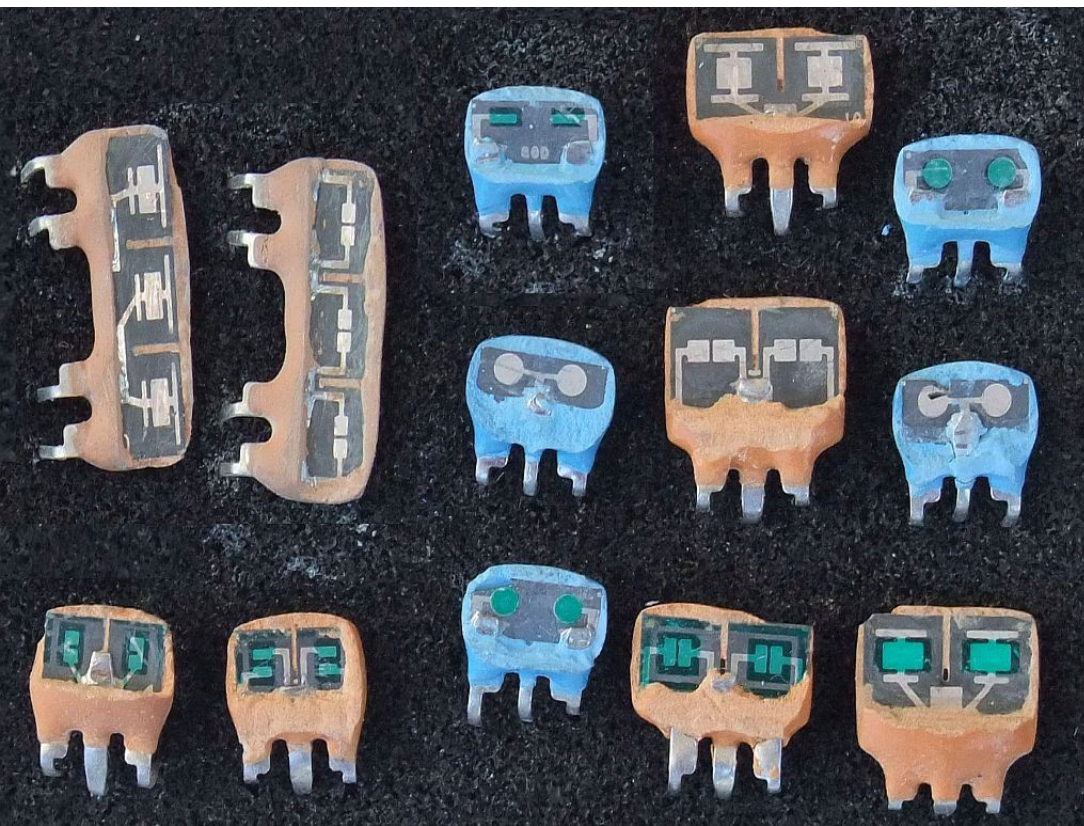
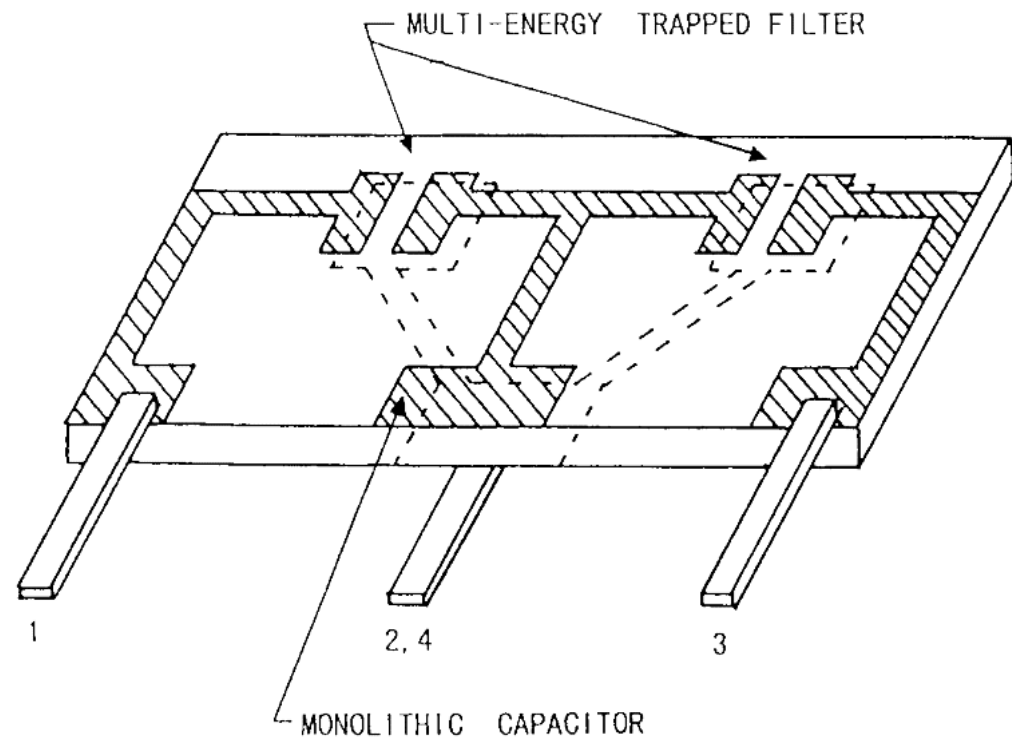
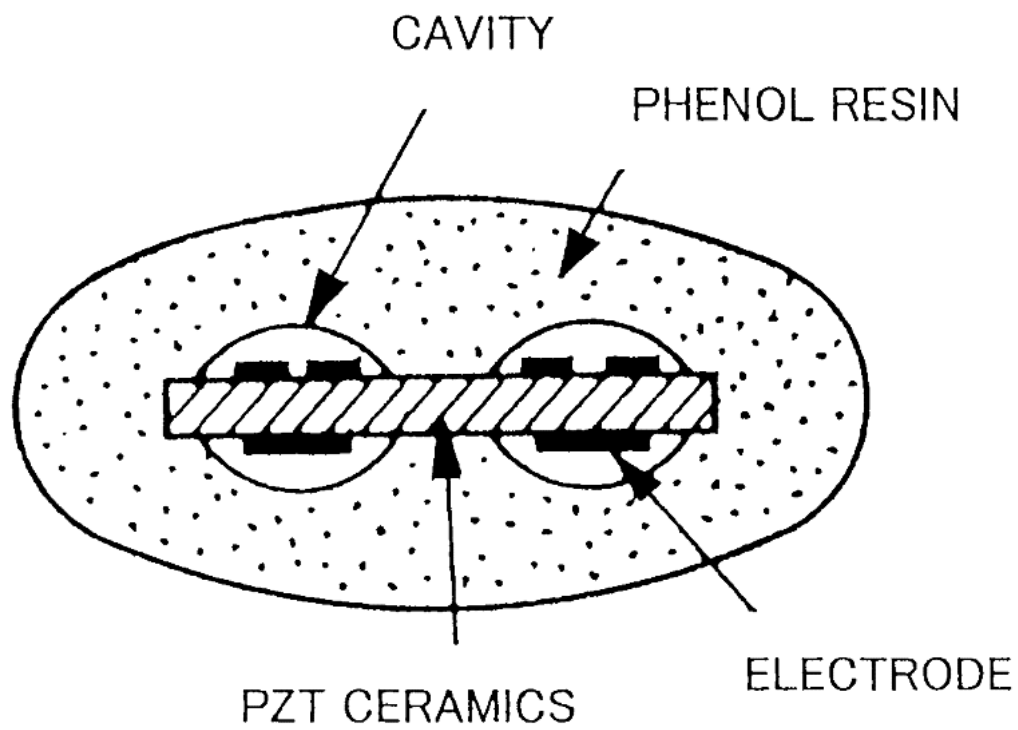


$$200\text{Hz} \leq B \leq 50\text{kHz}$$



Lestvičasto pasovno sito





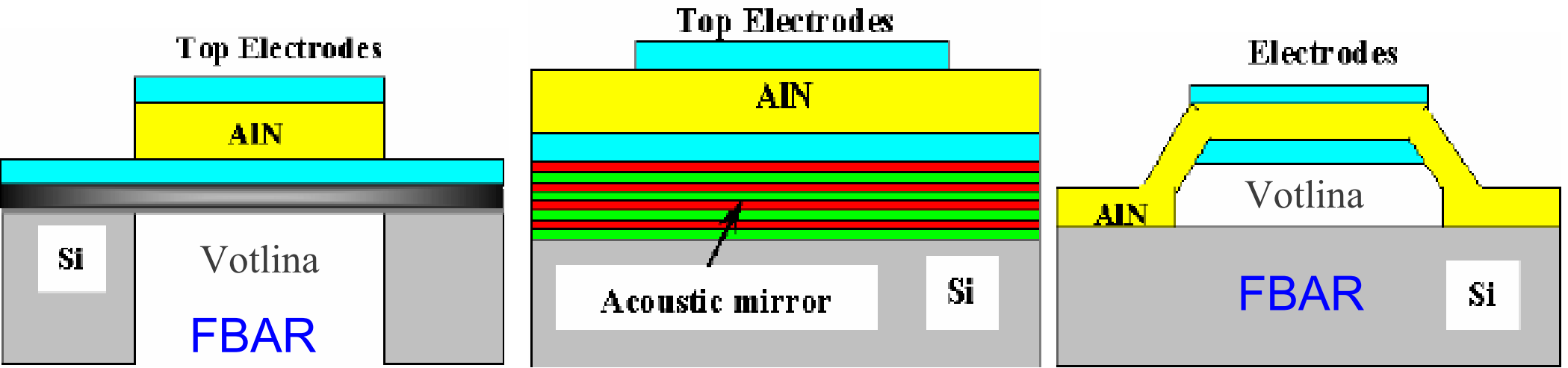
$$x \approx 0.52$$

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

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

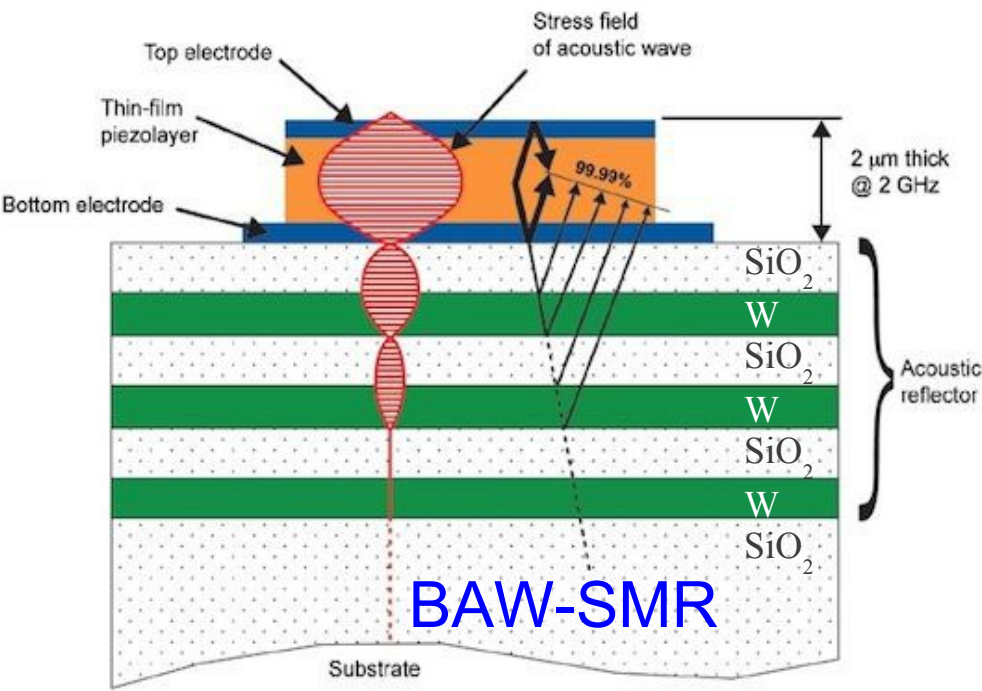
# Film Bulk Acoustic Resonator (FBAR)

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



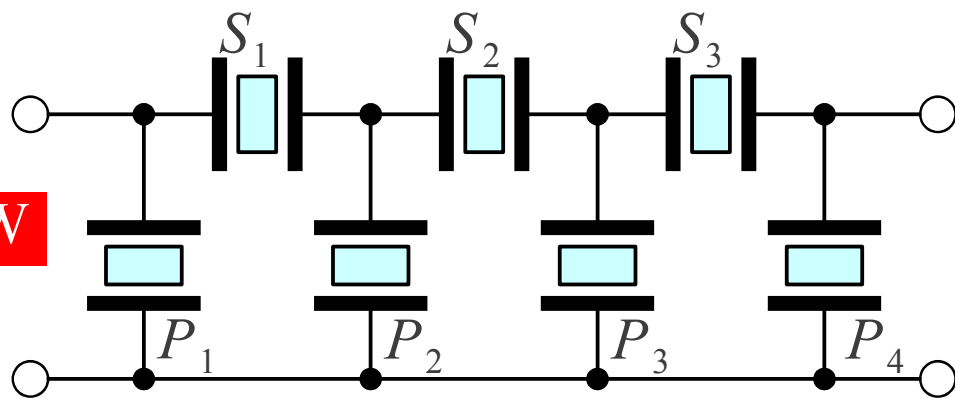
BAW-SMR

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

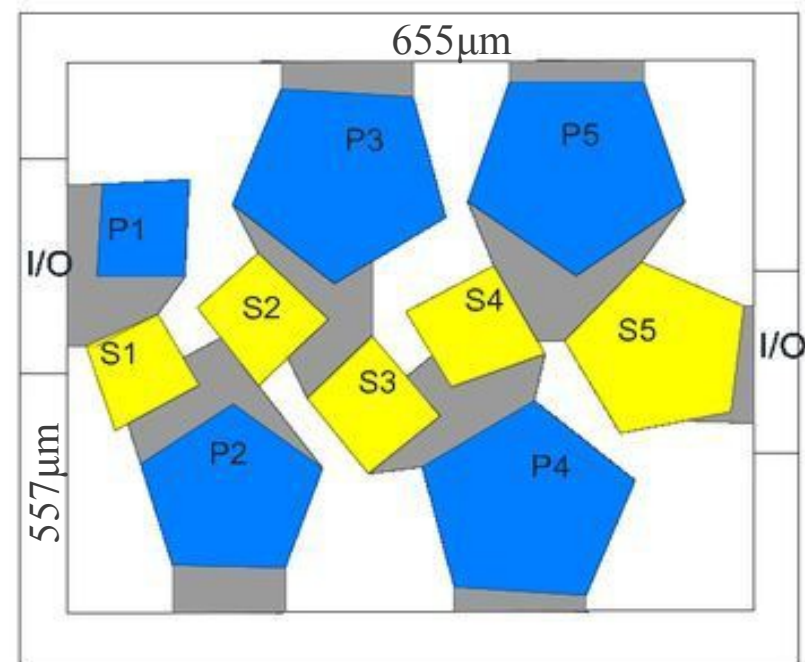
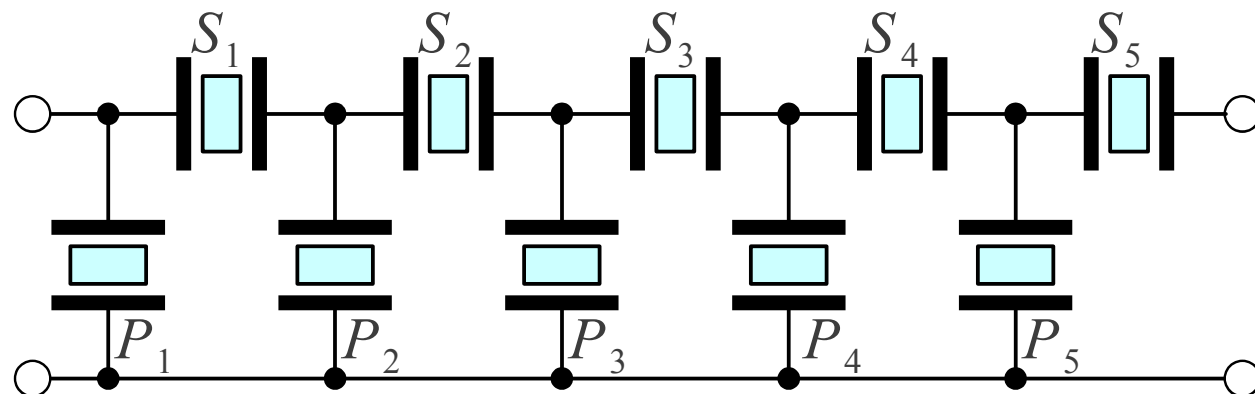
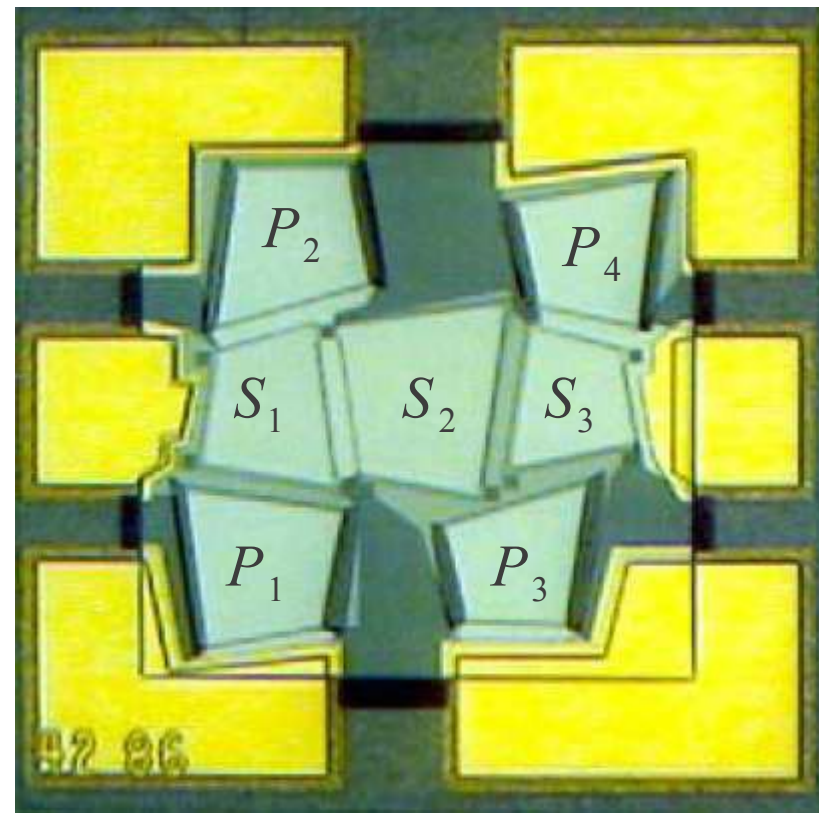
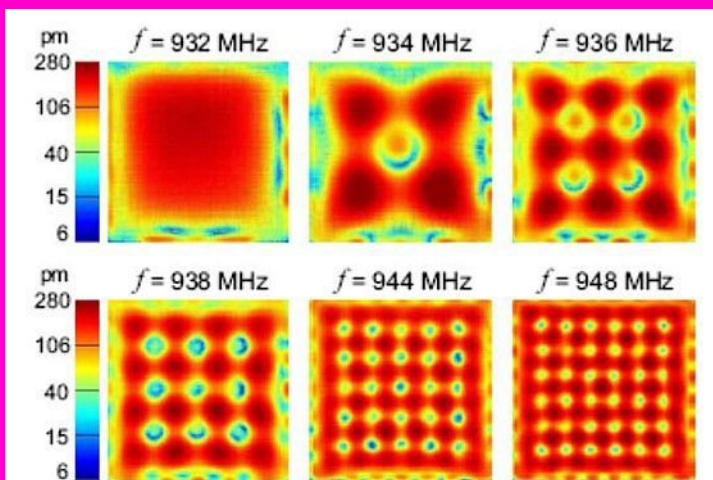


| Material    | Dielectric constant | Acoustic velocity (m/s) | Acoustic coupling | Acoustic loss dB/ $\mu\text{s}$ At 1 GHz |
|-------------|---------------------|-------------------------|-------------------|------------------------------------------|
| AlN (novo)  | 8.5                 | 10,400                  | 0.17              | ~5                                       |
| ZnO (staro) | 8.8                 | 6,330                   | 0.28              | 8.3                                      |

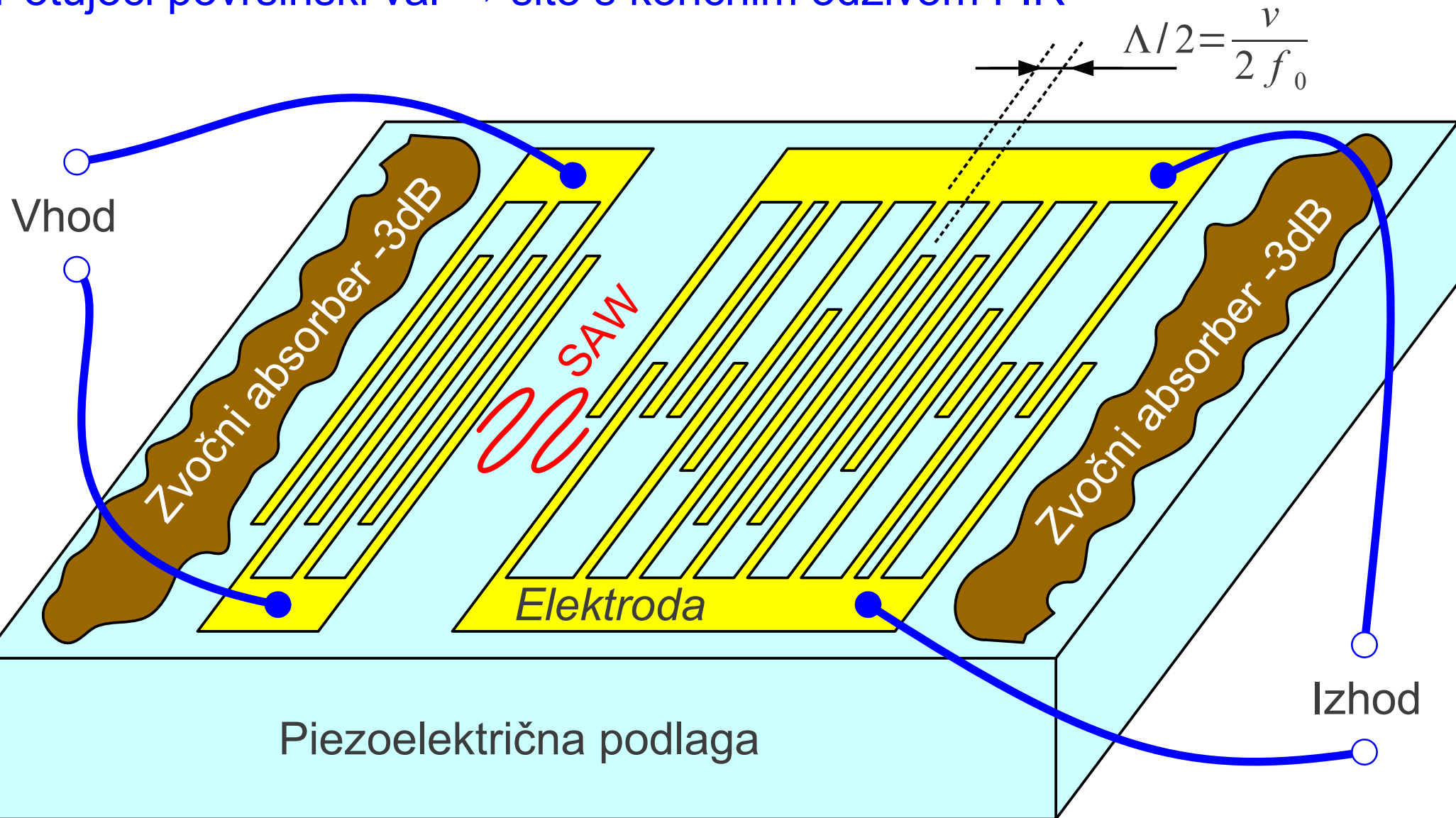
$$P_{MAX} \approx 1W$$



Prečni rodovi  
v kvadratnem  
rezonatorju  
FBAR



Potujoči površinski val → sito s končnim odzivom FIR

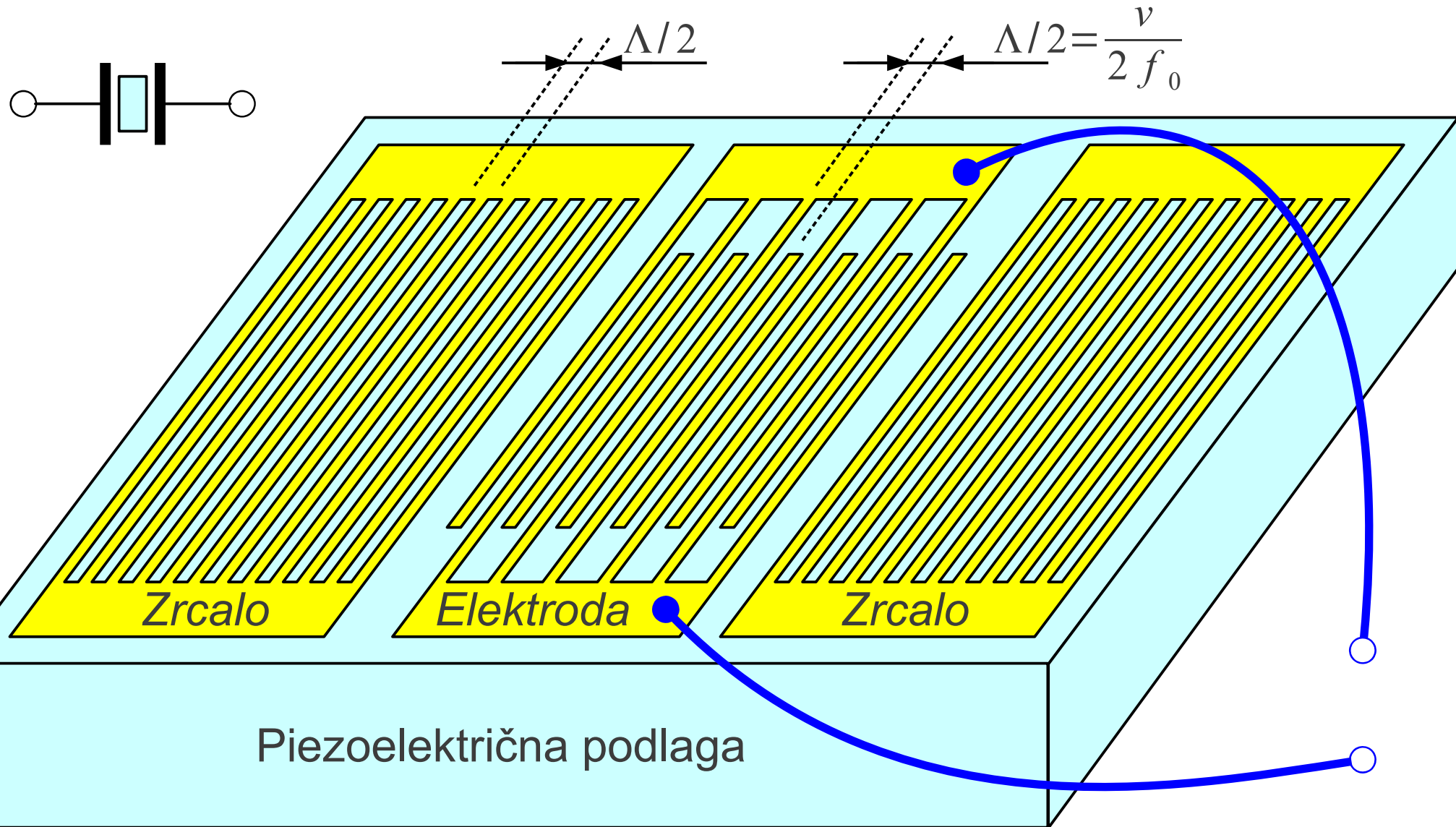


Kristalna podlaga:  $\text{SiO}_2$  ali  $\text{LiNbO}_3$  ali  $\text{LiTaO}_3$  ali  $\text{La}_3\text{Ga}_5\text{SiO}_{14}$   
(kvarc) (langasite)



32 – SAW sito za 36MHz

Stojni površinski val → rezonator ≡ sito z neskončnim odzivom IIR



Kristalna podlaga:  $\text{SiO}_2$  ali  $\text{LiNbO}_3$  ali  $\text{LiTaO}_3$  ali  $\text{La}_3\text{Ga}_5\text{SiO}_{14}$   
(kvarc) (langasite)