Superconducting Planar Filter Design

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- Kinetic inductance
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- Measurements
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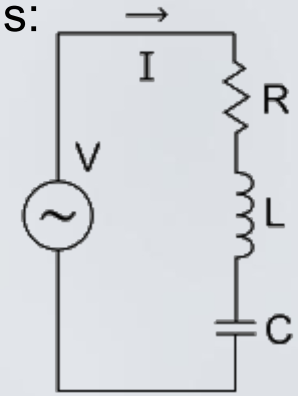
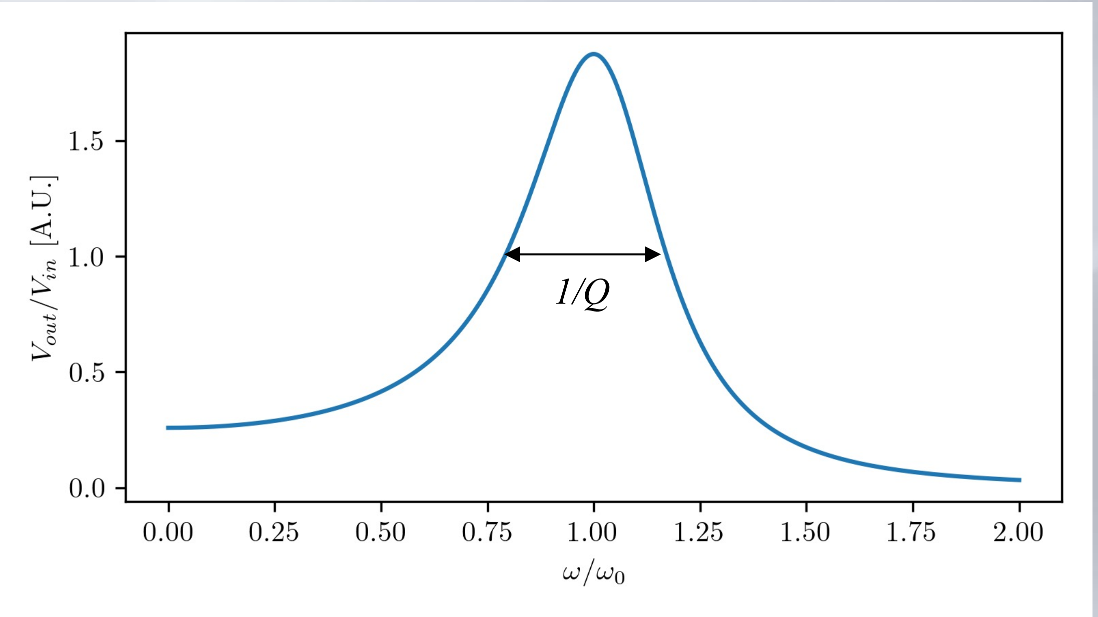
Electronic resonance circuits

- Frequency response of the system
- Resonance Quality factor (Q)
- Benefits of high Q-factor systems:
    - Selectivity
    - Amplification
- RLC lumped element model

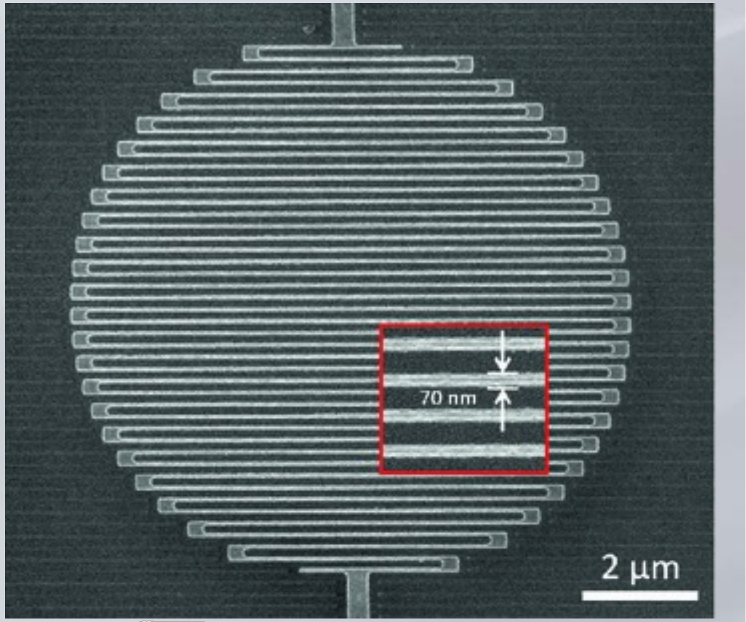


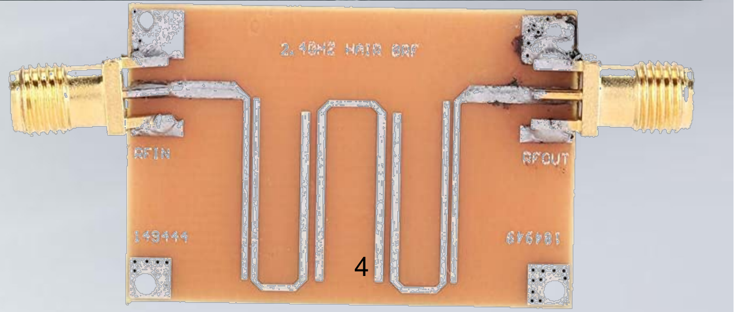


- Distributed resonance circuit
    - Characteristic dimensions - λ/2, λ/4 resonators
    - Phase velocity dependent

Resonance circuits applications

- Amplificiation
  - Wireless communication
  - Detectors
- Filters
  - Noise suppression

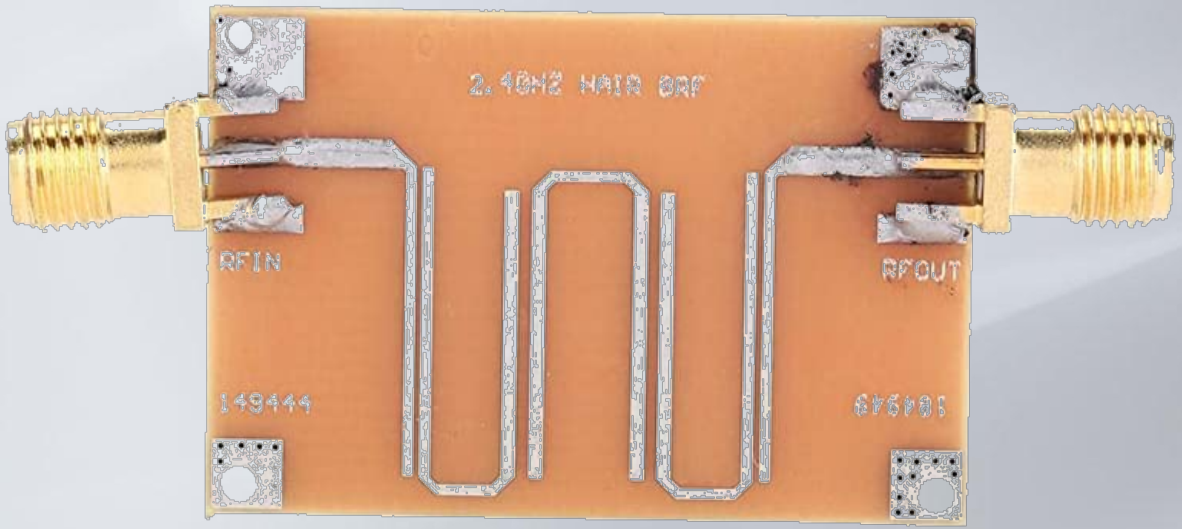


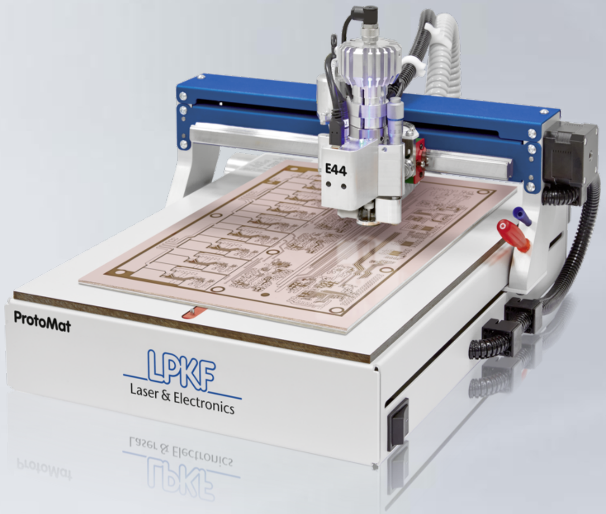


1.) https://opencircuit.shop/Product/ESP8266-ESP-12F-WIFI-Module
2.) F. Najafi et. Al., Superconducting Nanowire Architectures for Single Photon Detection, 2016
3.) http://www.giga.co.za/ocart/index.php?route=product/product&product_id=448

Fabrication of resonance circuits

- Printed circuit board base (PCB)
- Conductive layer – metals (Cu,…)
- Milling process

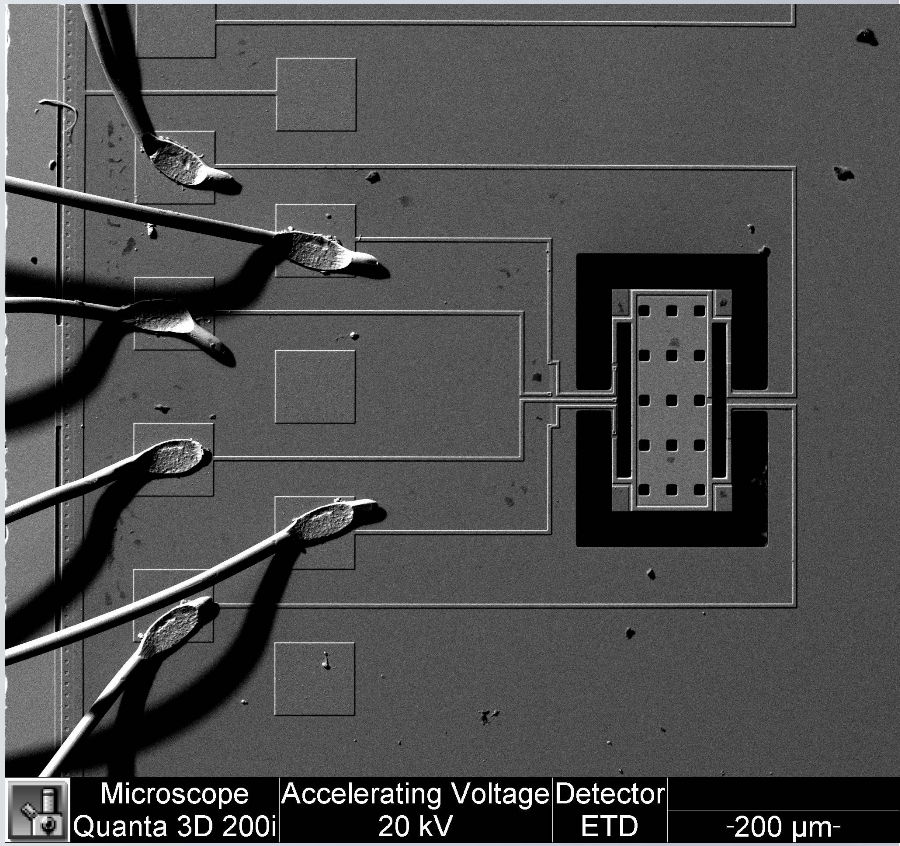




1.) http://www.giga.co.za/ocart/index.php?route=product/product&product_id=448
2.) https://www.lpkf.com/en/industries-technologies/research-in-house-pcb-prototyping/products/lpkf-protomat-e44

Resonance circuits fabrication

- Base - dielectric insulating layer (Si/Al2O3) substrate
- Conductive layer
  - Metals (Au, Ag, Cu,…)
  - Superconductors (Nb,NbN,MoC,…))
    - Low losses
    - Change of phase velocity
- Fabrication
  - Conductive layer sputtering on top of substrate
  - Photolithography



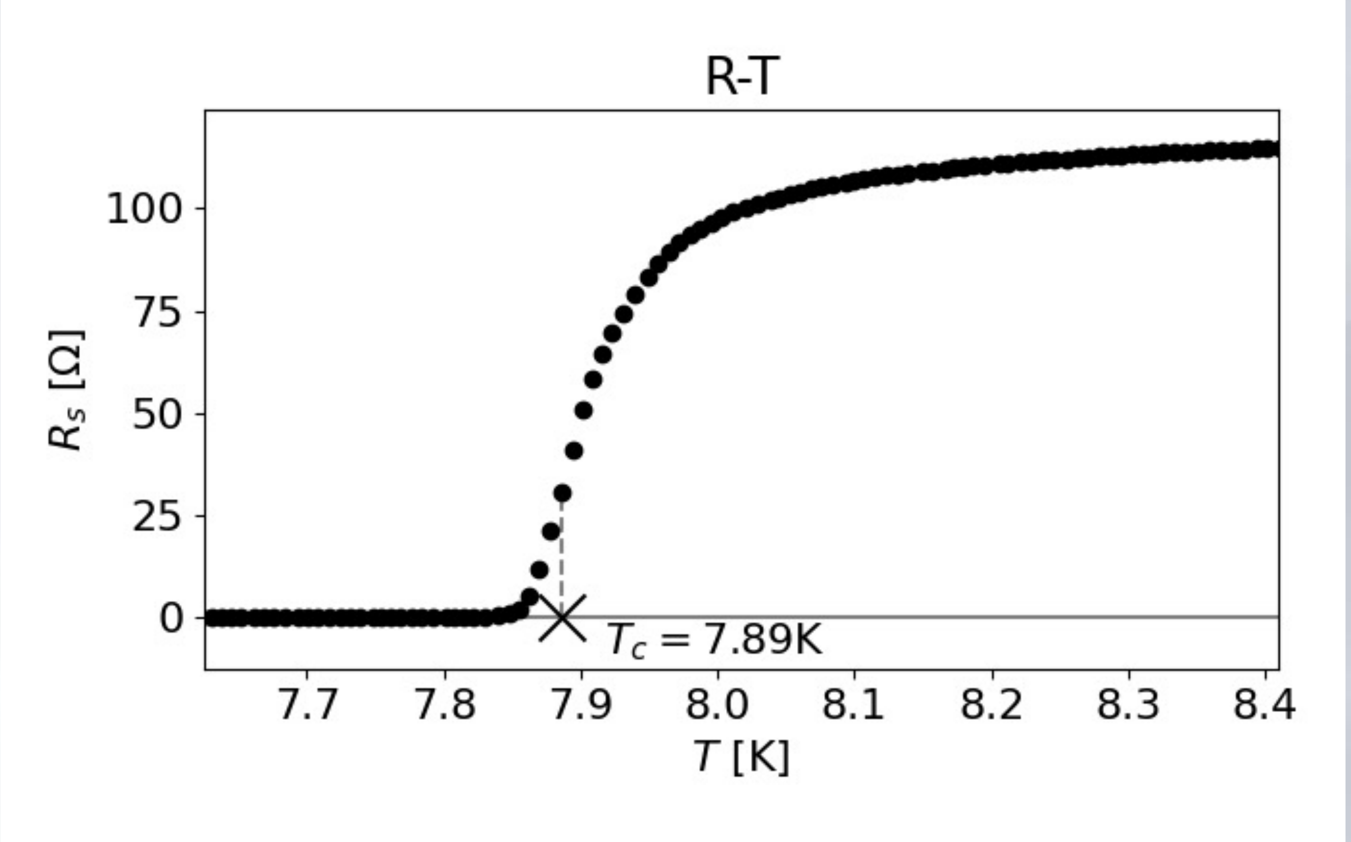
1.) Minin, Igor & Minin, Oleg & Editors,. (2016). Microsensors. DOI: 10.5772/16275

Superconductivity

- Temperature dependent DC sheet resistance

$$R_s = \frac{\rho l}{S} = \frac{\rho l}{hw} = \frac{\rho}{h}$$

h – sample thickness



Complex conductivity

- London Theory
- BCS Theory
  - Mattis-Bardeen equations for complex conductivity

$$\sigma = \sigma_1 - i\sigma_2$$

$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E) - f(E+\hbar\omega)]g_1(E)dE + \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{-\Delta}[1 - 2f(E+\hbar\omega)]g_1(E)\mathrm{d}E$$

$$\frac{\sigma_2}{\sigma_n} = \frac{2}{\hbar\omega}\int_{max(\Delta-\hbar\omega,-\Delta)}^{\Delta}[f(E) - f(E+\hbar\omega)]g_2(E)\mathrm{d}E$$

$$g_1 = ig_2 = \left(1 + \frac{\Delta^2}{E(E+\hbar\omega)}\right)N_S(E)N_S(E+\hbar\omega)$$

Resistance and reactance in thin-film limit

- Kinetic inductance

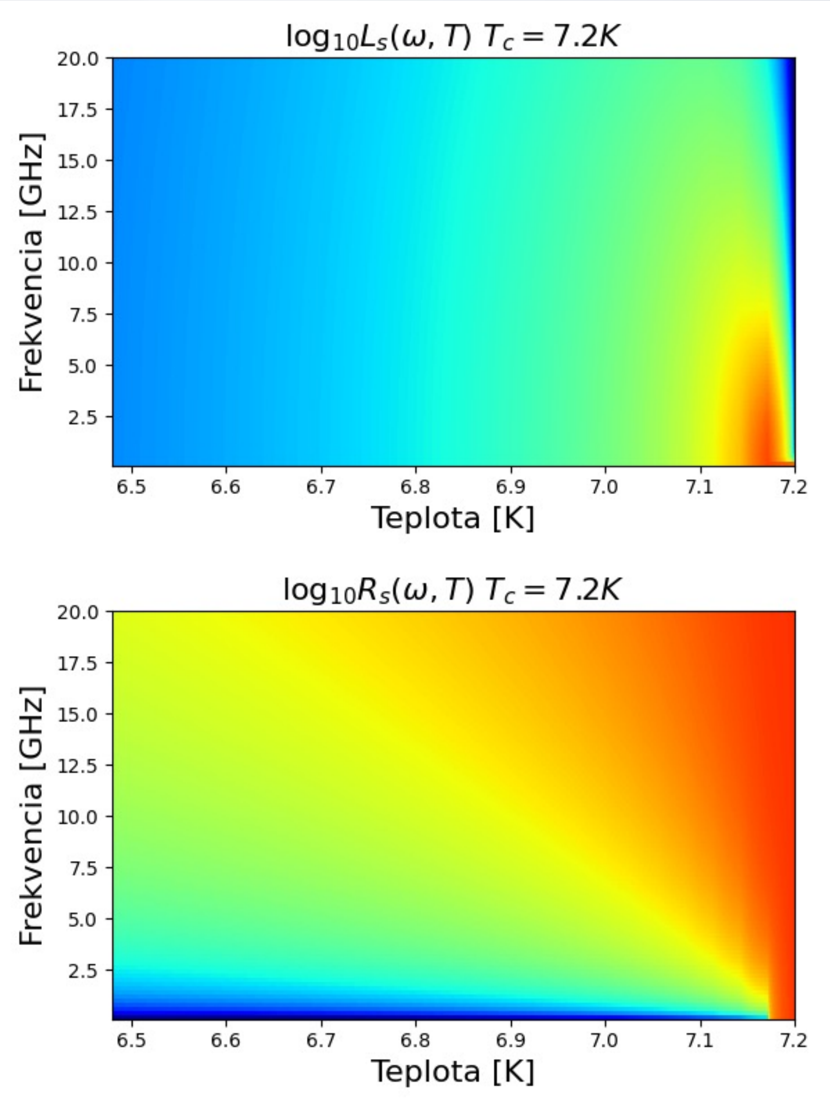
$$L_k(T) = \frac{\sigma_2(\omega, T)}{\omega(\sigma_1^2(\omega, T) + \sigma_2^2(\omega, T))}$$

- Resistance
  - Power loss contribution

$$R(T) = \frac{\sigma_1(\omega, T)}{(\sigma_1^2(\omega, T) + \sigma_2^2(\omega, T))}$$

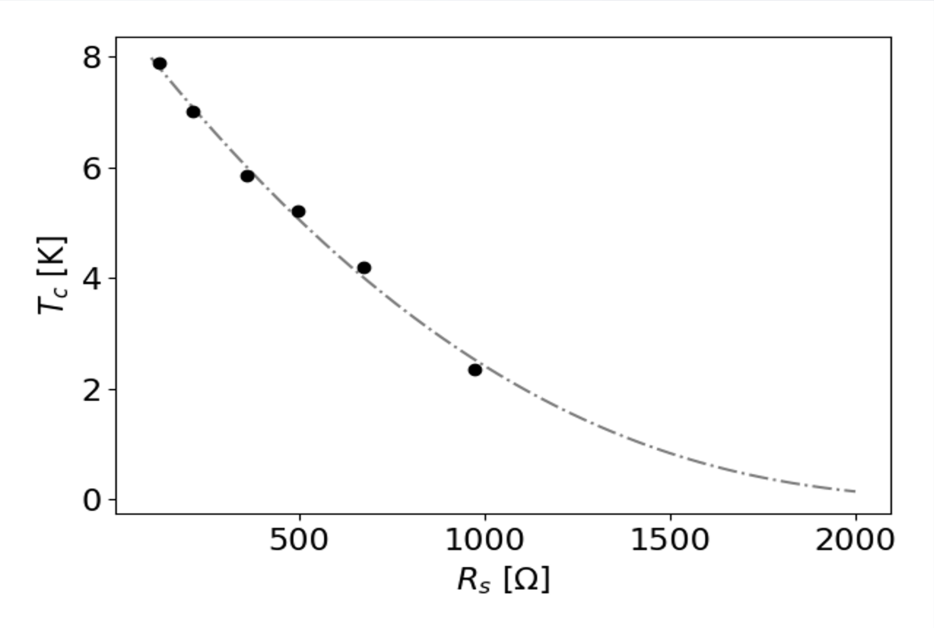
- Impedance

$$Z(\omega, T) = R(\omega, T) + i\omega L_k(\omega, T)$$



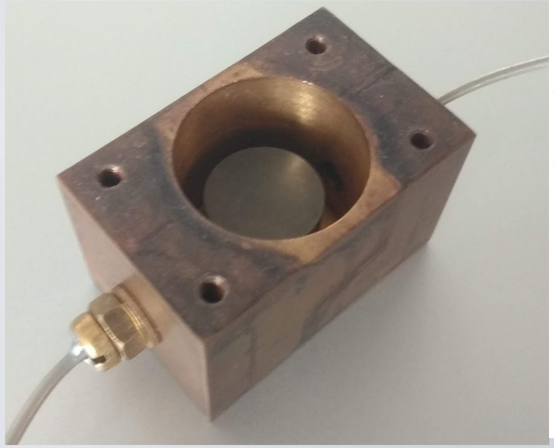
Disordered superconductors

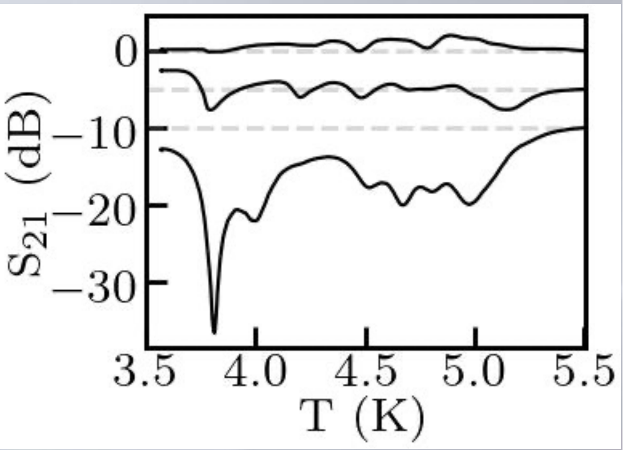
- Disorder – inelastic scattering
- Suppressing Tc
- Characterization by sheet resistance
- Conductivity
  - Dynes’ superconductivity
    - numeric model [1]
  - Disorder parameter Γ

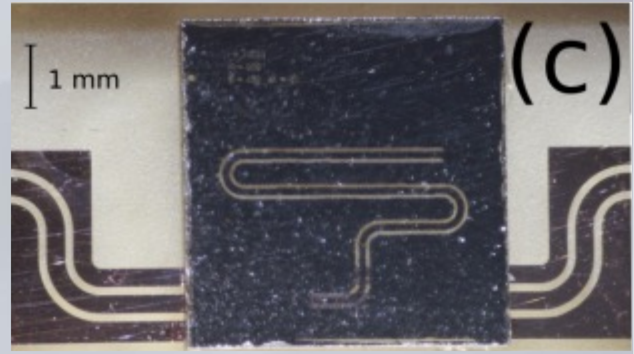


Experimental methods

- Narrowband
    - cavity / dielectric resonator
- Broadband
    - Coplanar waveguide spectroscopy
    - Corbino spectroscopy



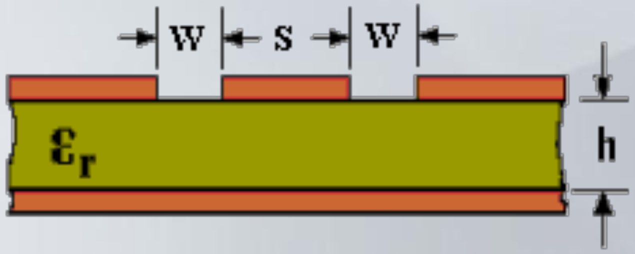


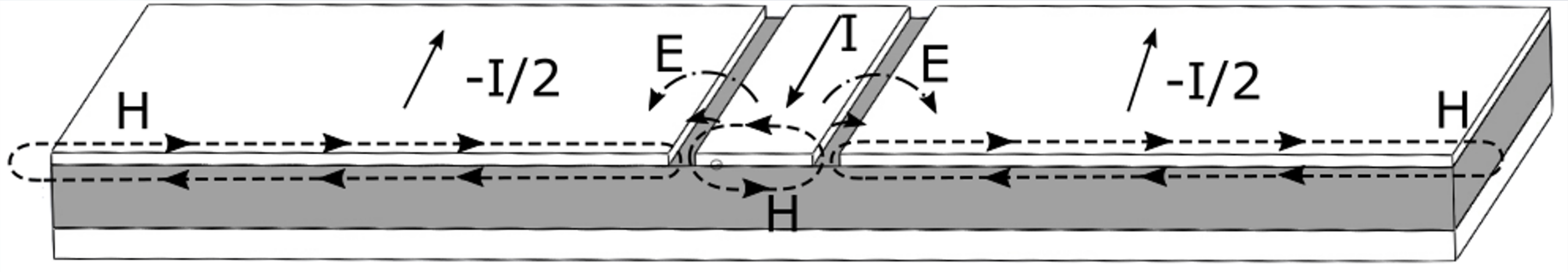


1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483
(c) L. Wendel et. al.: Microwave probing of bulk dielectrics using superconducting coplanar resonators in distant-flip-chip geometry, Review of Scientific Instruments, May 2020

Coplanar waveguide

- Dielectric with permittivity ε
- Conductive signal line with ground planes
- Impedance matching (50Ω) by:
  - Dimensions (s,w,h)
  - substrate properties
- Example: PCB



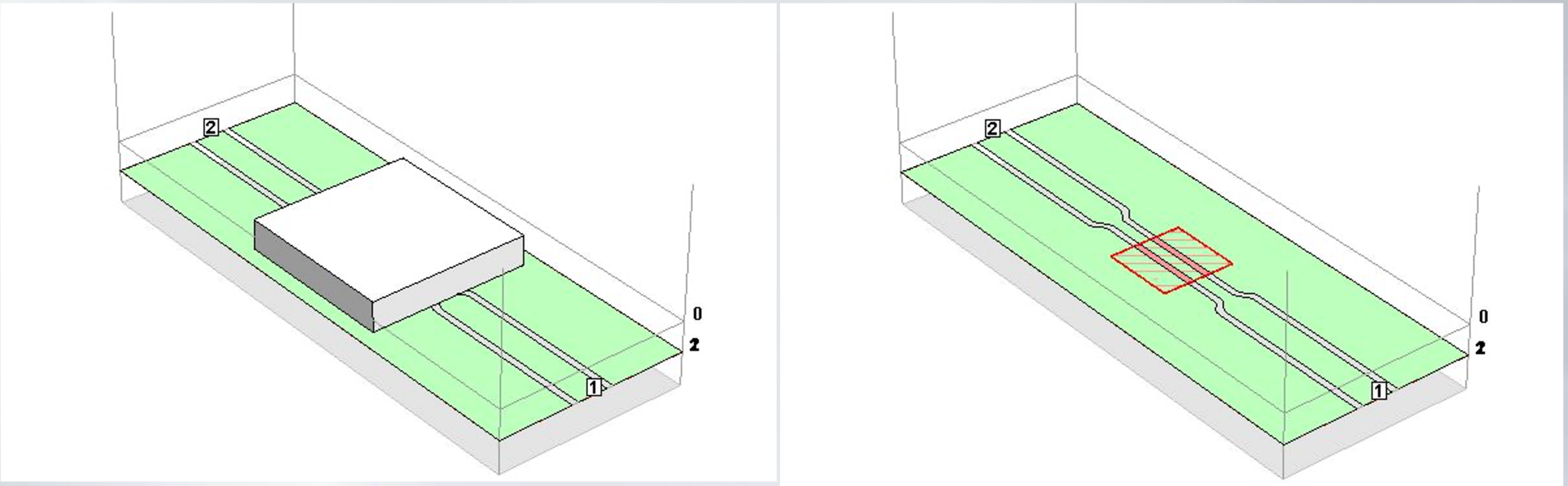


1. https://chemandy.com/calculators/coplanar-waveguide-with-ground-calculator.htm
2. M. Baránek, Conductivity of strongly disordered ultra-thin MoC superconducting films, 2020, Diplomová práca

Broadband flip-chip spectroscopy

- Coplanar waveguide (CW)
- Superconductor facing CW
- Measurement of transmission (S21)
- Transmission of CW affected by sample

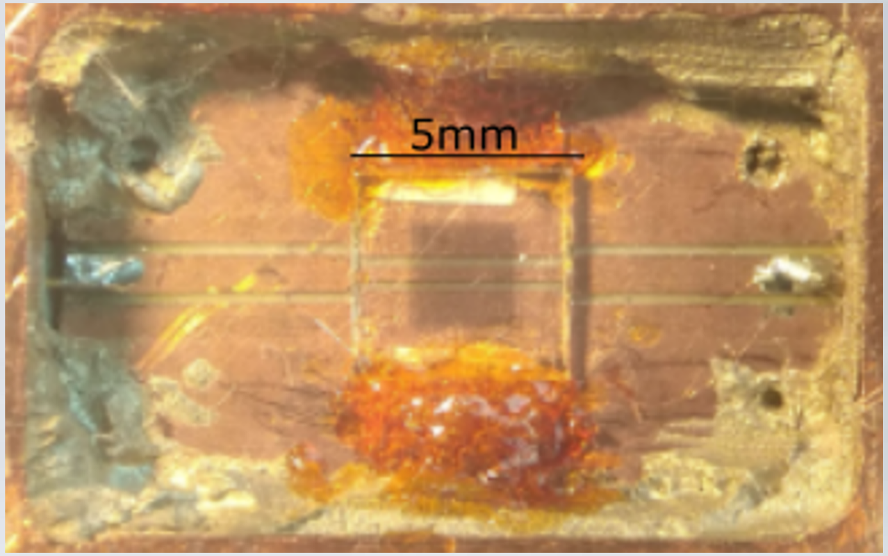
$$S_{21} = 10\log\left|\frac{V_2}{V_1}\right|^2$$



1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483

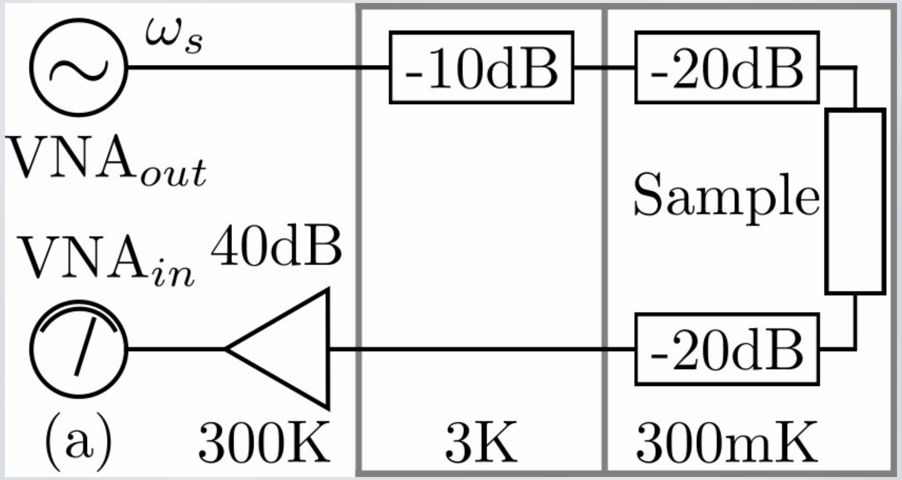
Samples

- Thin MoC layers (5 - 30nm)
- Magnetron sputtering in acethylene atmosphere
- Disorder
  - Acethylene partial pressure → Carbon content
  - Deposition time → thickness
- Photolithography



1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483

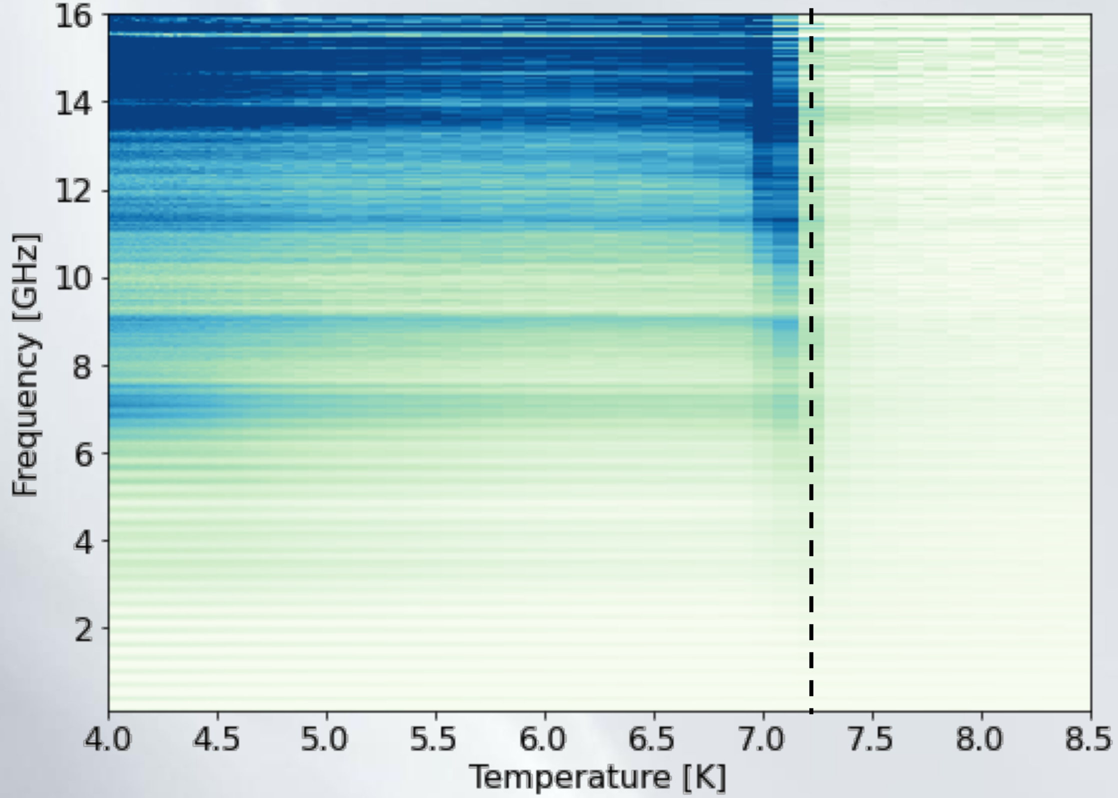
Experiment scheme

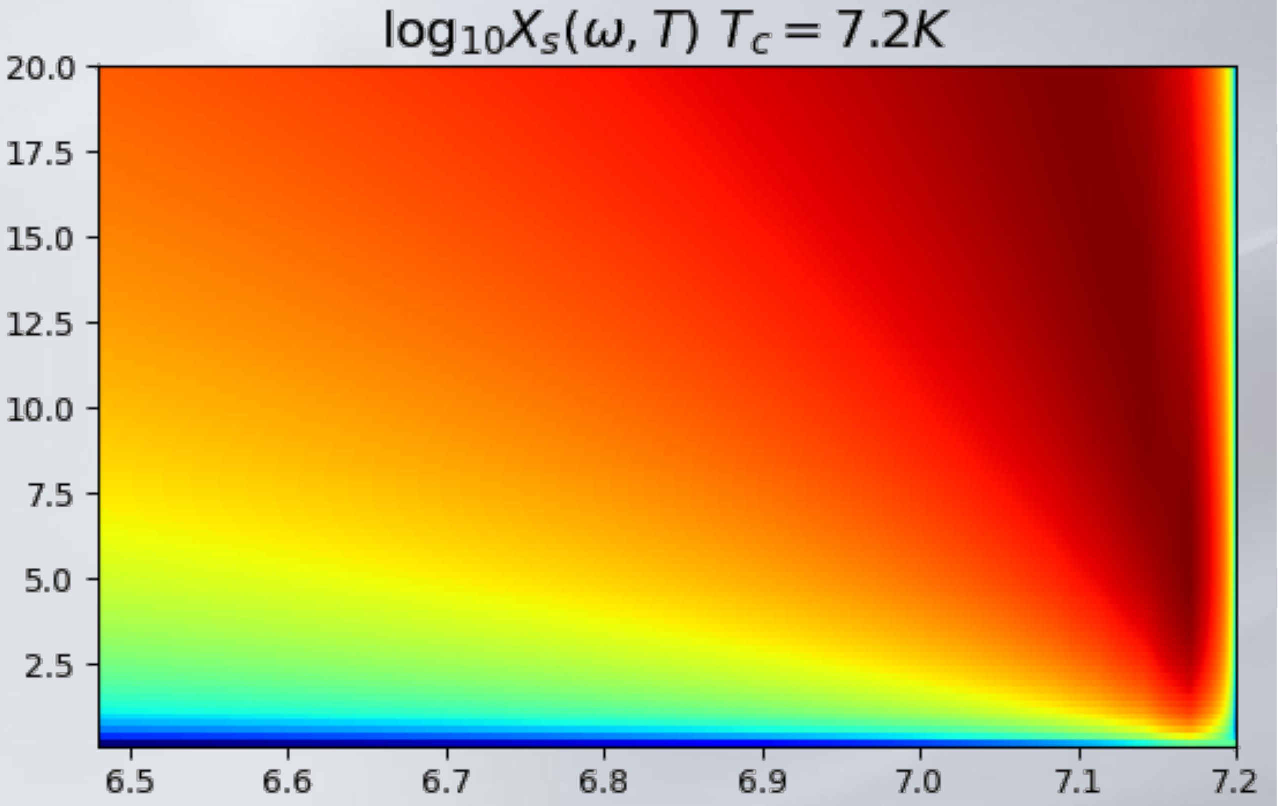


- VNA - Vector Network analyzer
- Dry sorption pump He3 refrigerator
    - Temperatures down to ~ 360mK

1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483

Transmisné spektrum, fáza S21, Rs = 200Ω





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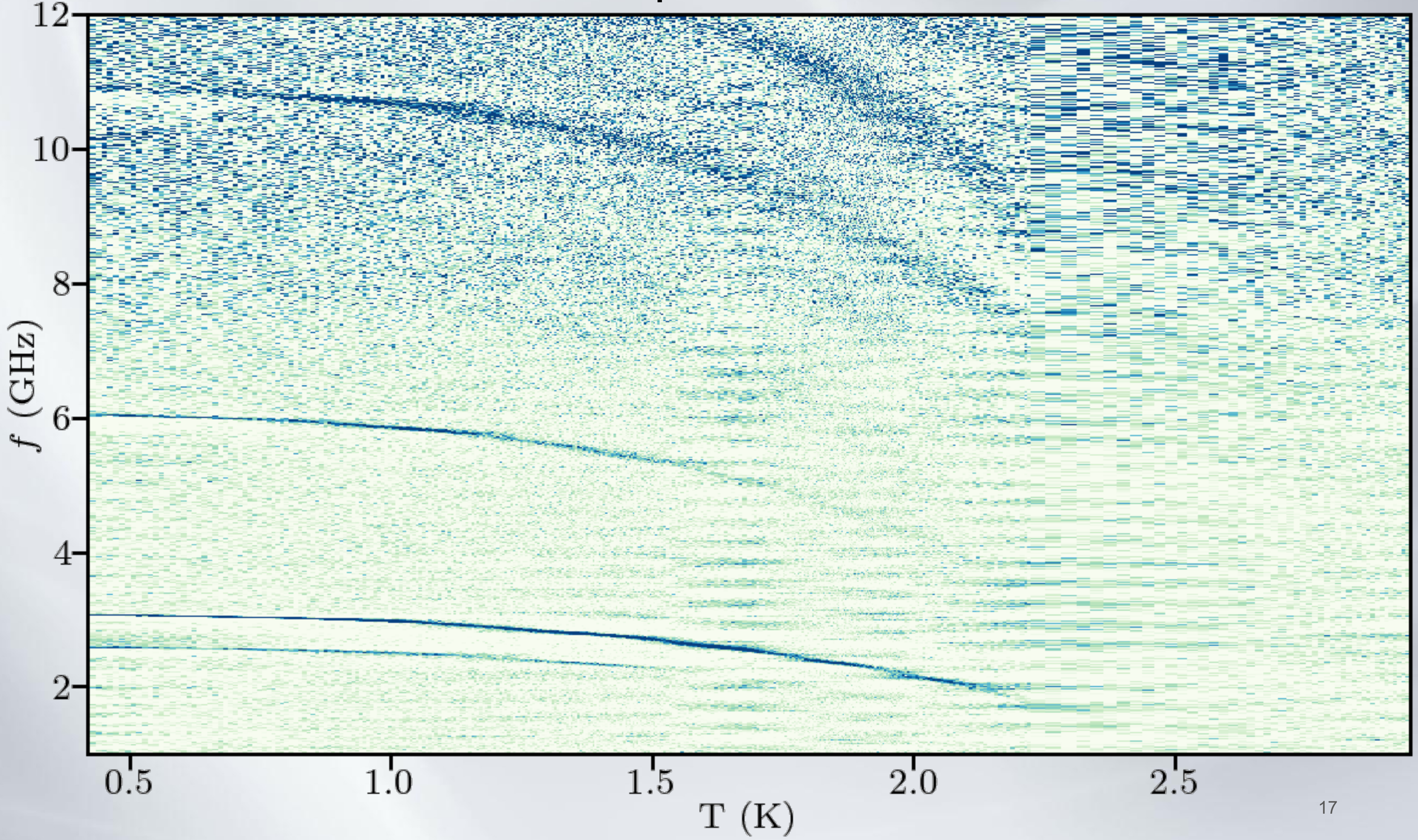
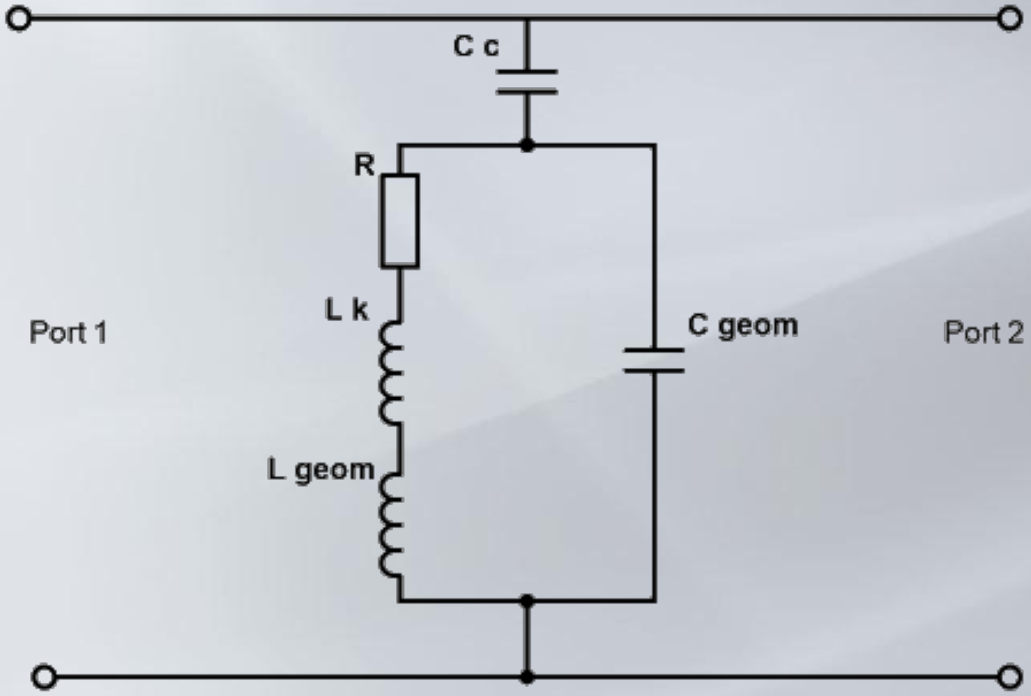
Transmisné spektrum, Rs = 970Ω



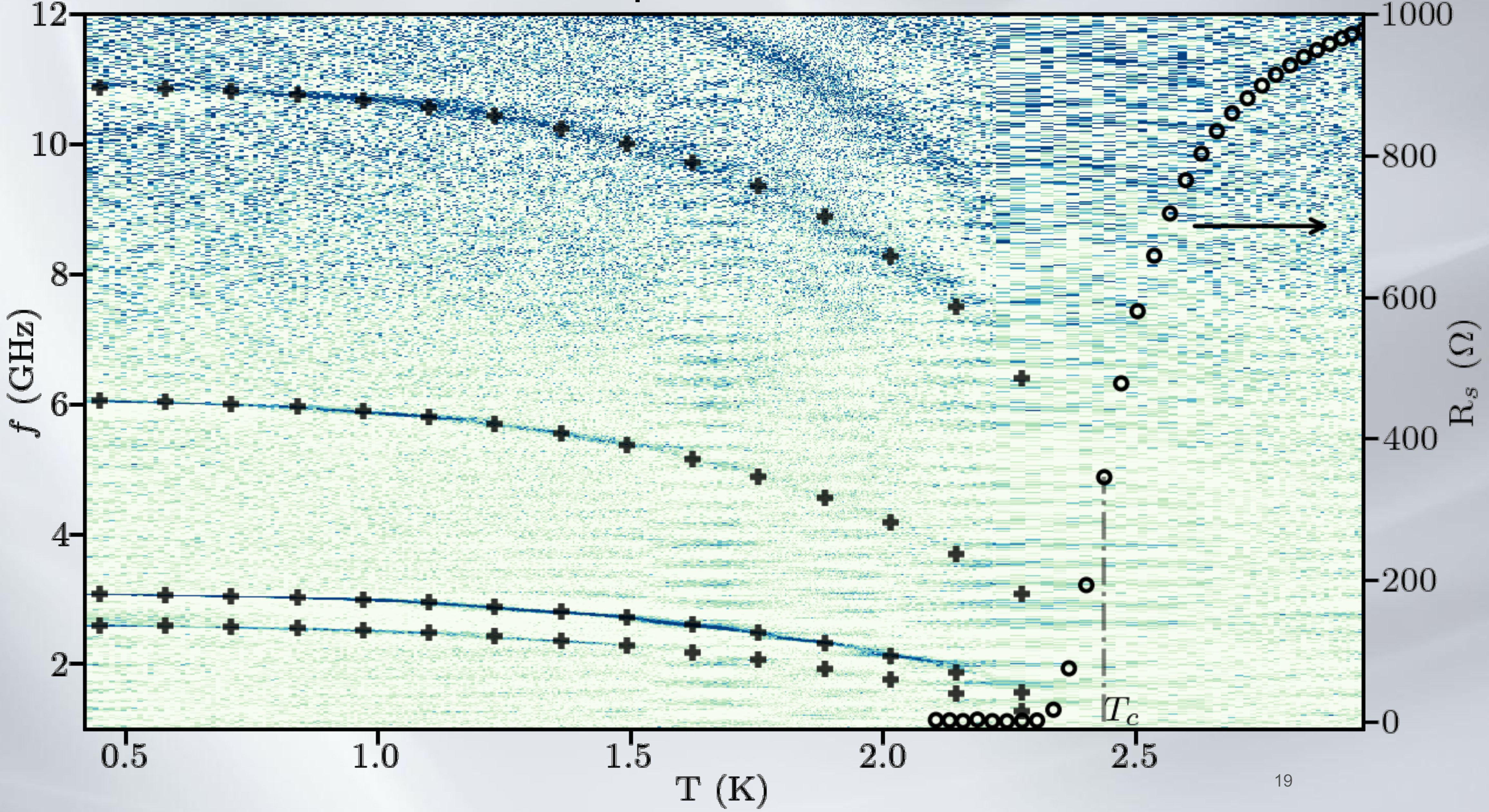
LC Resonance circuit model

$$\omega_n^*(T) \approx \frac{1}{\sqrt{(L_{geom} + L_k(T))C'_{geom}}}$$

- Kinetic inductance and geometric inductance
- Temperature dependence of kinetic inductance dominant
- L_k (σ) dependent on T, Tc (Δ_0), γ, ω



Transmisné spektrum, Rs = 970Ω



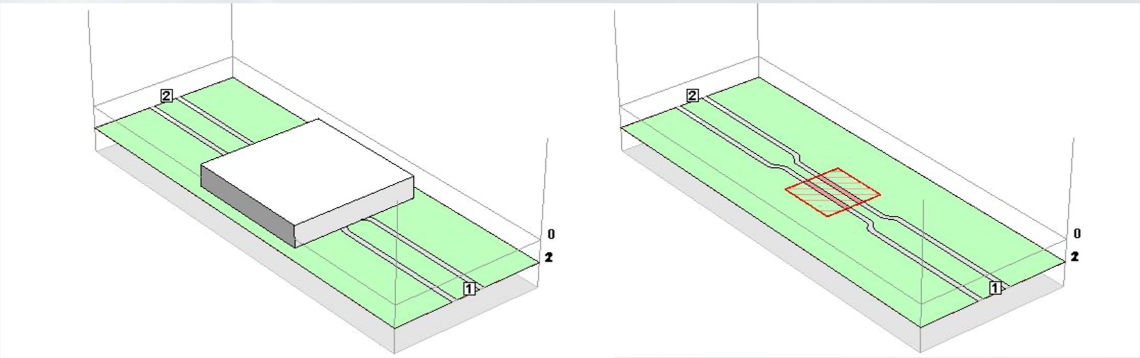
Analýza teplotnej závislosti rezonancií

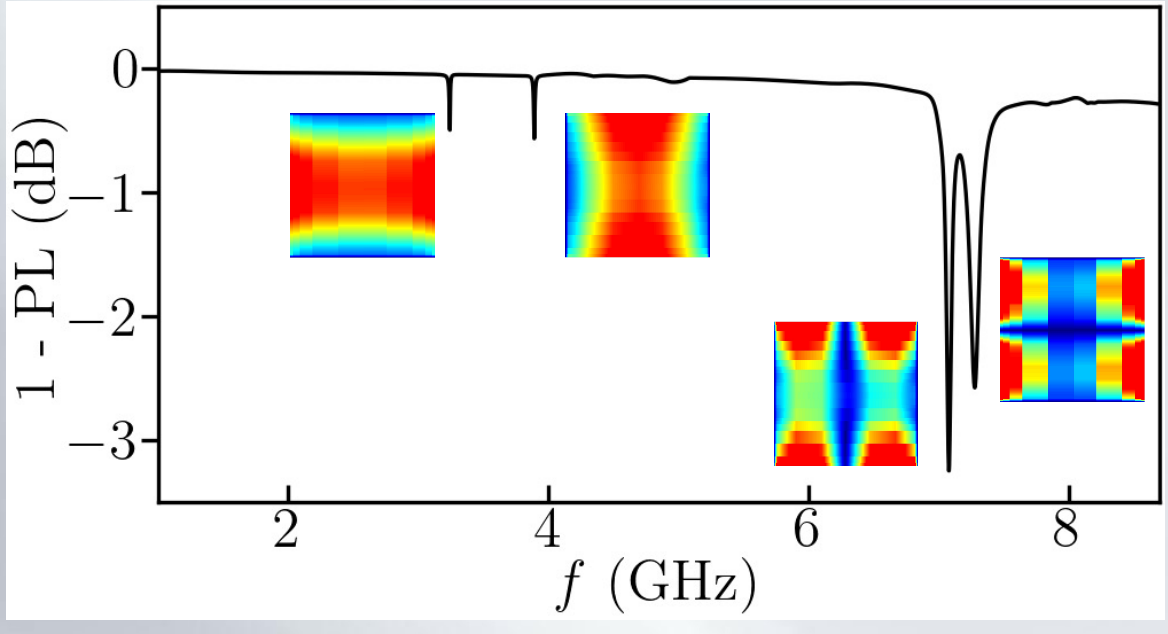
Vzorka	**Rs [Ω]**	**Tc [K] R-T**	**Tc [K] spec**	**γ STS**	**γ spec**
B	212	7.04	7.02	0.03	0
C	565	4.85	5.11	0.2	0.2
D	974	2.44	2.52	0.44	0.5

- Parametre fitu teplotnej závislosti [2]
  - Korešpondujú s STS meraniami na supravodiči
  - Korešpondujú s R-T DC meraniami na supravodiči
- Dominantný príspevok od supravodiča
  - Doteraz publikované - tenká vrstva - perturbácia k dielektrickým/dutinovým rezonanciám [3]

1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483
2. M.M. Felger et. Al., Microwave resonances in dielectric samples probed in Corbino geometry: Simulation and experiment, 2013, Review of Scientific Instruments 84 114703

Numerical simulations of resonances

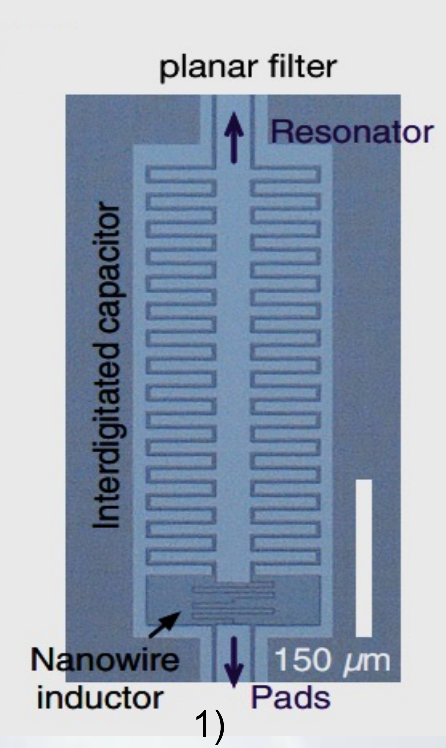




- Planar superconductor resonances at low frequencies
- Low phase velocity
- Sensitive to sample position

1. M. Baránek et. Al., Kinetic planar resonators from strongly disordered ultra-thin MoC superconducting films investigated by transmission line spectroscopy, 2021, arXiv:2102.13483

Planar filters



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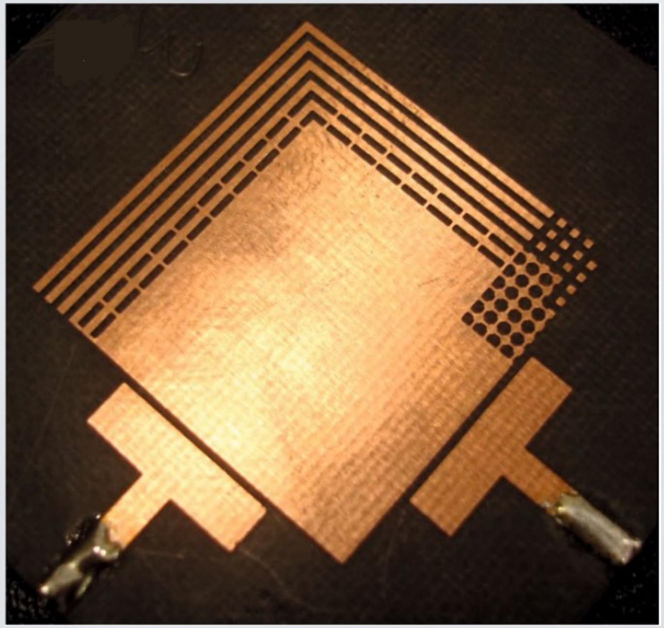

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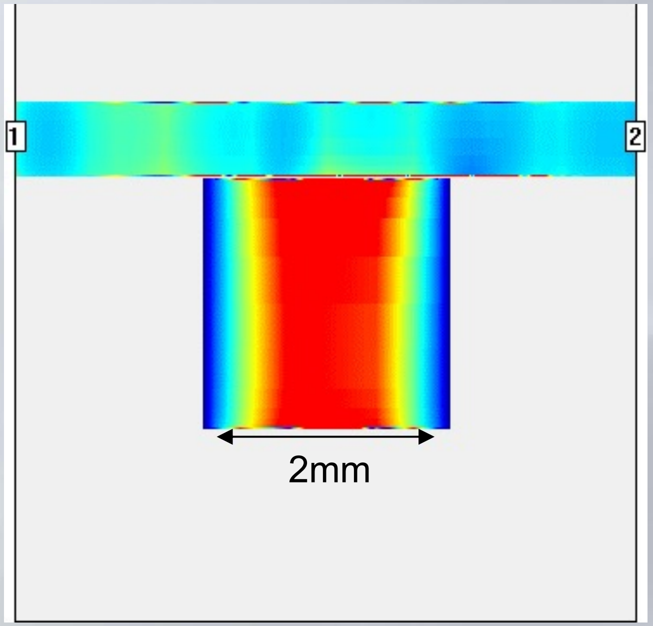

3)

- Quantum circuitry
- Complex filters

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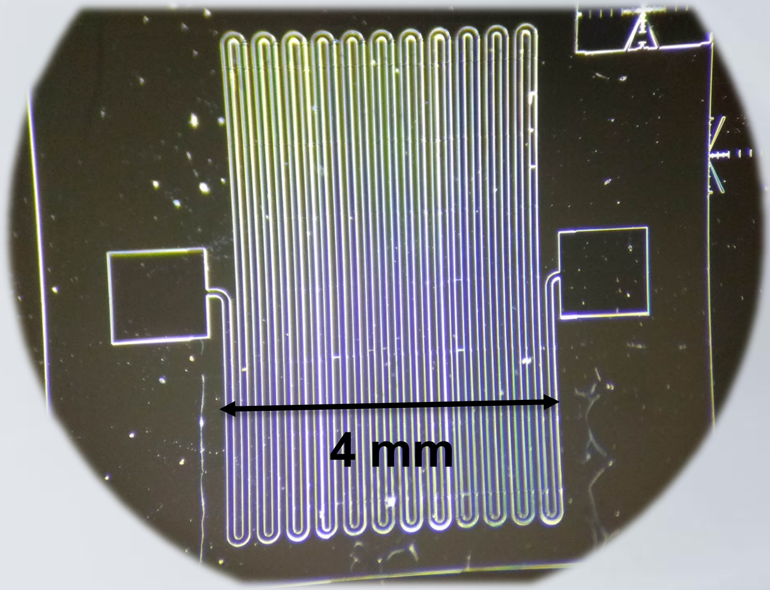
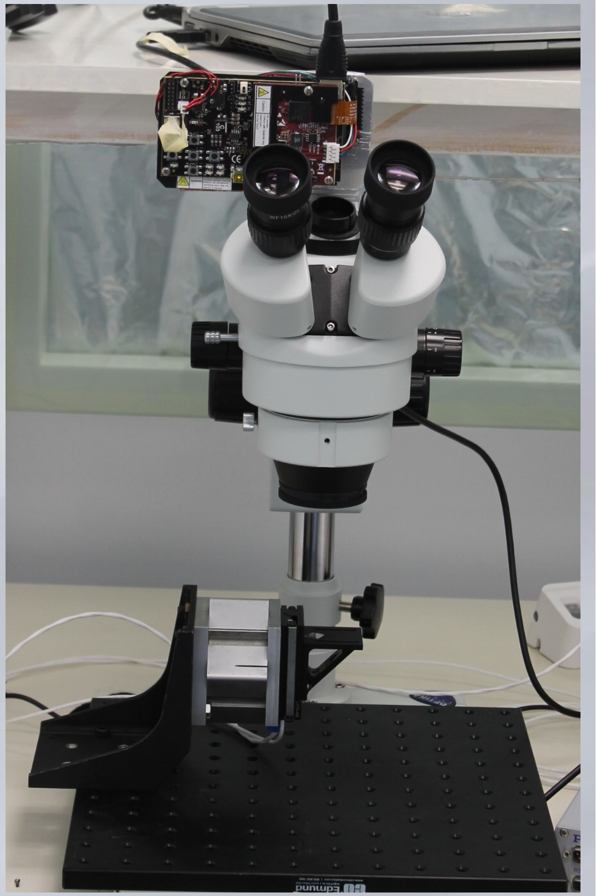
1. P. Harvey-Collard, On-chip microwave filters for high-impedance resonators with gate-defined quantum dots, 2020, Physical Review Applied, 14(3), 034025.
2. A. Naji, P. A. Warr, Geometrical Perturbation Techniques and Approximate Analysis for Eigenmode Splitting and Shifting in Electromagnetic Planar Dual-Mode Resonators, 2019, Scientific Reports 9, 2417
3. M. Baránek, Conductivity of strongly disordered ultra-thin MoC superconducting films, 2020, Diplomová práca

Planar filters - photolithography

- Projecting patterns using DLP projector
- Theoretical resolution up to 1 µm

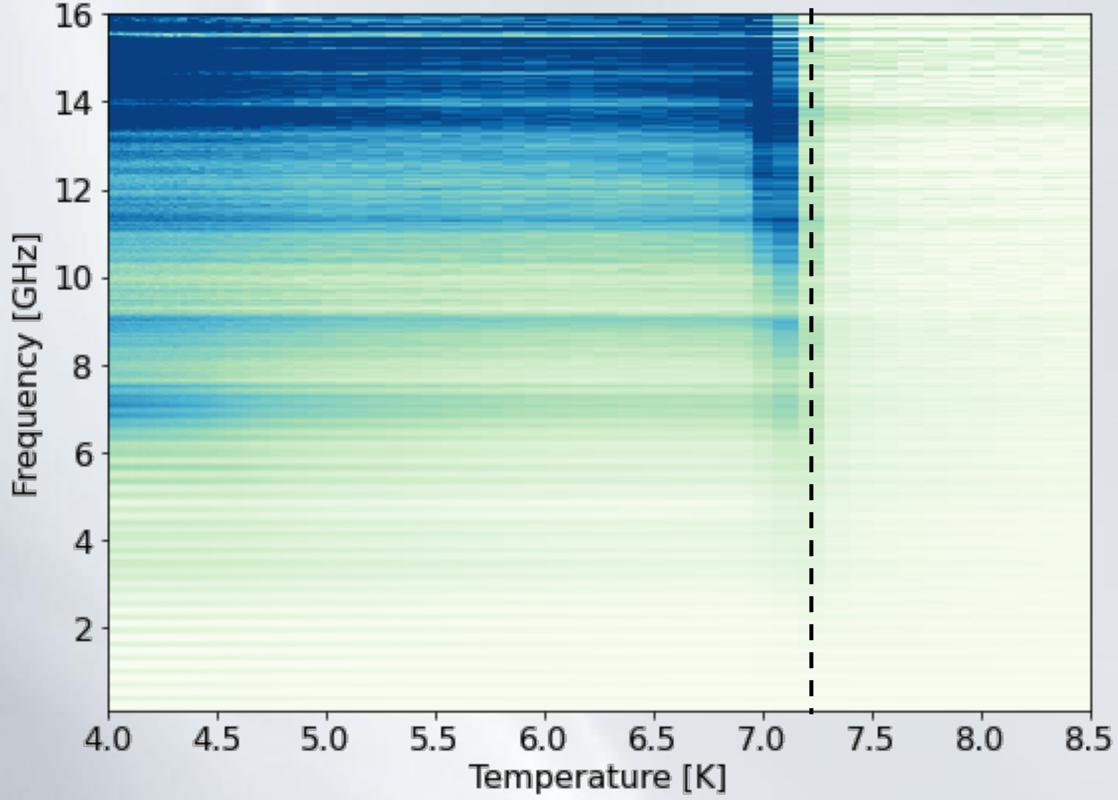


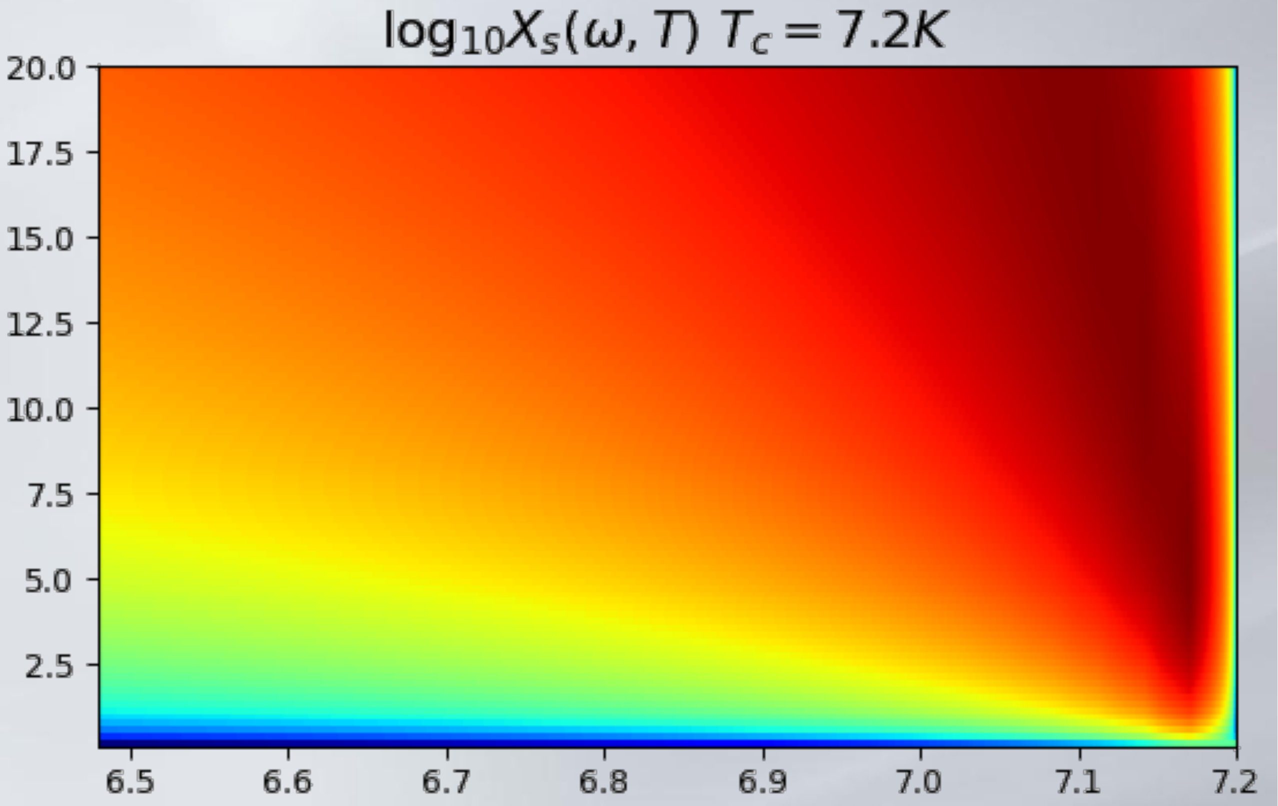


Conclusion

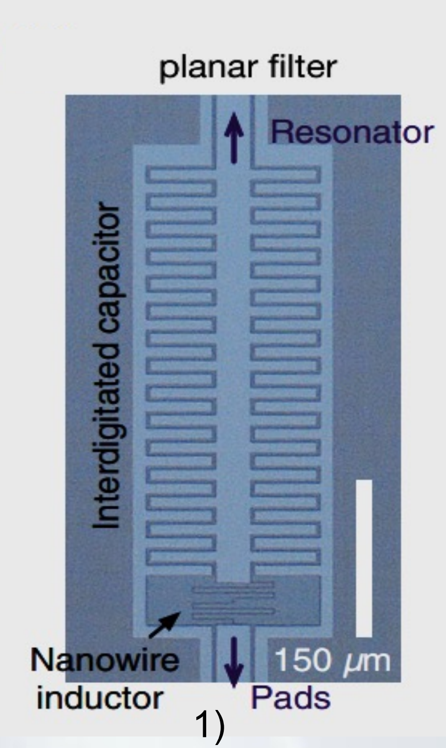
- Thin MoC films as band-stop filters
    - Eigenmodes of standing waves in MoC
    - Decreased size due to the high kinetic inductance
    - Temperature dependence by theoretical model of conductivity
    - Numerical simulations

Transmisné spektrum, fáza S21, Rs = 200Ω





Aplikácia - planárne filtre



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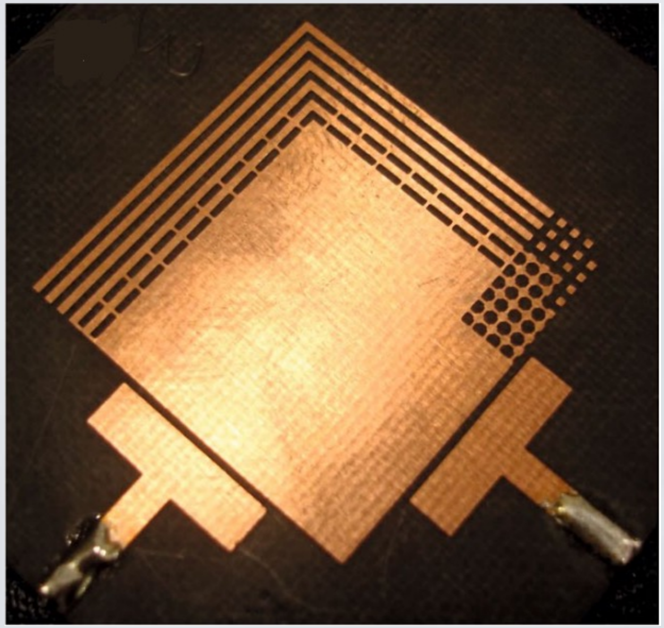

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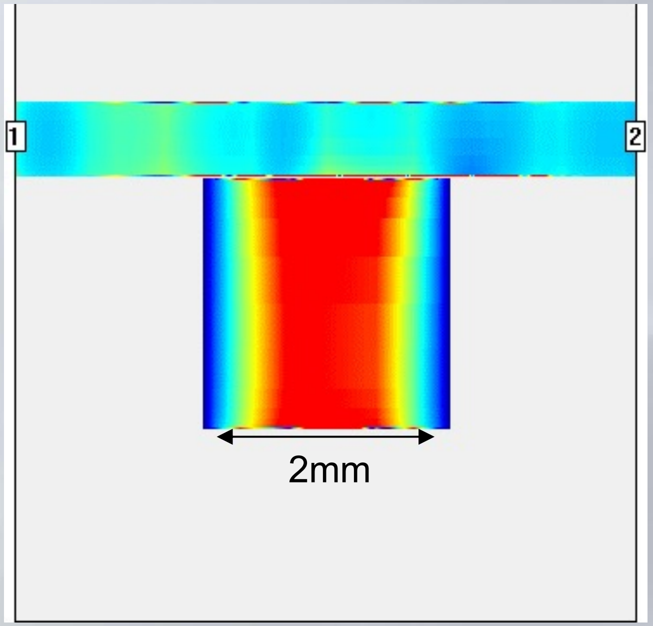

3)

- Využitie v kvantových elektrických obvodoch
- Komplexné filtre

1. P. Harvey-Collard, On-chip microwave filters for high-impedance resonators with gate-defined quantum dots, 2020, Physical Review Applied, 14(3), 034025.
2. A. Naji, P. A. Warr, Geometrical Perturbation Techniques and Approximate Analysis for Eigenmode Splitting and Shifting in Electromagnetic Planar Dual-Mode Resonators, 2019, Scientific Reports 9, 2417
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