# Dynamically controllable metamaterials

Irina Vendik
St. Petersburg Electrotechnical University
E-mail: IBVendik@eltech.ru

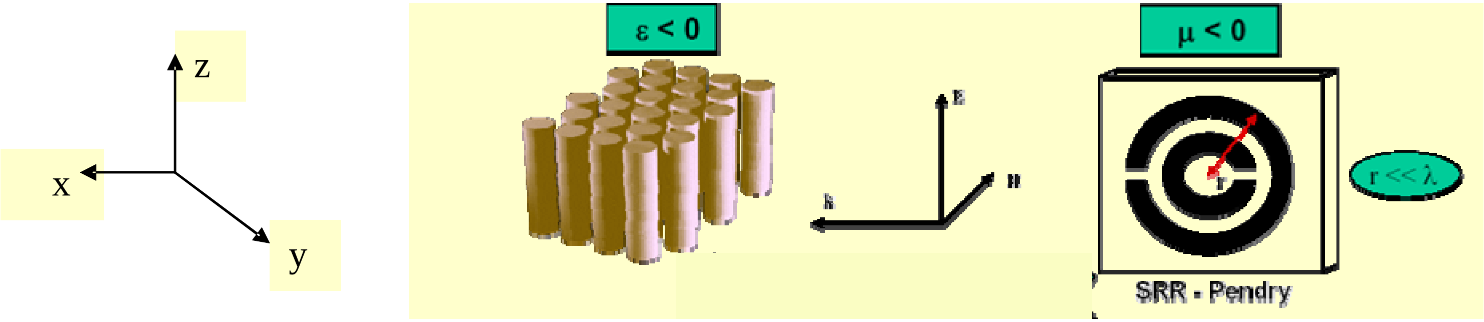
# Content

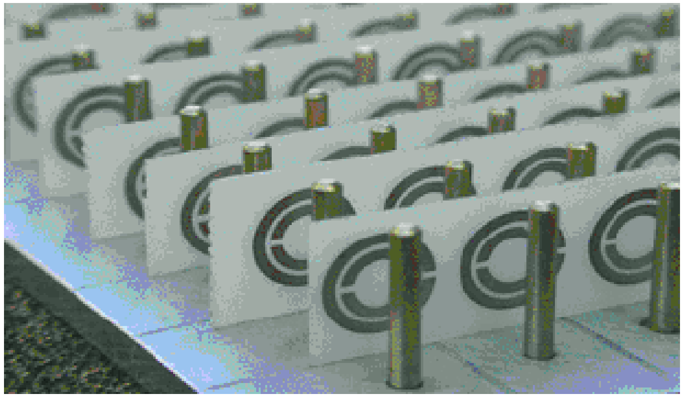
- Introduction
- Tunable components
- Commutation quality factor (CQF) of tunable components
- Figure of merit of tunable devices:
- *Tunable resonator*
- *Tunable filter*
- *Phase shifter*
- Comments and conclusions

# Introduction

- Metamaterials are artificial structures designed to exhibit specific electromagnetic properties not commonly found in nature.
- Double-negative (DNG) metamaterials are characterized by simultaneously negative permittivity ($\varepsilon < 0$) and permeability ($\mu < 0$)
- Single-negative (SNG) metamaterials are characterized by the negative permeability $\mu < 0$ or by the negative permittivity $\varepsilon < 0$
- The DNG and SNG properties are realized in a limited frequency range, which is conditioned by the resonance nature of the constituents of the metamaterial

# First experimental DNG structures





a)

b)

D.R. Smith, W.J. Padilla et al. “Composite medium with simultaneously negative permeability and permittivity,” *Phys. Rev. Lett.*, V. 84, p. 4184, May 2000
R.A. Shelby, D.R. Smith, and S. Schultz, “Experimental verification of a negative index of refraction,” *Science*, V. 292, p. 77, April 2001

# Resonant nature of artificial particles in metamaterials

- SRR is a resonant “particle” generating an equivalent magnetic dipole; resonance is used for providing effective negative permeability
- DNG medium can be formed as a regular lattice of magnetic and electric dipoles generated by resonant “particles”
- DNG medium can be formed as a regular lattice of magnetic dipoles generated by resonant “particles” placed in the medium with effective negative dielectric permittivity in the frequency range below the electric plasma frequency or cut-off frequency of the guiding structure

# Effective ε and μ of the SRR/wire medium

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + i\omega\zeta}$$

**Effective dielectric permittivity of the thin-wire regular structure: $\omega_{pe}$ is the electric plasma frequency depending on the geometry; ζ is the loss factor**

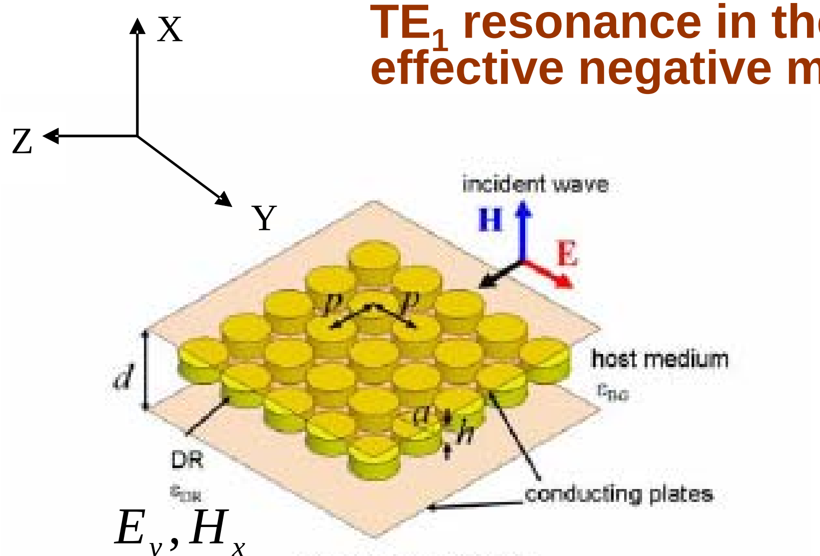
$$\mu_r(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{0m}^2 + i\omega\zeta}$$

**Effective magnetic permeability of the SRR regular structure: $\omega_{om}$ is the magnetic resonance frequency depending on the geometry; ζ is the loss factor**

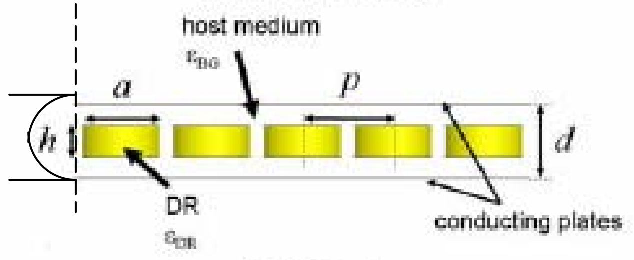
***The magnetic resonance frequency $\omega_{om}$ depends on the gap dimension and the dielectric constant of the substrate***

# Cut-off parallel-plate waveguide loaded with 2D lattice of dielectric resonators

**$TE_1$ resonance in the dielectric resonators provides the effective negative magnetic permittivity**



(a) Perspective view



(b) Side view

**2-D lattice structure for the DR array in the cutoff waveguide; $\varepsilon_{d,r}$ can be tuned**

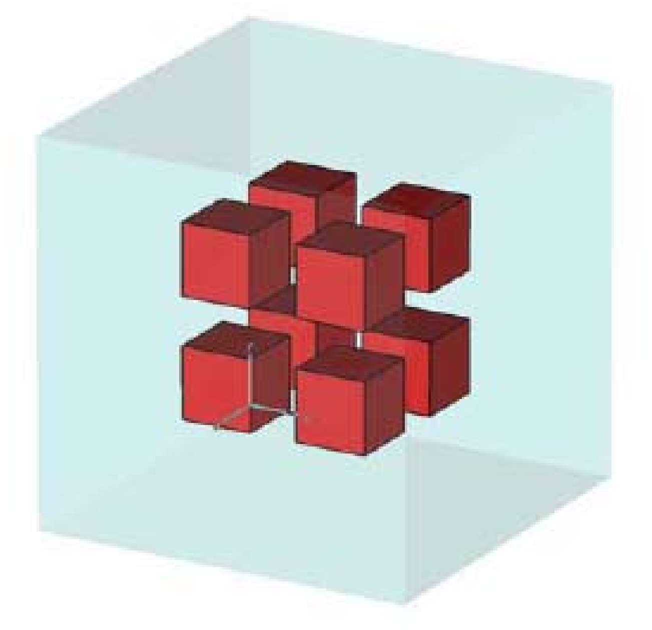
**The effective permittivity for the parallel-plate $TE_n$ mode is**

$$\boxed{\varepsilon_{ef,n} = \varepsilon_{d,r}\left[1 - \left(\frac{\omega_{c,n}}{\omega}\right)^2\right]}$$

$$\omega_{c,n} = \frac{n \cdot \pi \cdot c}{d\sqrt{\varepsilon_{d,r}}}$$

Tetsuya Ueda, Anthony Lai, and Tatsuo Itoh, Negative Refraction in a Cut-Off Parallel-Plate Waveguide Loaded with Two-Dimensional Lattice of Dielectric Resonators, *Proc. EuMC36*, Manchester 2006, pp. 435-438

# Controlling the magnetic resonance frequency of SNG material



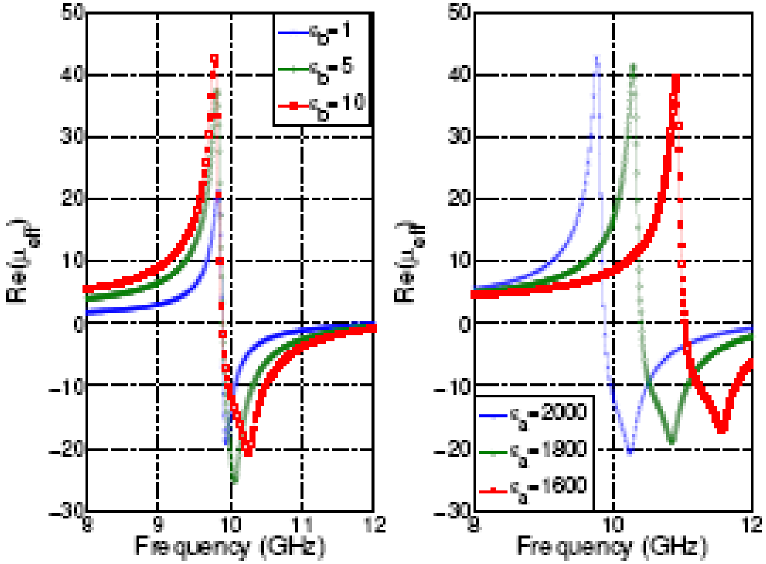
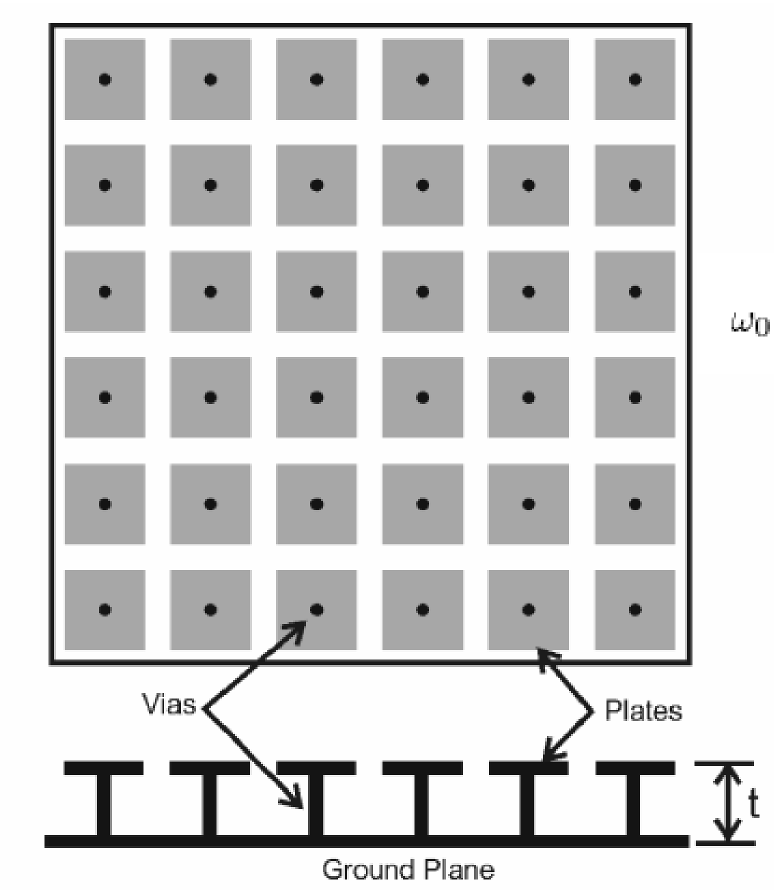
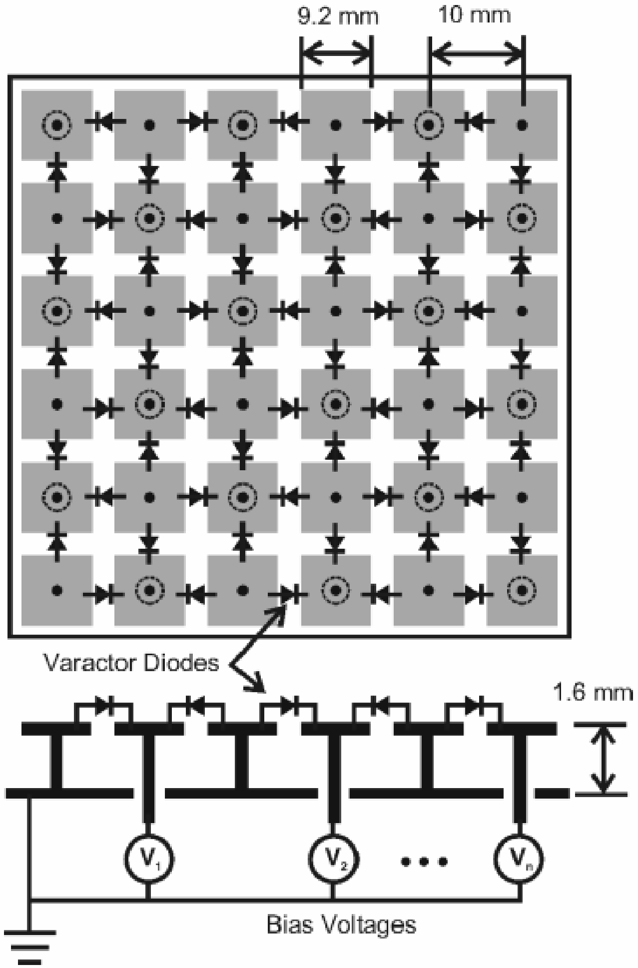


Figure 5: Effective permeability for a square lattice ($a = 0.60mm$) of square cylinders ($l = 0.48mm$). On the left hand-side the real part of the effective permeability is computed as a function of $\epsilon_b$ with $\epsilon_a = 2000$ and on the right hand-side as a function of $\epsilon_a$ with $\epsilon_b = 10$.

# Electrically tunable impedance surface



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



Daniel F. Sievenpiper, James H. Schaffner *et al,* Two-Dimensional Beam Steering Using an Electrically Tunable Impedance Surface, IEEE TRANS. AP, VOL. 51, NO. 10, 2003, p. 2713

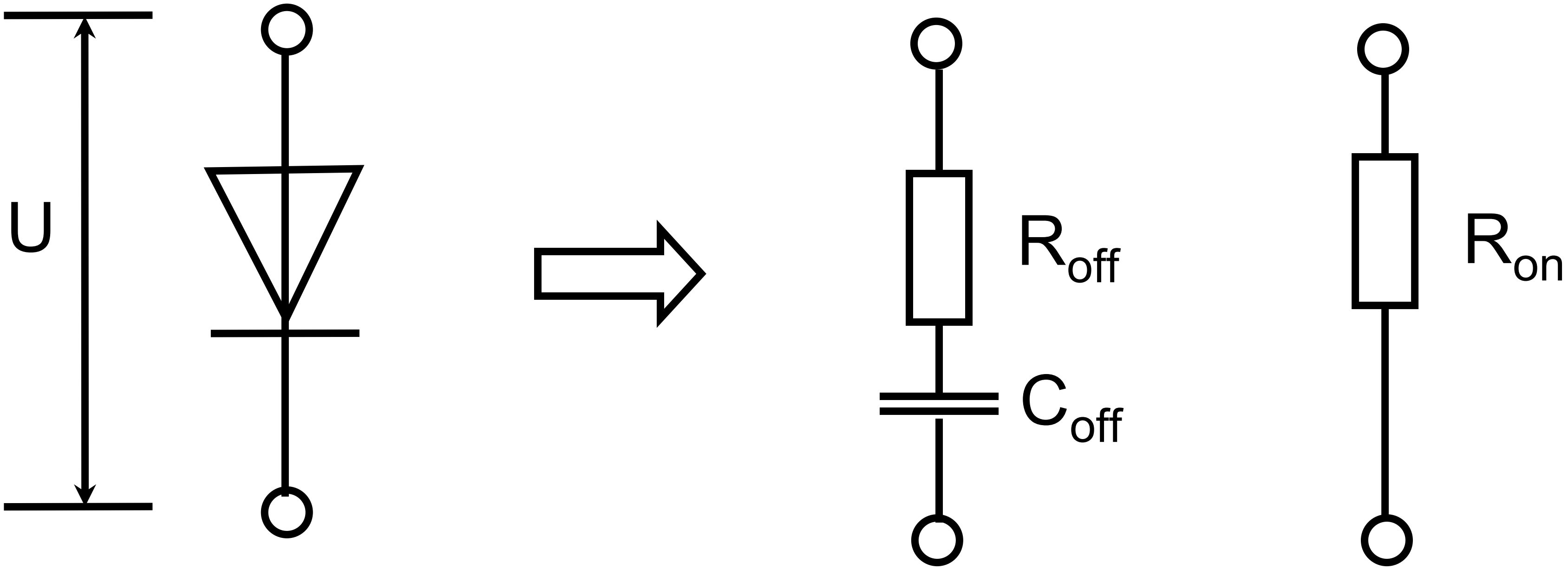
# How to control the metamaterial parameters?

- To change the capacitance as the constitutive component of the metamaterial particle
- To change the dielectric permittivity of the material used for a design of the metamaterial

# Tunable components

- *P-i-n* diode
- MEMS
- FET
- Semiconductor varactor
- Ferroelectric varactor
- *(Piezoelectric components)*

# *p-i-n* diode



$U \leq 0$ V

$U > 0$

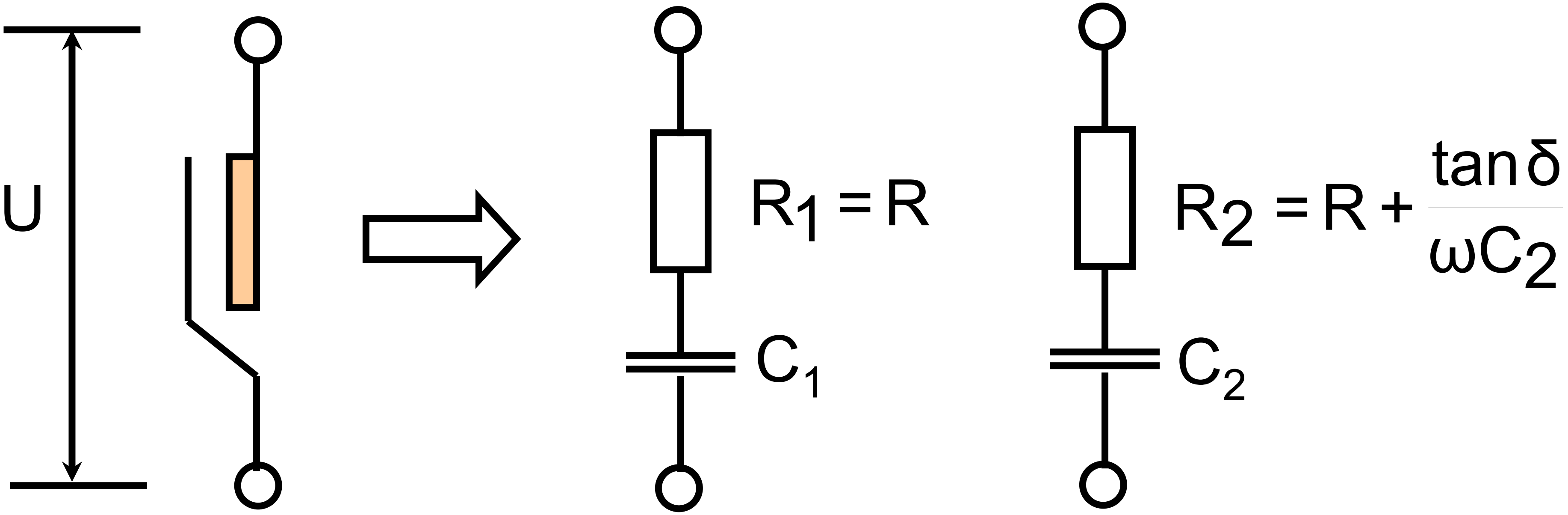
**Typical parameters:**

**$R_{on}$ = 1 Ohm;**

**$R_{off}$ = 1 Ohm;**

**$C_{off}$ = 0.05-0.5 pF.**

# MEMS



**Typical:**

**$\tan\delta = 0.001$;**

**R = 0.5 Ohm;**

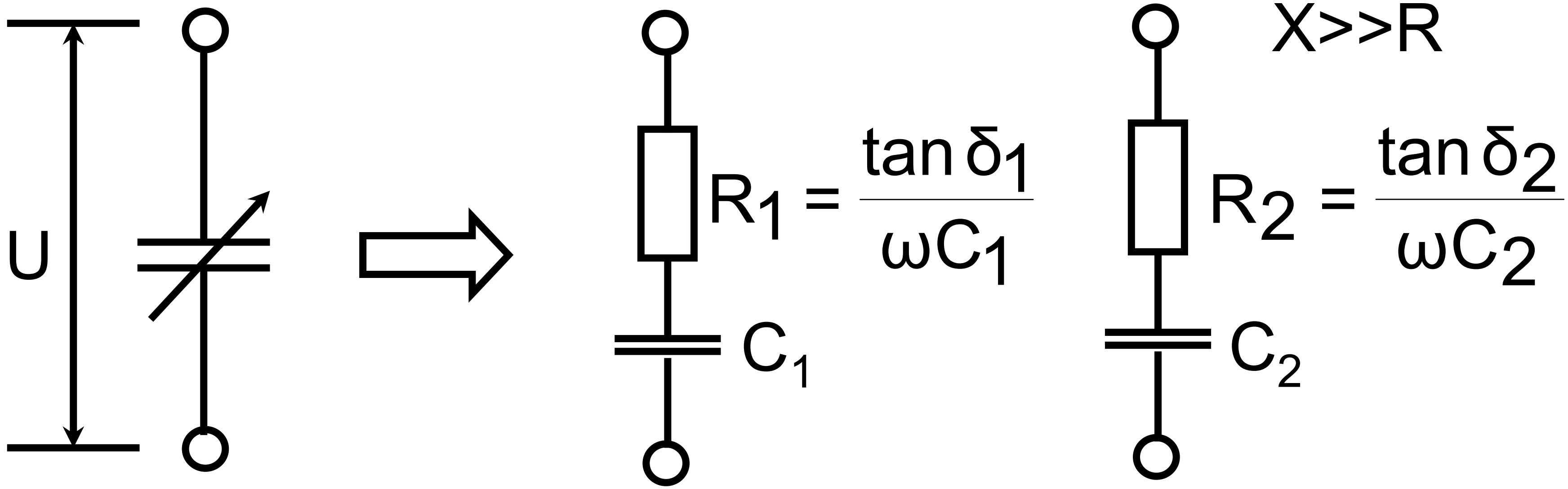
**$C_1 = 1.4$ pF;**

**$C_2 = 3.0$ pF**

$U = 0$ V

$U = U_{max}$

# Devices based on a tunable capacitor: FET, semiconductor or ferroelectric *varactor*



$$R_1 = \frac{\tan\delta_1}{\omega C_1}$$

$$R_2 = \frac{\tan\delta_2}{\omega C_2}$$

$U = 0$ V

$U = U_{max}$

**Ferroelectric:**
**$\tan\delta_1 = 0.01$**
**$\tan\delta_2 = 0.005$**
**$C_1 = 1.0$ pF**
**$C_2 = 0.5\text{-}0.7$ pF**

**Semiconductor:**
**R1~R2 = 0.5-0.8 Ohm**
**C1 = 1.5 pF**
**C2 = 0.3 pF**

**FET:**
**R1 = 1- 5 Ohm**
**C1 = 0.3 pF**
**R2 = 1.0 Ohm**

# Estimation of quality of tunable components

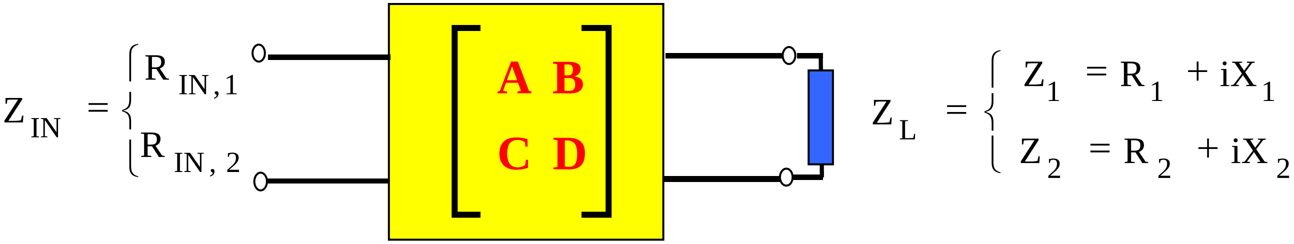
- ***The commutation quality factor (CQF) is the generalized criterion for estimation of quality of tunable components***

The following components are compared by the CQF:

- *p-i-n diode*
- *MEMS*
- *FET*
- *Semiconductor varactor*
- *Ferroelectric varactor*

# Commutation quality factor (CQF) of tunable components (definition)

**The commutation quality factor (CQF) is defined as the ratio of the input impedances of a lossless reciprocal two-port terminated in the impedance pair $Z_1$ and $Z_2$ under condition $\mathrm{Im}\, Z_{in,1,2}=0$**



$$Z_{IN} = \begin{cases} R_{IN,1} \\ R_{IN,2} \end{cases} \qquad Z_L = \begin{cases} Z_1 = R_1 + iX_1 \\ Z_2 = R_2 + iX_2 \end{cases}$$

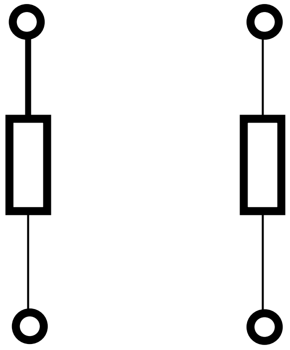
**Generally CQF is denoted *K* and determined as**

$$\boxed{K \doteq \frac{R_{in,1}}{R_{in,2}}}$$

$$\boxed{K + \frac{1}{K} = \frac{R_1}{R_2} + \frac{R_2}{R_1} + \frac{\left(X_1 - X_2\right)^2}{R_1 R_2}}$$

# Commutation quality factor (CQF) of tunable components

X>>R



$Z_1 = R_1 + jX_1$

$Z_2 = R_2 + jX_2$

State 1

State 2

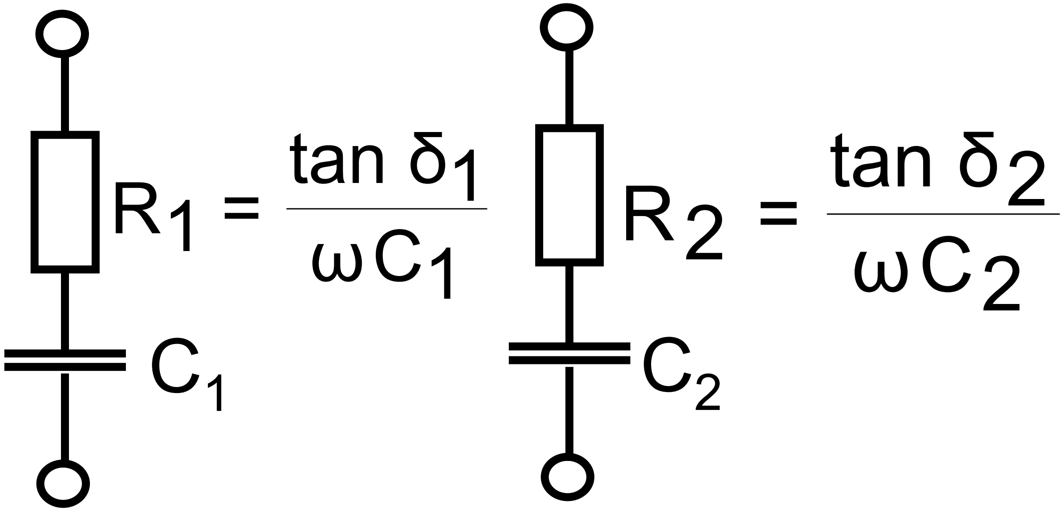
**The CQF is used for a comparison of different tunable components**

$$K = \frac{\left(X_2 - X_1\right)^2}{R_1 \cdot R_2}$$

I. B. Vendik, O. G. Vendik, E. L. Kollberg, “Commutation quality factor of two-state switching devices”, IEEE Trans. on Microwave Theory and Tech., Vol. 48, No. 5, May 2000, pp. 802-808.

# More convenient form of the CQF for tunable capacitors

$$\boxed{K = \frac{(n\text{-}1)^2}{n\cdot\tan\delta_1\tan\delta_2}}$$



$$R_1 = \frac{\tan\delta_1}{\omega C_1}$$

$$R_2 = \frac{\tan\delta_2}{\omega C_2}$$

$U = 0\ V$ $\qquad$ $U = U_{max}$

**Tunability of the capacitor:** $\boxed{n = C_1 / C_2}$

# Definitions of the tunability of a tunable dielectric material

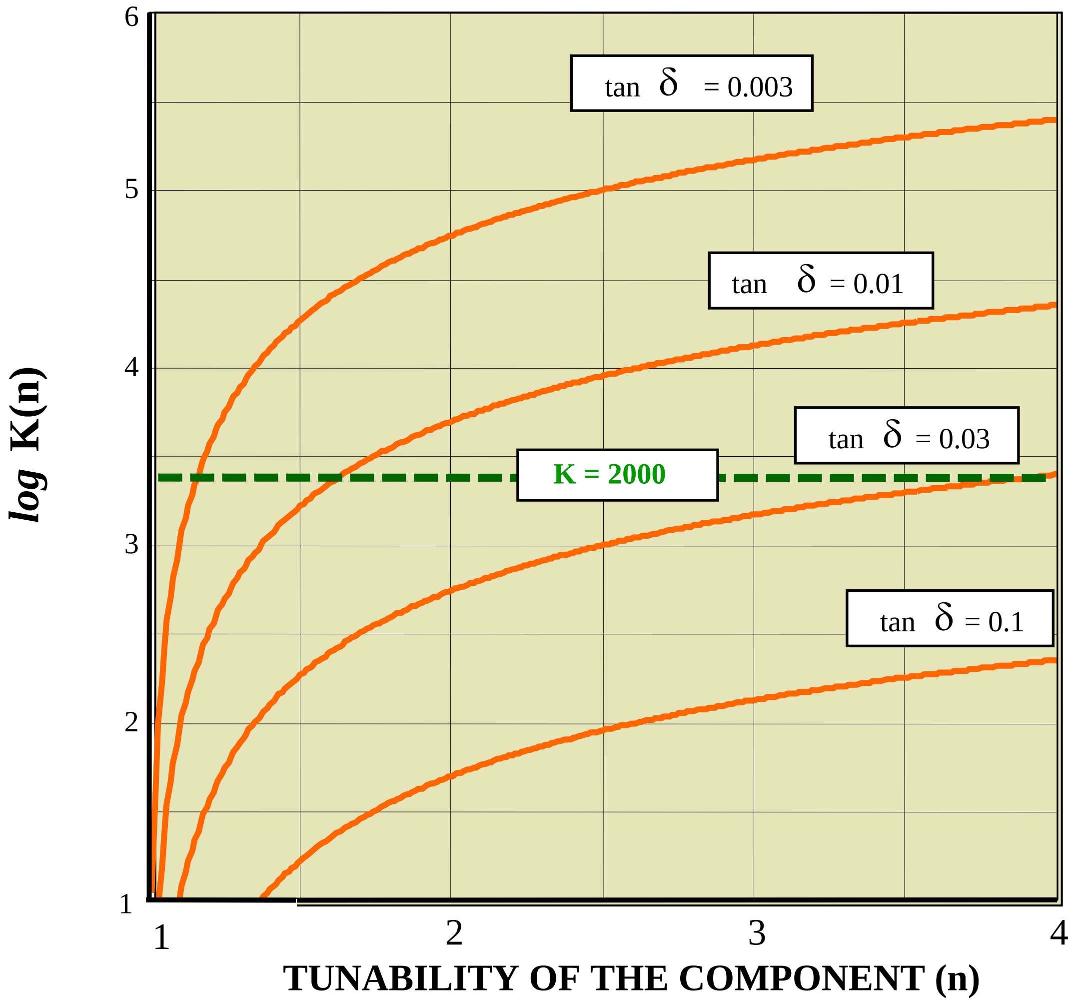
$$K = \frac{(n\text{-}1)^2}{n \cdot \tan\delta_1 \tan\delta_2}$$

$$n = 1/(1 - 0.01n^*)$$

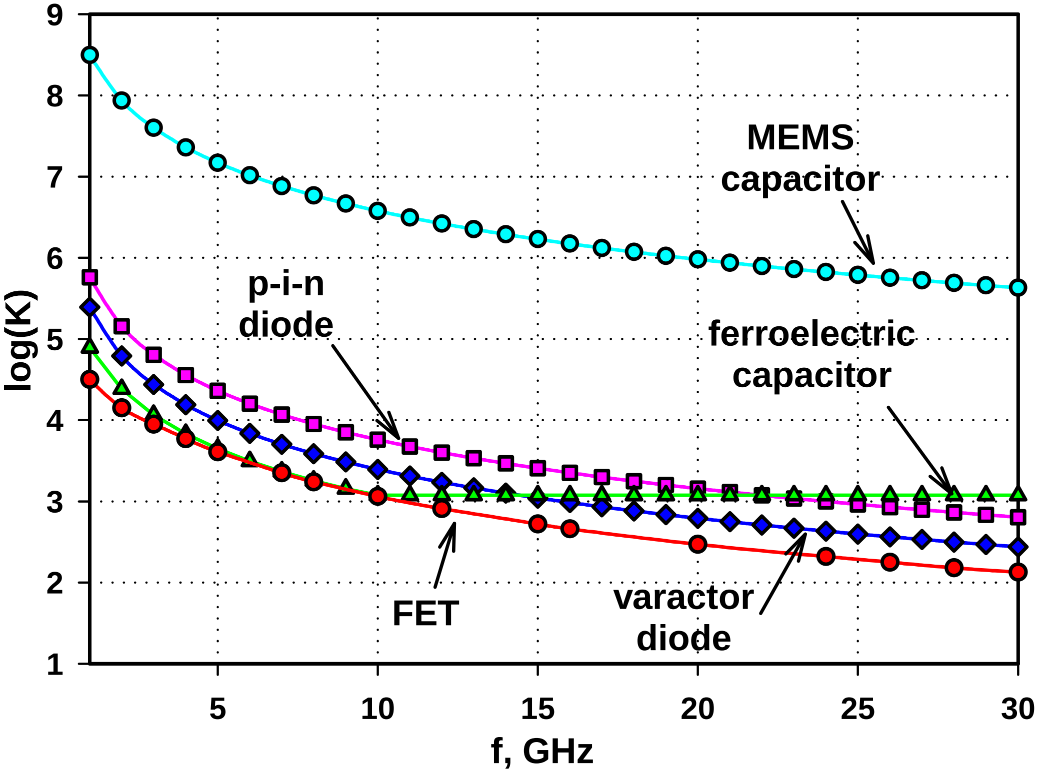
| **Tunability** | **Relative tunability** |
|---|---|
| $n = \frac{\varepsilon(0)}{\varepsilon(U_{\max})} = \frac{C(0)}{C(U_{\max})}$<br>$n \geq 1$ | $n^* = \frac{\varepsilon(0) - \varepsilon(U_{\max})}{\varepsilon(0)} \cdot 100\%,$<br>$n^* < 100\%$ |

| n | 1.11 | 1.25 | 1.43 | 1.67 | 2.0 |
|---|---|---|---|---|---|
| $n^*$, % | 10 | 20 | 30 | 40 | 50 |

# Commutation quality factor of a tunable capacitor

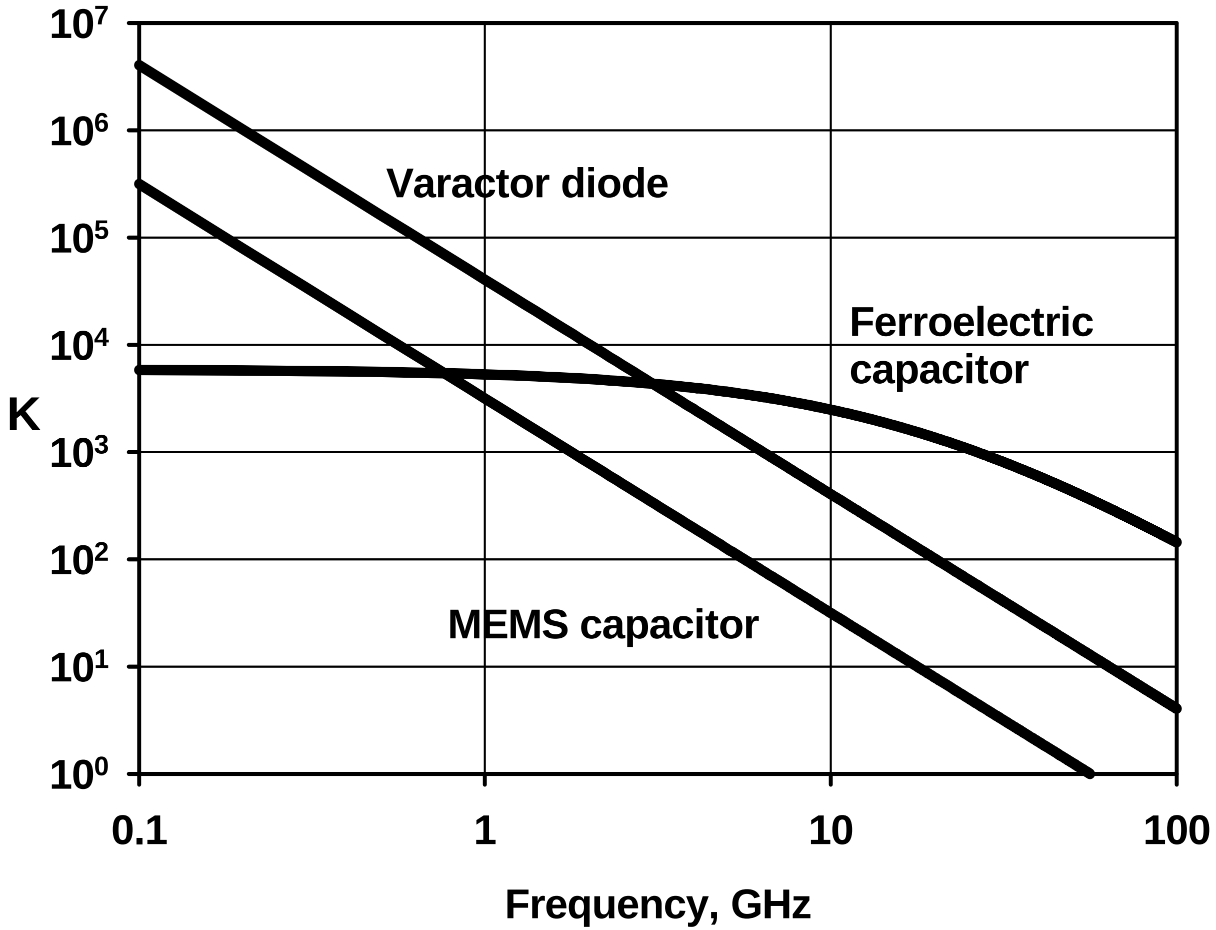


# Comparison of the CQF (2003)

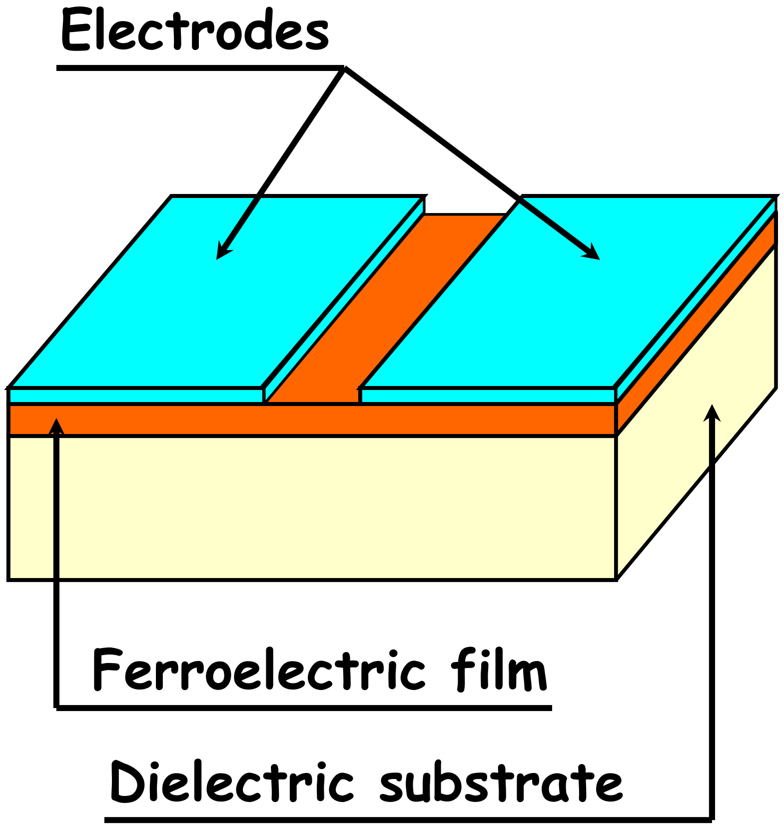


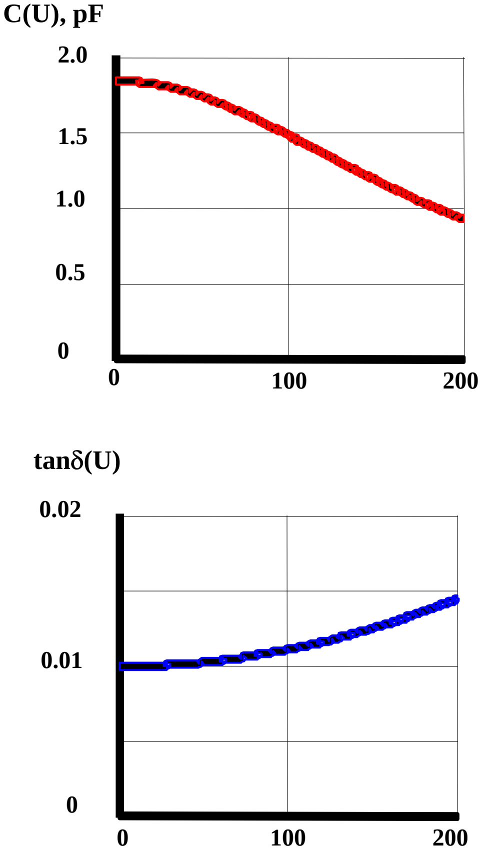
V.V.Pleskachev, I.B. Vendik, The Commutation Quality Factor of Electrically Controlled Microwave Device Components, *Tech. Phys. Letters,* Vol. 29, No. 12, pp. 1018- 1020, 2003.

# Comparison of the CQF (2006)



# Using of ferroelectric capacitor as a tunable component





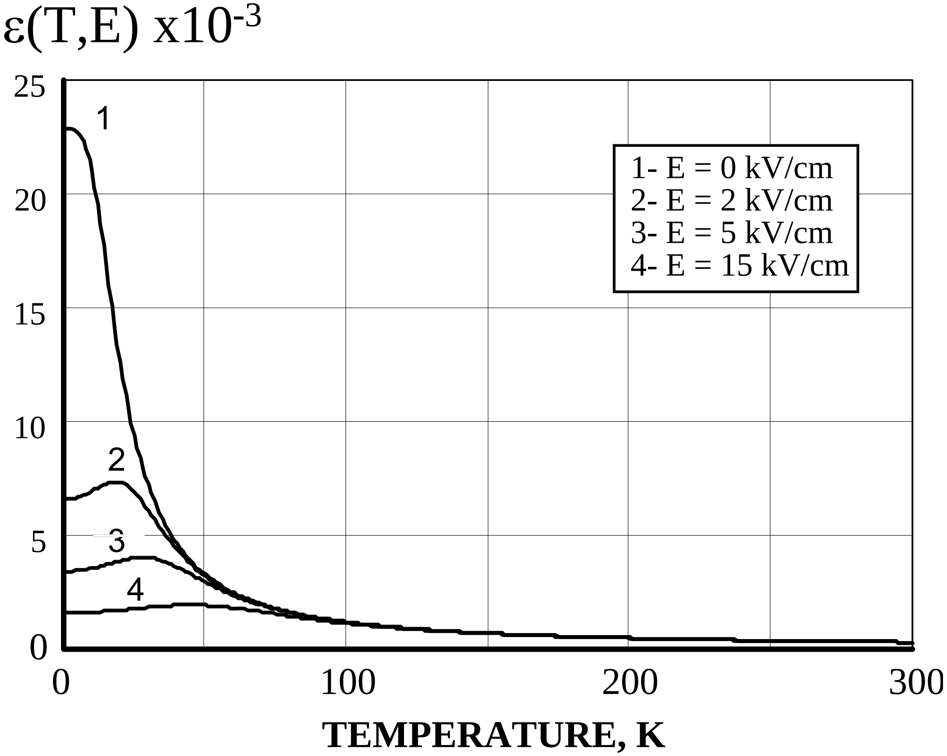
Biasing voltage (V)

# Using of ferroelectric capacitor as a tunable component

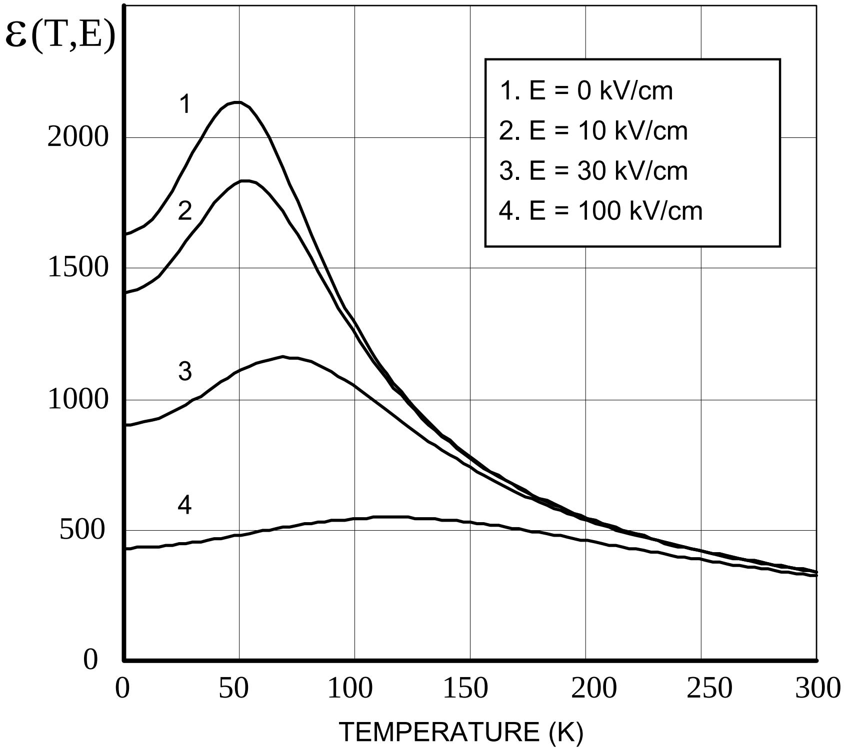
Dielectric constant $\varepsilon$ depends on the temperature $T$ and the biasing field $E$

Loss factor $tan\delta$ depends on the temperature $T$ and the biasing field $E$

# Characteristics of ferroelectric material: dielectric permittivity

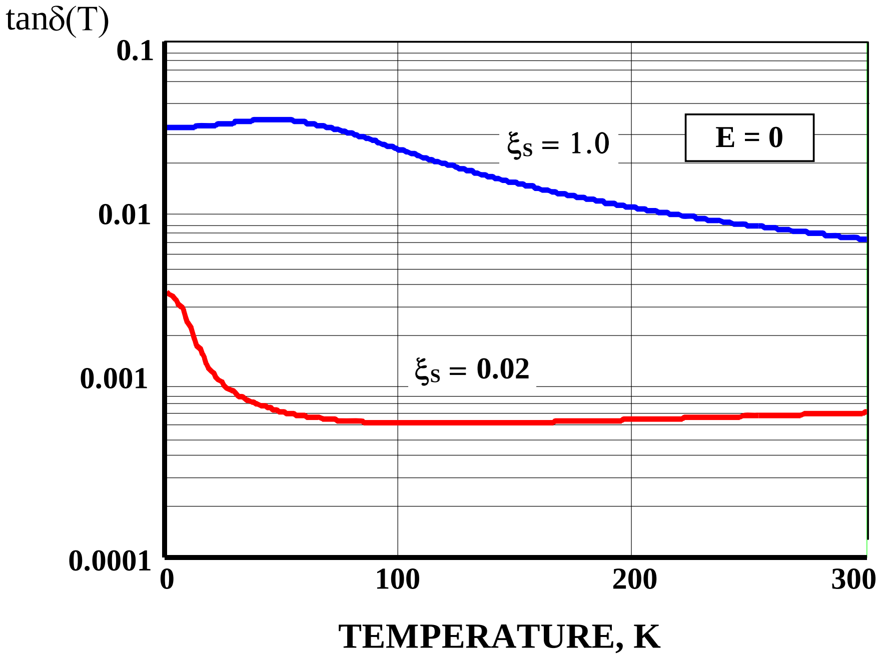


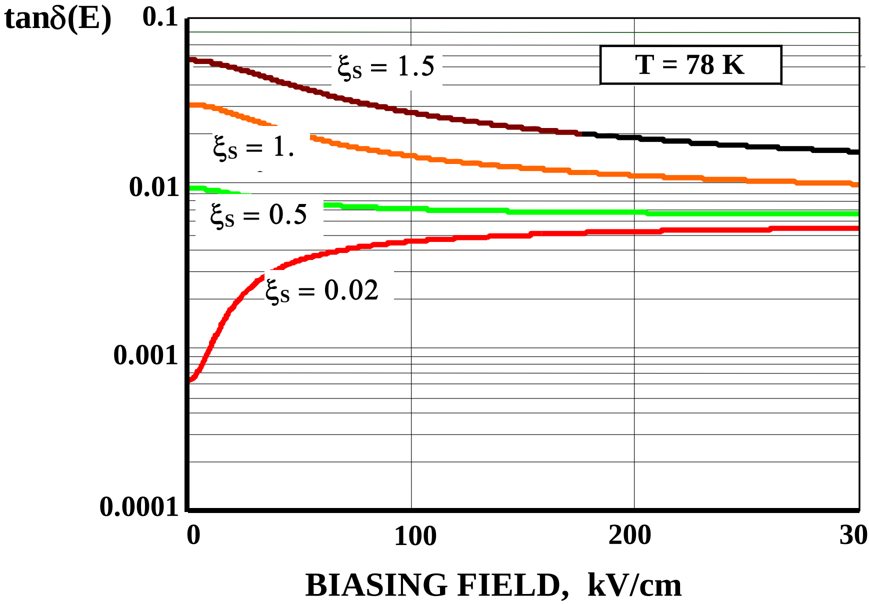
Dielectric constant of single crystal $SrTiO_3$ (STO) ($\xi_S = 0.018$)



Dielectric constant of STO polycrystalline film ($\xi_S = 0.7$ )

# Characteristics of ferroelectric material: loss tangent

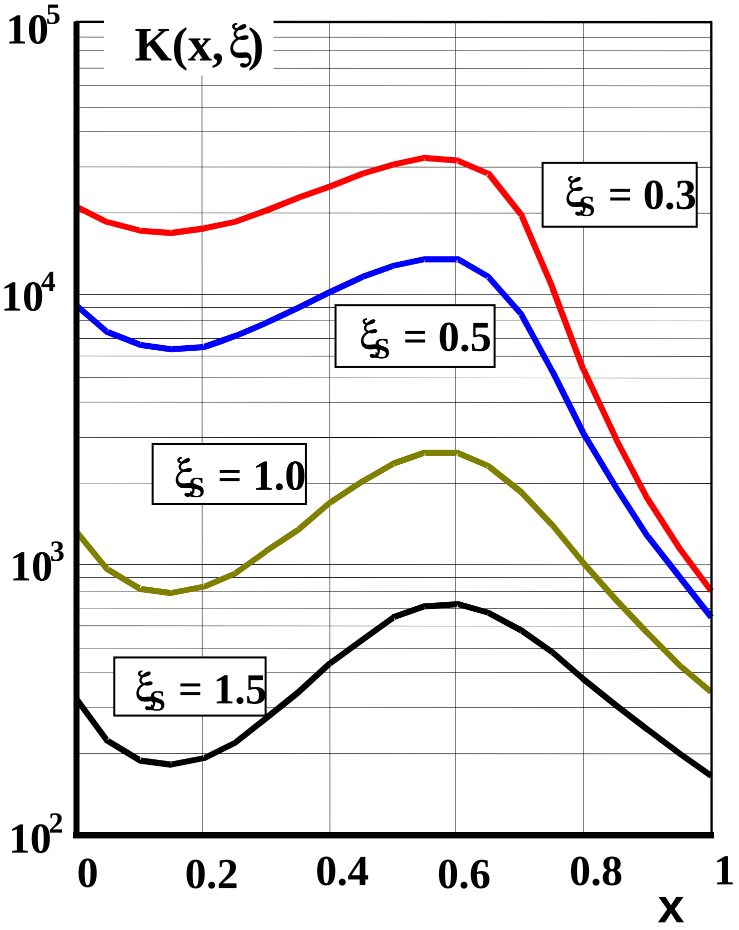




f = 10 GHz; ξ = 0.02 corresponds to single crystal STO.

Parameter ξ characterizes the material quality: the lower ξ , the lower is tanδ

# CQF of BSTO capacitor as a function of Ba concentration (x) and the film structural quality ($\xi_S$)



## $Ba_xSr_{1-x}TiO_3$

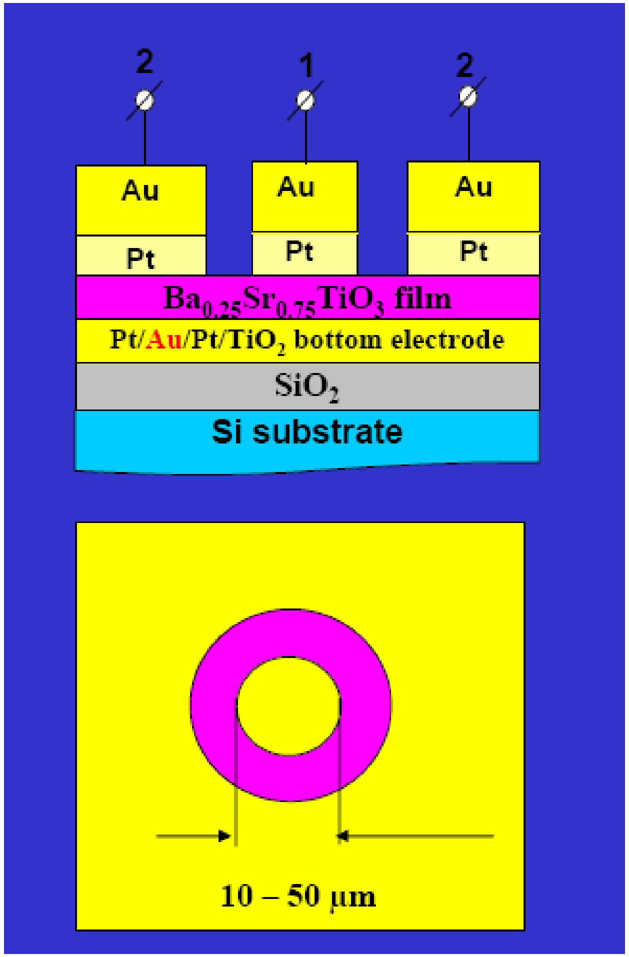
$E_{max}$ = 200 kV/cm,

T = 300 K, f = 3 GHz

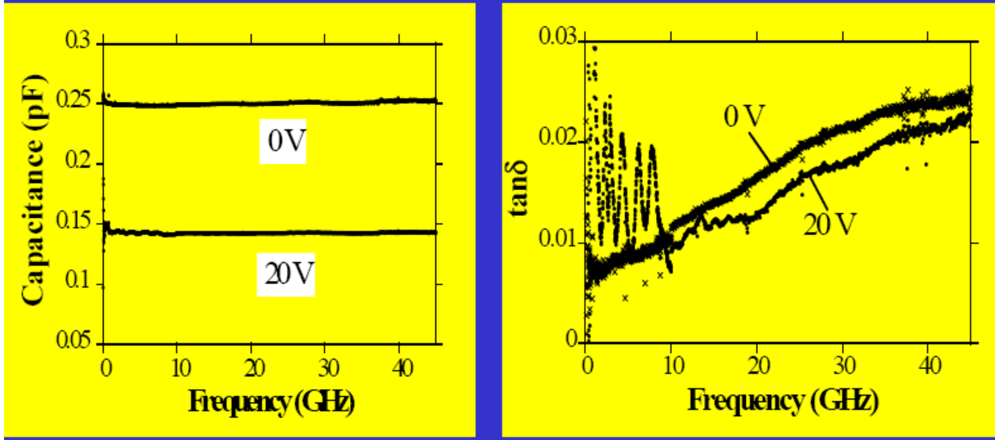
**$\xi_s$ is the statistical dispersion of the built-in-field in the sample: the smaller $\xi_s$ , the higher is the CQF**

O. G. Vendik, S. P. Zubko, and M. A. Nikol'ski, "Microwave loss-factor of BSTO", *Journal of Applied Physics*, Vol. 92, No. 12, pp. 7448-7452, Dec., 2002

# Ferroelectric (BSTO) varactor



**Microwave Performance at V=0 and 20V**



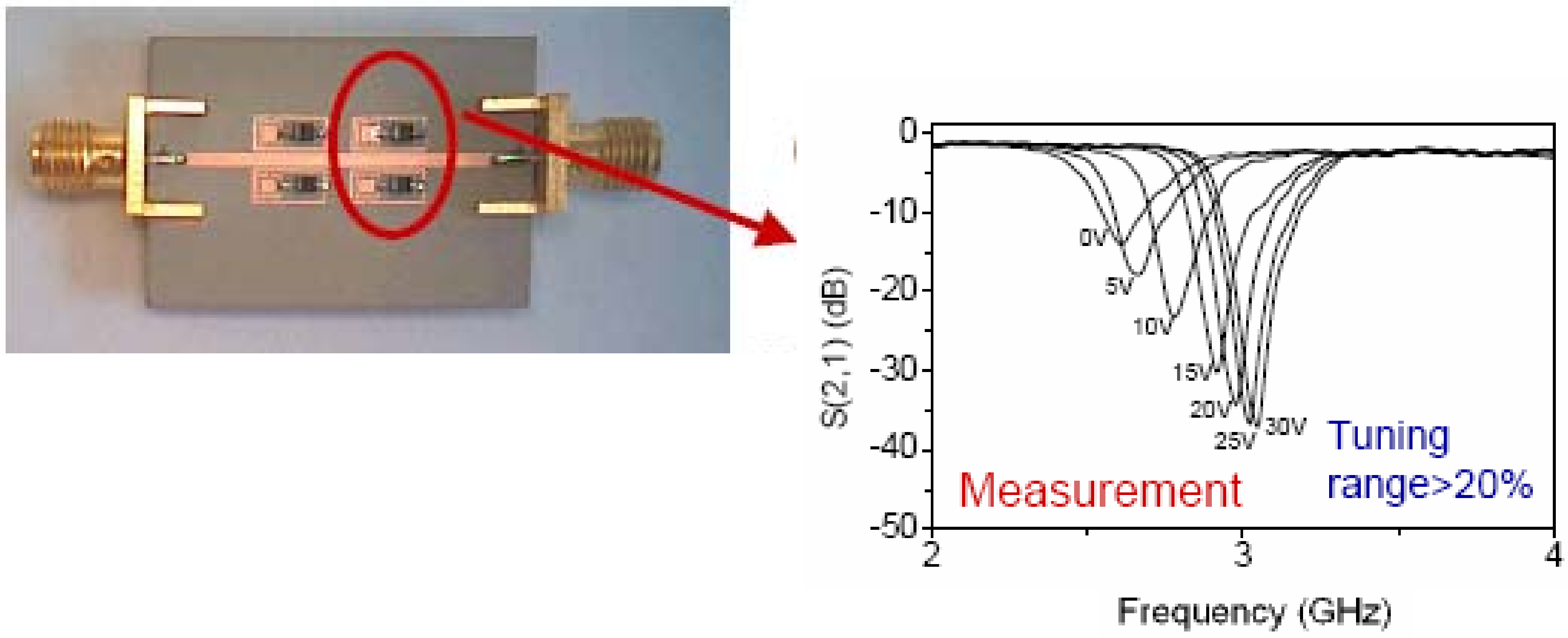
- **No dispersion in permittivity and tuneability**
- **Tuneability *T(20V)*> 40 %**
- **Q~50 @ 50.0 GHz**

A. Vorobiev, P. Rundqvist, K. Khamchane, S.Gevorgian, “Silicon substrate integrated high Q-factor parallel-plate ferroelectric varactors for microwave/millimeterwave applications”, Appl. Phys. Letters, Vol.83, pp. 1344-1346, 2003

# Tunable and switchable devices based on left/right-handed transmission lines

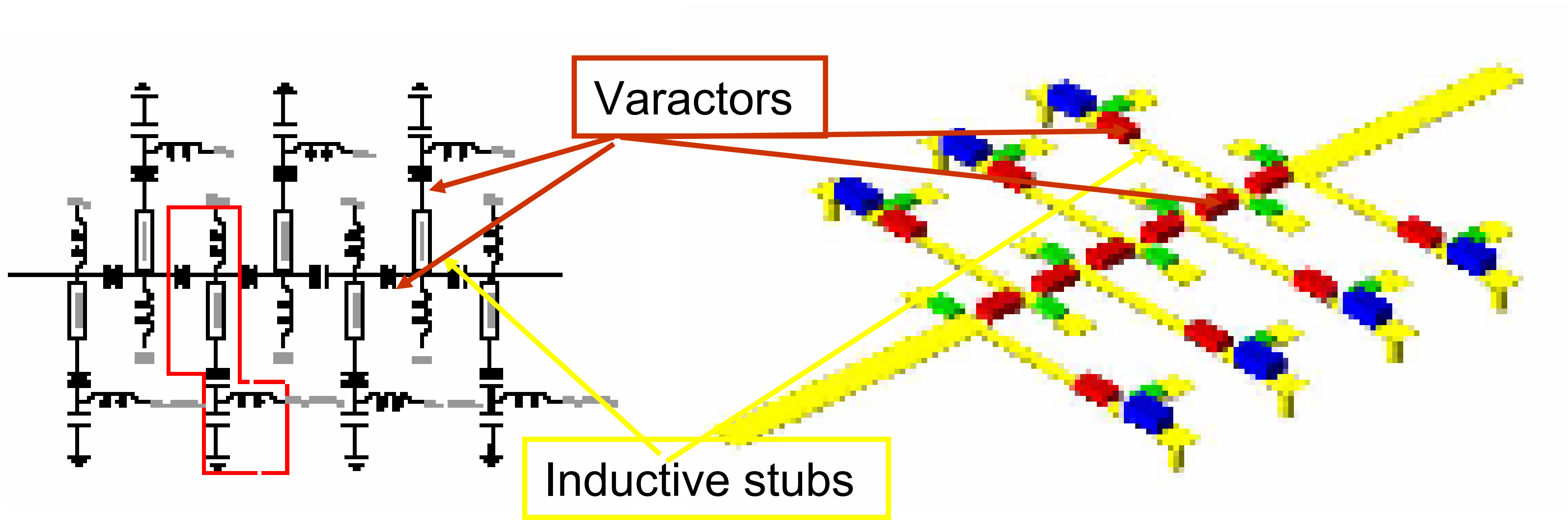
- Tunable resonators using semiconductor or ferroelectric varactors
- Reconfigurable filters
- Switchable and tunable phase shifters

# Reconfigurable varactor loaded SRR transmission line



I. Gil et al. Elect. Lett, October2004.

# Artificial LH TL with separately tunable phase and line impedance



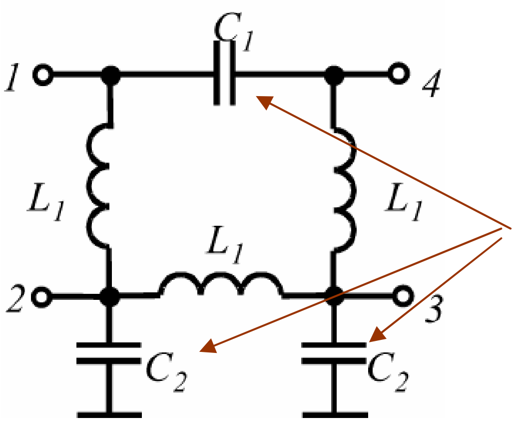
$$\varphi(x) = -\frac{1}{\omega}\sqrt{\frac{1}{xL_0}\cdot\frac{1}{xC_0}}$$

$$Z_0(x) = \sqrt{\frac{xL_0}{xC_0}}$$

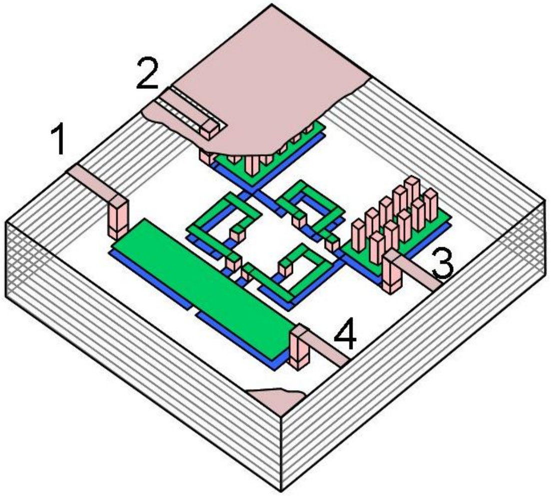
In the tunability range the matching is kept constant!

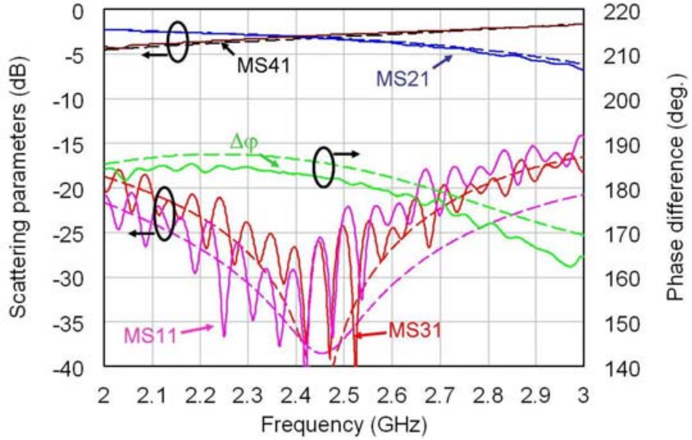
Christian Damm,Martin Schu.ler,Jens Freese,and Rolf Jakoby, Artificial Line Phase Shifter with separately tunable phase and line Impedance, Proc. EuMC, Manchester 2006

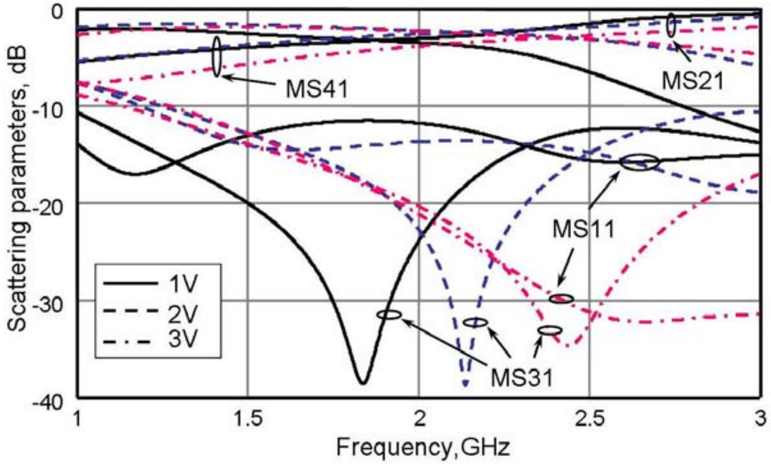
# Tunable RH/LH TL 3-dB directional coupler



Varactor diodes



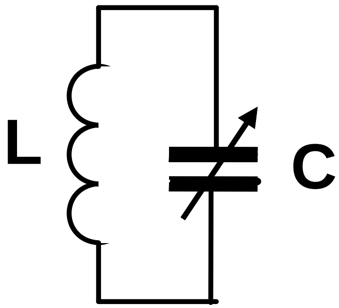


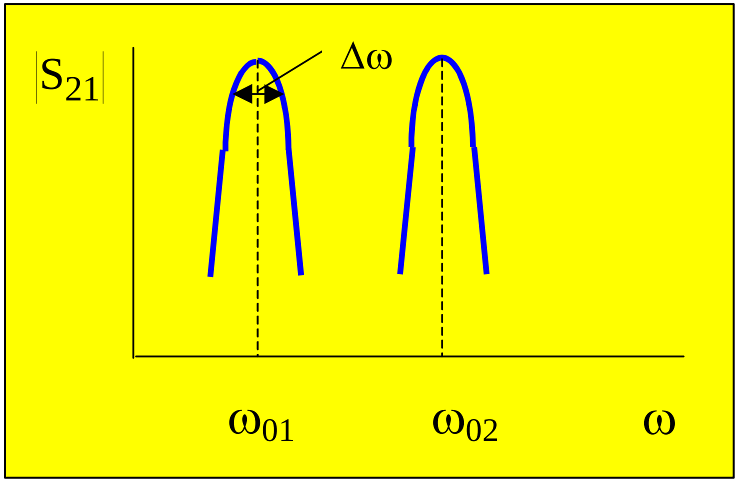


# Estimation of quality of tunable devices (Figure of Merit)

- The quality of the devices is estimated by the figure of merit (FM) determined by a combination of general parameters of the device.
- The FM is defined for
  - ¤ *Tunable resonator*
  - ¤ *Tunable filter*
  - ¤ *Phase shifter*

# Tunable resonator





**Tunability** of the resonator:

$$\gamma = \omega_{02} / \omega_{01} = \sqrt{LC_1} / \sqrt{LC_2} = \sqrt{n}$$

**Q-factor** of the resonator (depends on loss):

$$Q_0 = \omega_0 / \Delta\omega$$

# Figure of merit of a tunable resonator

$$\boxed{F_0 = \frac{\omega_{02} - \omega_{01}}{\Delta\omega} = (\gamma - 1) \cdot Q_0}$$

If the Q-factor depends on the loss in the FE tunable capacitor only, the FM is determined by the commutation quality factor ***K*** and is defined as

$$\boxed{F_{0,\max} \approx 0.5 \cdot \sqrt{K}}$$

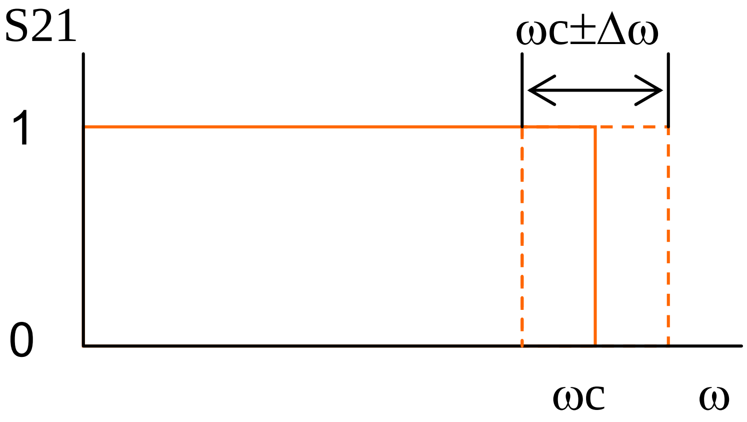
**For K = 5000, F = 35**

# What is the filter?

- The ideal filter is a passive lossless and perfectly matched 2-port providing electromagnetic wave transmission in a limited frequency range and full reflection outside this range.
- There are four main filters: low-pass (LP), high-pass HP), band-pass (BP), and band-stop (BS)
- The filter design is based on using lumped or distributed components
- **Tunable filters are supposed to be able to change the width of the frequency band or to shift the characteristic as a whole over the frequency range**

# Tunable filter (LP) characteristics

**The transmission coefficient $S_{21}$ of the LP filter versus frequency $\omega$**

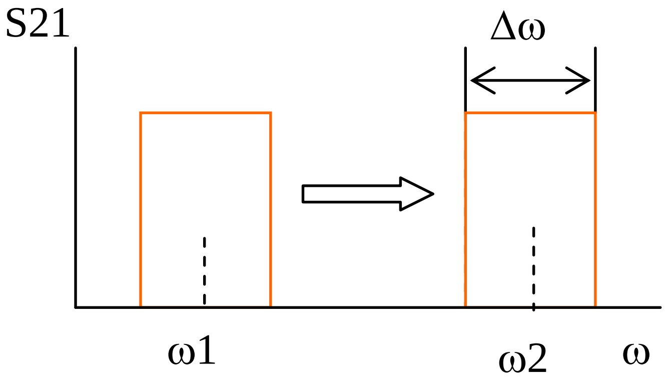


$$S_{21} = \left| \frac{U_{out}}{U_{in}} \right|$$

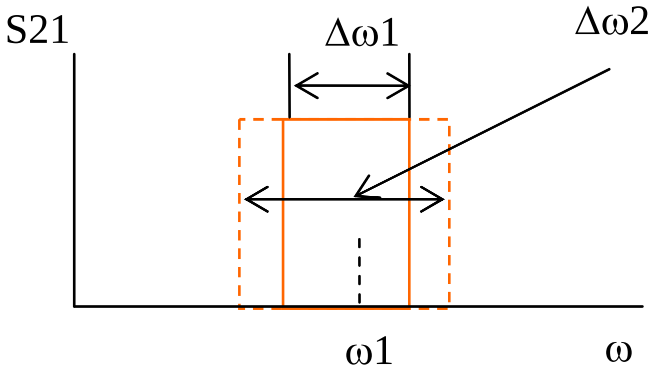
The cut-off frequency $\omega_c$ is shifted while tuning; at the same time the pass band is changed

# Tunable filter (BP) characteristics (two versions)

**The transmission coefficient $S_{21}$ of the BP filter versus frequency ω**



The central frequency $\omega_1$ is shifted to $\omega_2$ while tuning; at the same time the pass band remains the same

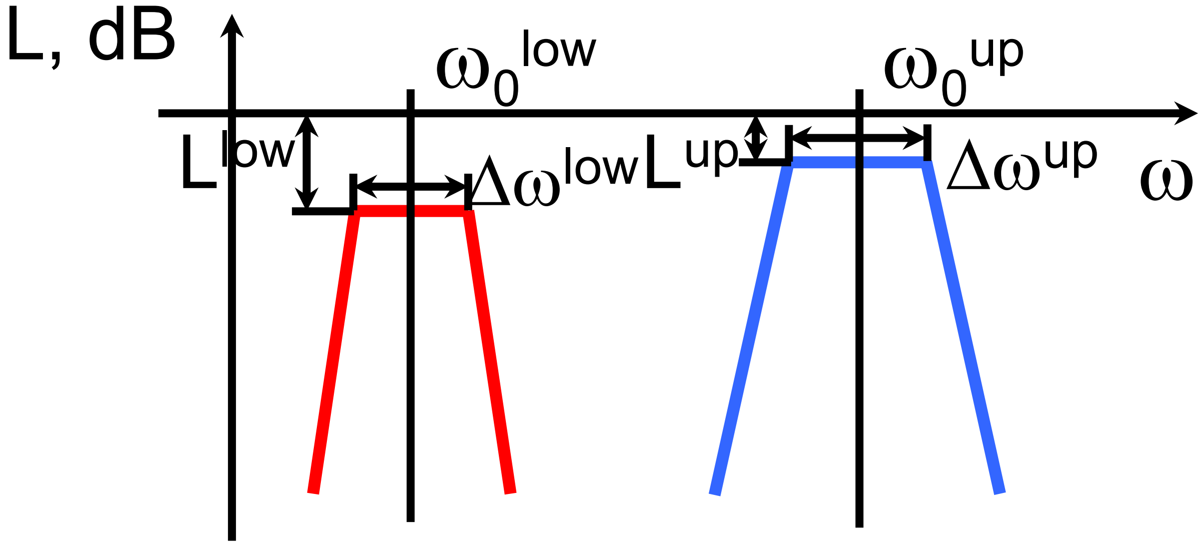


The central frequency $\omega_1$ is kept constant; at the same time the pass band is changed

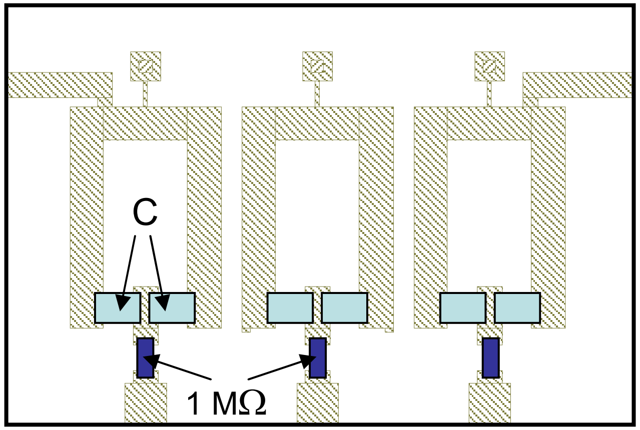
# Figure of merit of a tunable N-pole filter

**General definition:**

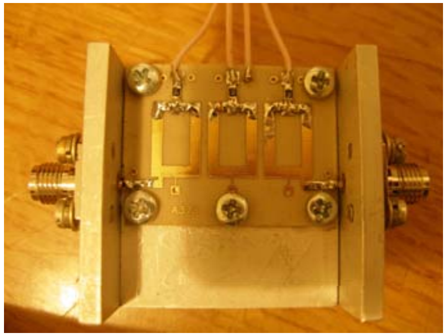
$$F_0 = \frac{\omega_0^{up} - \omega_0^{low}}{\sqrt{\Delta\omega_0^{up} \cdot \Delta\omega_0^{low}}}$$



# 3-pole tunable filter



30 x 20 mm$^2$



**BST capacitors:**

**C(0 V) = 0.941 pF**

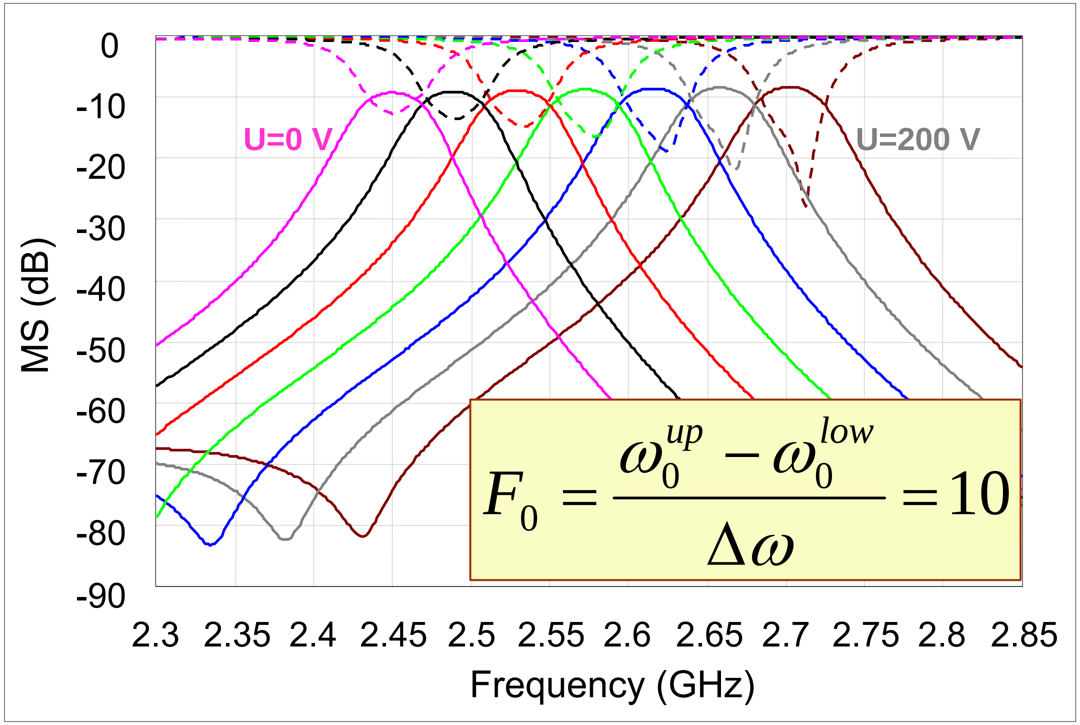
**C(200 V) = 0.655 pF**

**n = 1.44**

**tan δ = 0.01**

**Substrate:**

**Arlon 25N ($\varepsilon_r$ = 3.38)**



$$F_0 = \frac{\omega_0^{up} - \omega_0^{low}}{\Delta\omega} = 10$$

**$f_0$ = 2.45 – 2.7 GHz;   Δf = 25 MHz (1%)**

# Advanced definition of the figure of merit of the N-pole filter

$$F = \frac{F_0}{\sqrt{L^{up} \cdot L^{low}}}$$

dB$^{-1}$

$$F_{\max} = \frac{\sqrt{K}}{8.68 \cdot N}$$

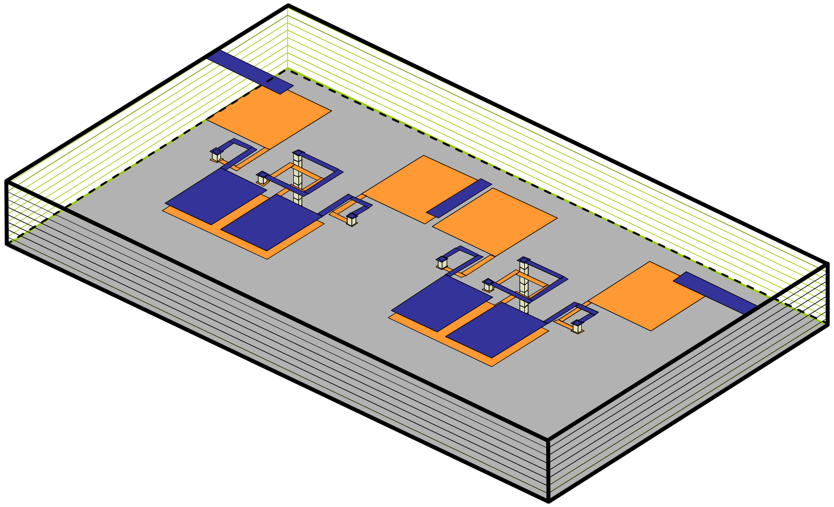
dB$^{-1}$

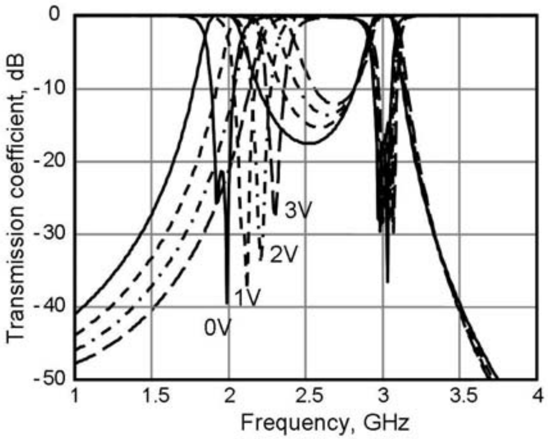
***K*** is the commutation quality factor

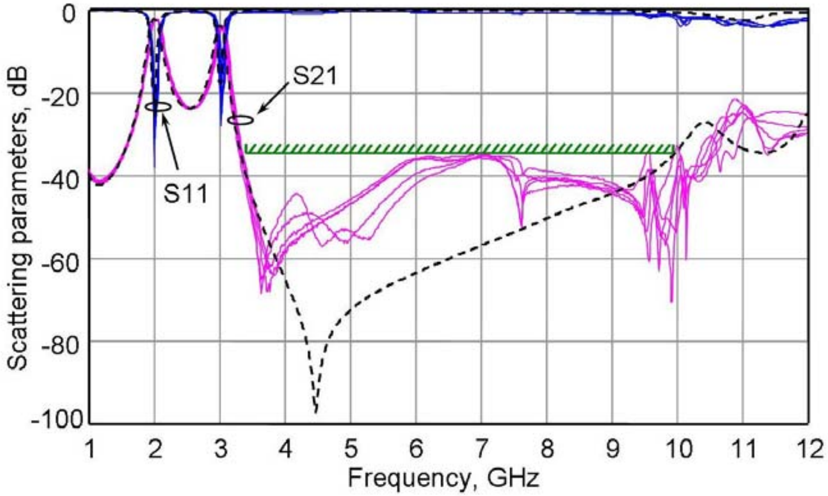
***N*** is the number of the resonators

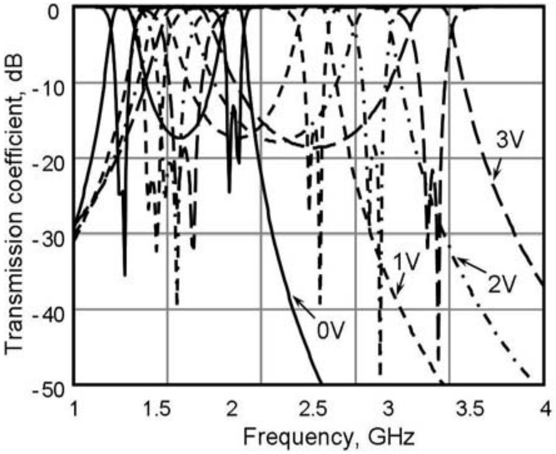
V. Pleskachev, I. Vendik, Figure of merit of tunable ferroelectric planar filters, Proc. 33rd EuMC, Vol. 1, pp. 191-194, October 2003.

# Tunable dual-band filter on RH/LH TL sections







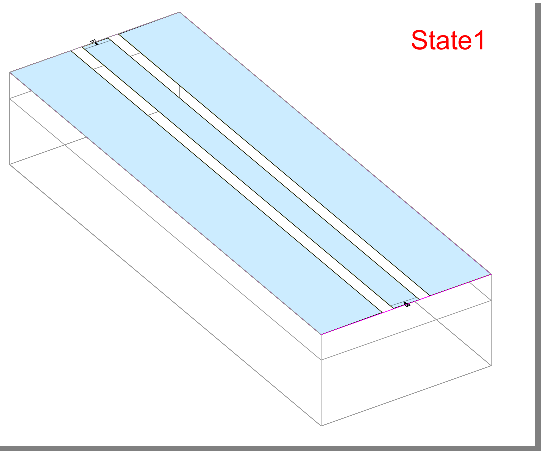


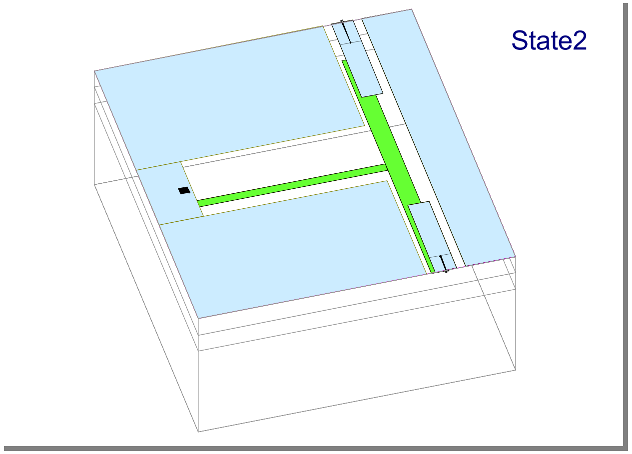
# What is the phase shifter?

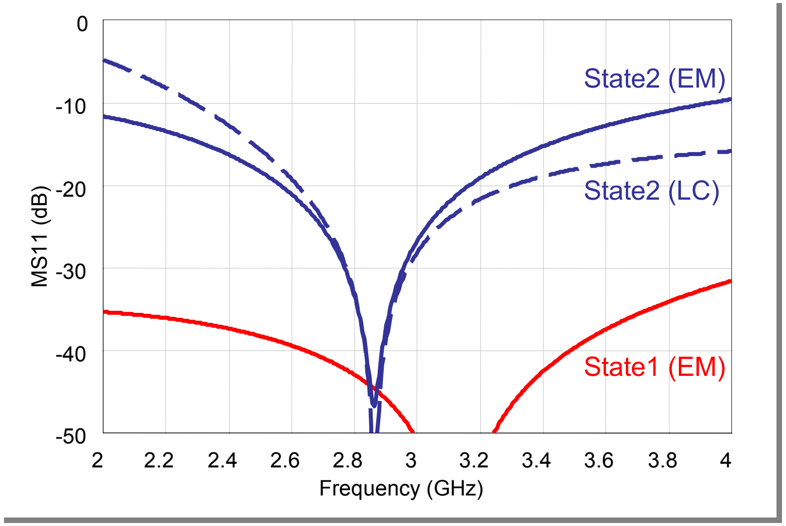
- The phase shifter is the device, which provides continuous or digital change of the phase of transmitted or reflected electromagnetic wave under the control signal and is characterized by the differential phase shift:

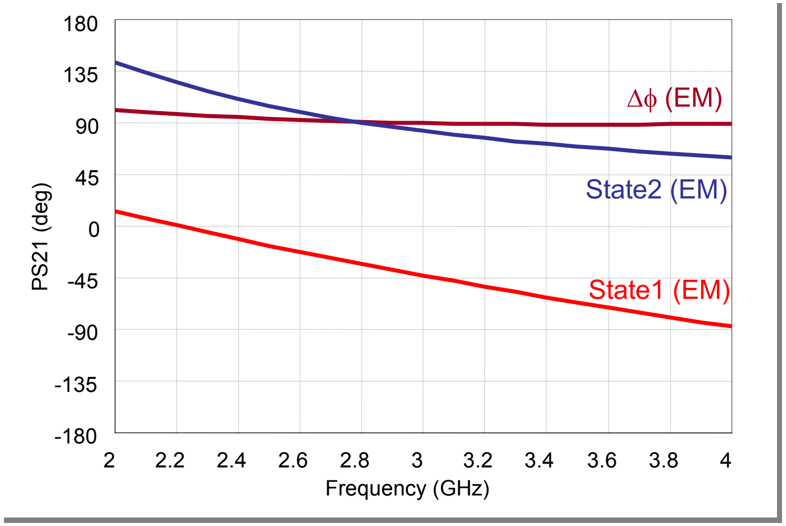
$$\boxed{\Delta\varphi = \varphi_1 - \varphi_2}$$

# 90° phase shifter on switchable RH/LH TL sections

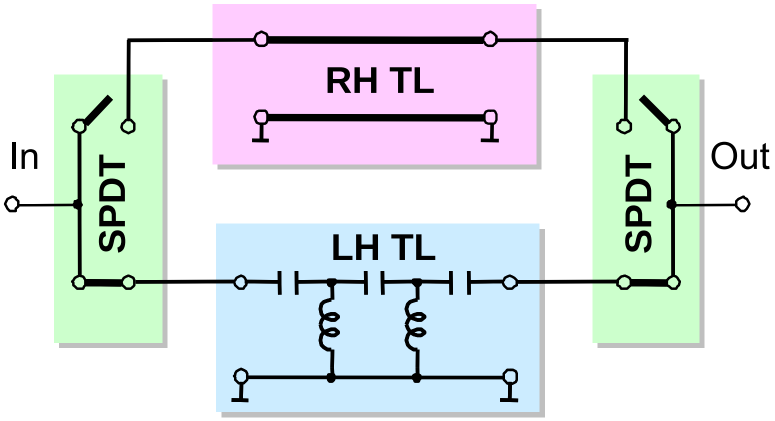


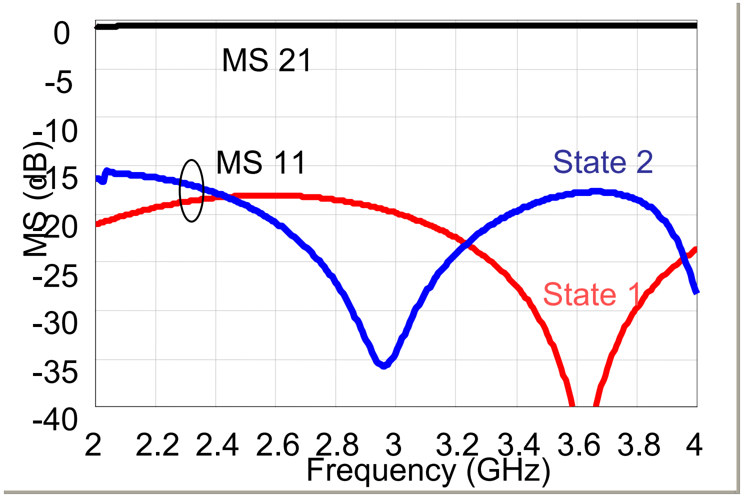


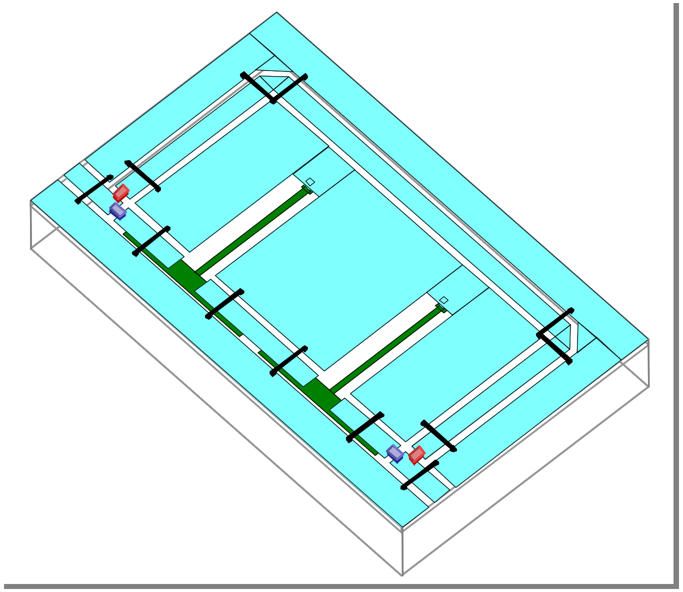


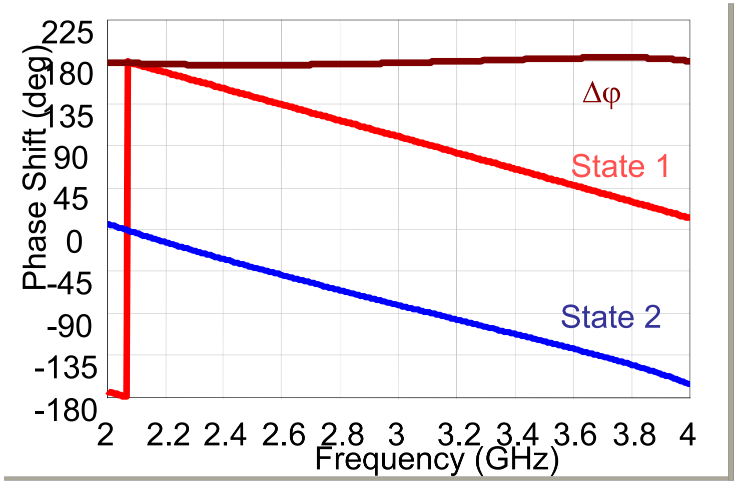


# Coplanar design of the180° phase shifter (switchable TLs)









# Figure of merit of a phase shifter

$$F = \Delta\varphi_{\mathrm{degree}} / L_{\mathrm{dB}}$$

For a digital reflection type one-bit phase shifter

$$F = 6.6\left(\sin\frac{\Delta\varphi}{2}\Big/\frac{\Delta\varphi}{2}\right)^{-1}\cdot\sqrt{K}$$

***K* is the commutation quality factor (CQF)**

# Comments and conclusions

- **The characteristics of metamaterial can be controlled by a variation of the dielectric permittivity of the host material and/or constitutive resonant inclusions**
- **The characteristics of TL metamaterial can be controlled by a variation of parameters of capacitive components**
- **The control of the dielectric permittivity can be performed by the temperature or *dc* biasing electric field (optical control is possible)**
- **The quality of tunable material/component can be estimated by the CQF, which is determined by the tunability and the loss factor of the tunable material/component**
- **The quality of tunable devices based on tunable matamaterial is determined by the figure of merit FM, which is fully determined by the CQF**