Piezoelectric MEMS resonators for 5G filters

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MICRO-331

EPFL
École polytechnique fédérale de Lausanne

Who am I?

- Professor in Mechanical Engineering
  - I also teach for SMT ☺
- Our lab is in the MED building
- Pas francophone (Espagnol)
- We work on/with Micro/Nano Electro Mechanical Systems (MEM/NEMS)

My talk today...

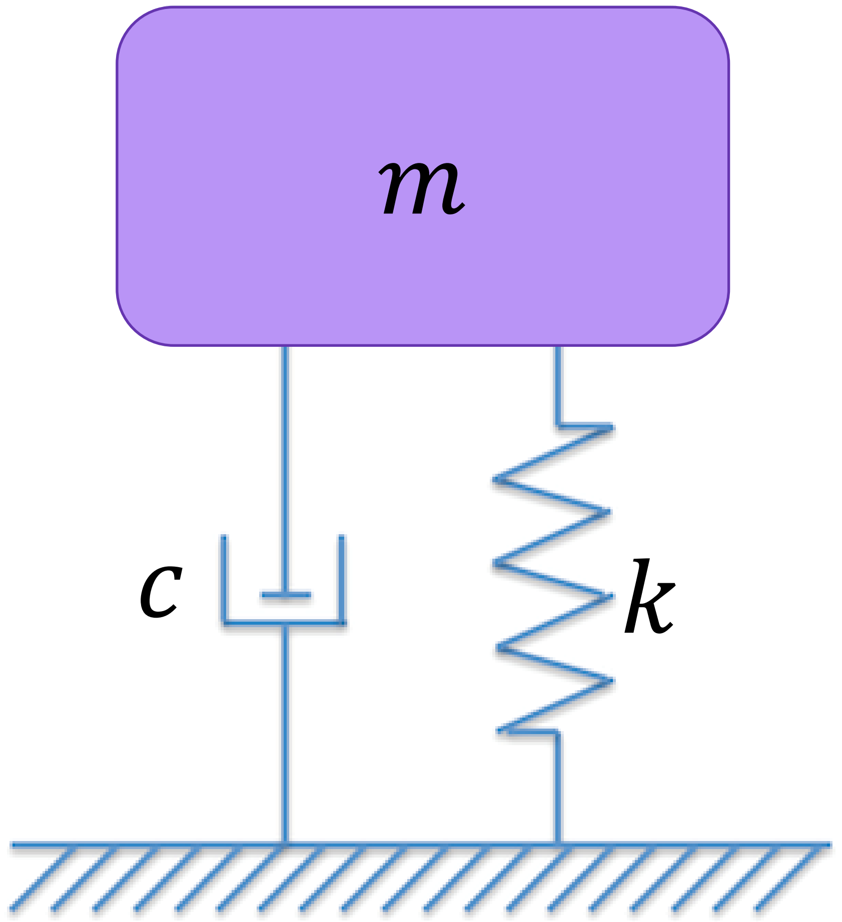
- Resonators
- MEMS
- What do we do?
- How to use MEMS Resonators for communications (cellphones)?
  - Different types of resonators for filters
- In-depth fabrication

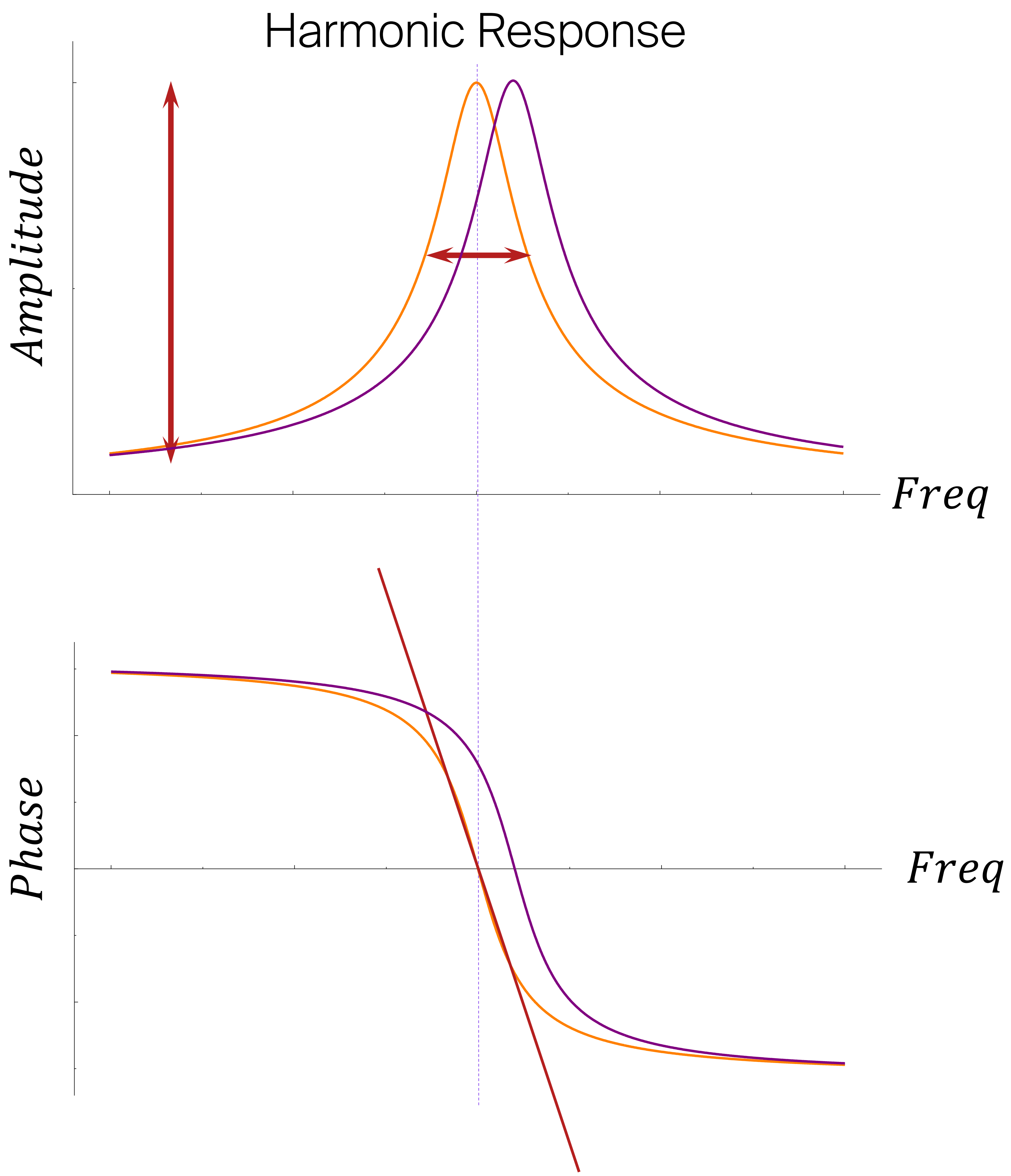
Resonators

Resonators

- Resonance frequency
- Quality factor

$$\omega_r = \sqrt{\frac{k}{m}} \xrightarrow[\delta m]{\delta k} \delta\omega_r$$





EPFL

MEMS
(Micro ElectroMechanical Systems)

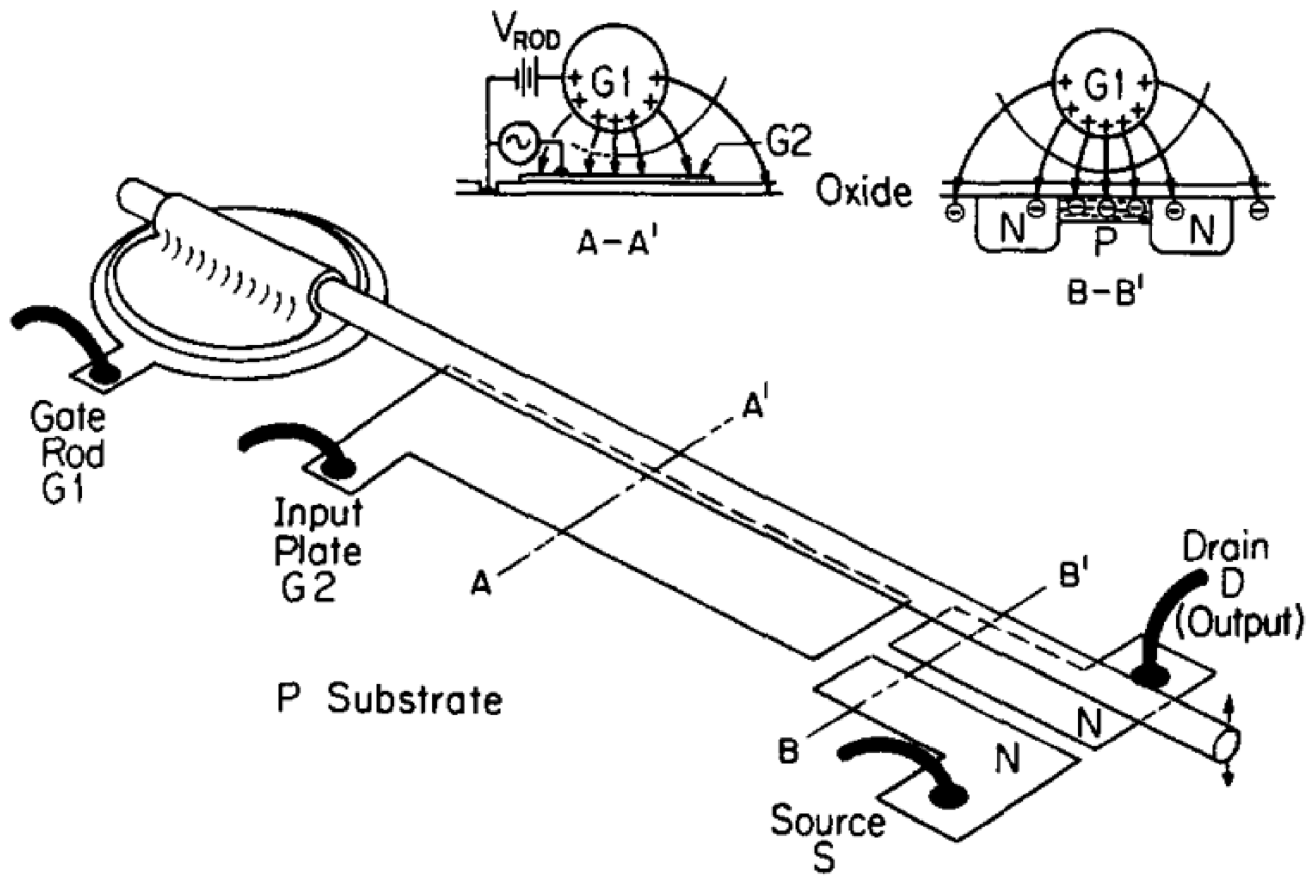
How it started…

Volume 7, Number 4 APPLIED PHYSICS LETTERS 15 August 1965

A RESONANT-GATE SILICON SURFACE TRANSISTOR WITH HIGH-Q BAND-PASS PROPERTIES

H. C. Nathanson and R. A. Wickstrom
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania
(Received 9 June 1965)

(surface state modulation; MOS devices; E/T)



- Silicon was a game changer:
  - Stiff
  - Light
  - Brittle
  - Easy to machine

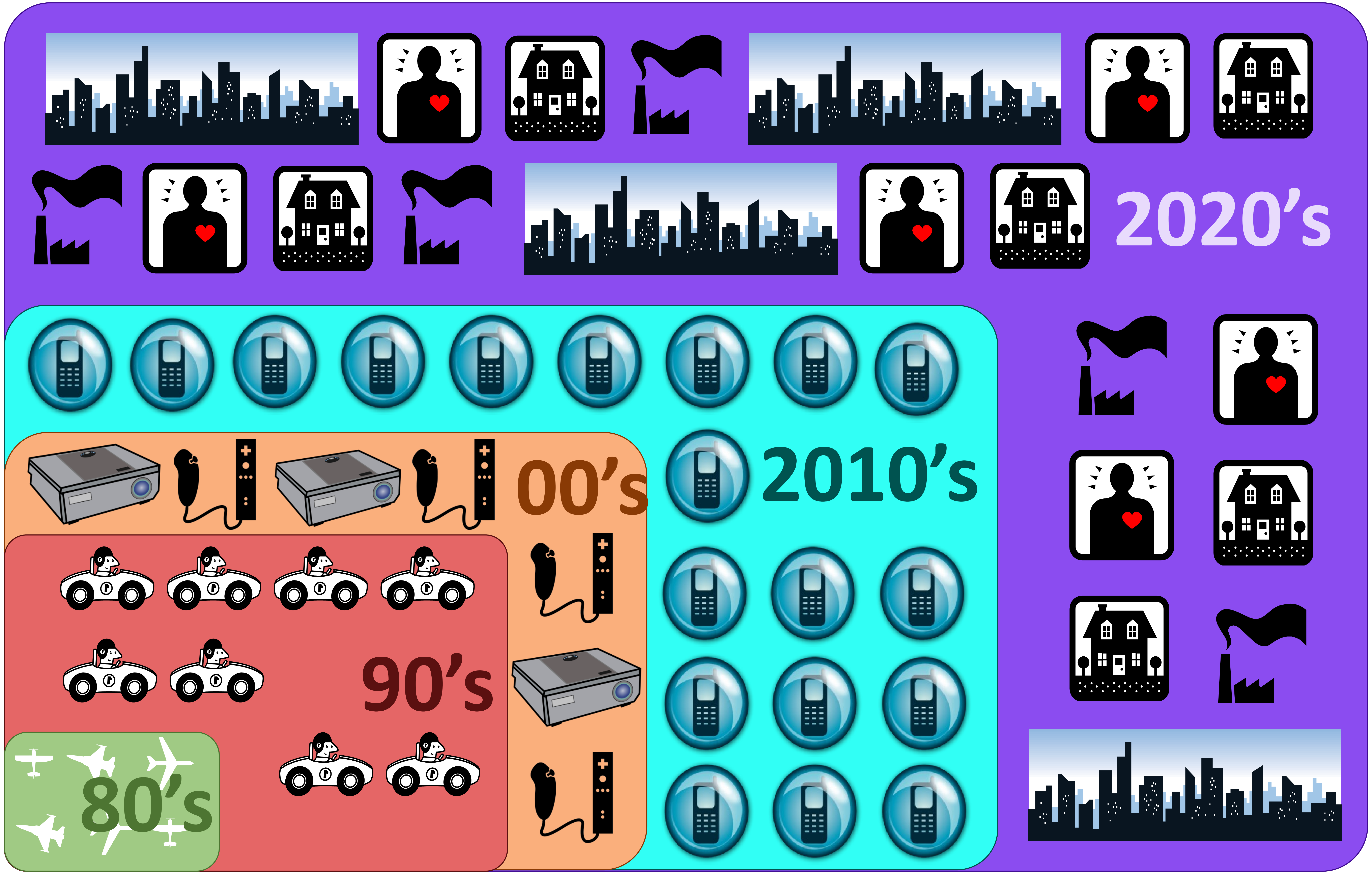
420 PROCEEDINGS OF THE IEEE, VOL. 70, NO. 5, MAY 1982

Silicon as a Mechanical Material

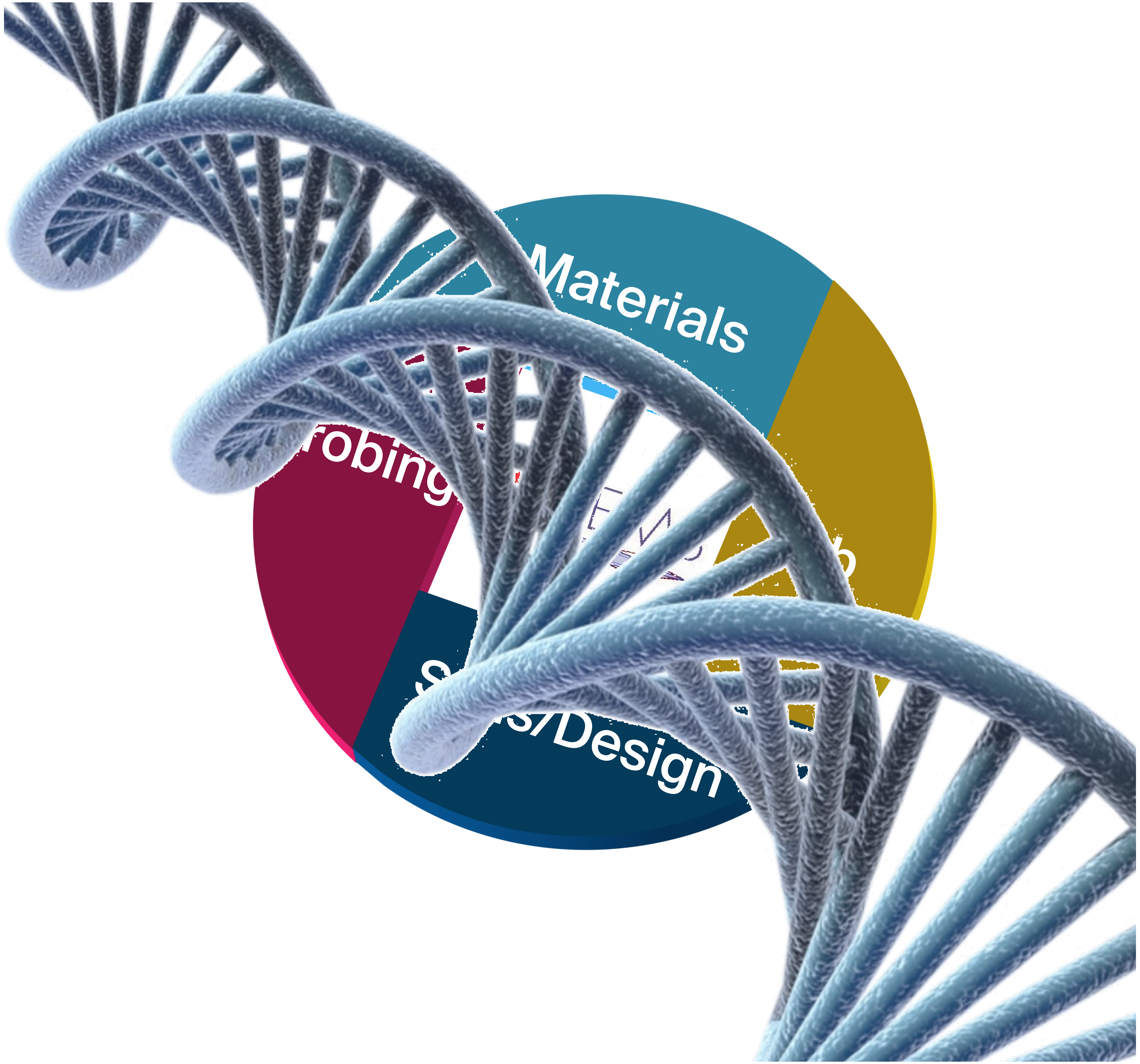
KURT E. PETERSEN, MEMBER, IEEE

How it developed...

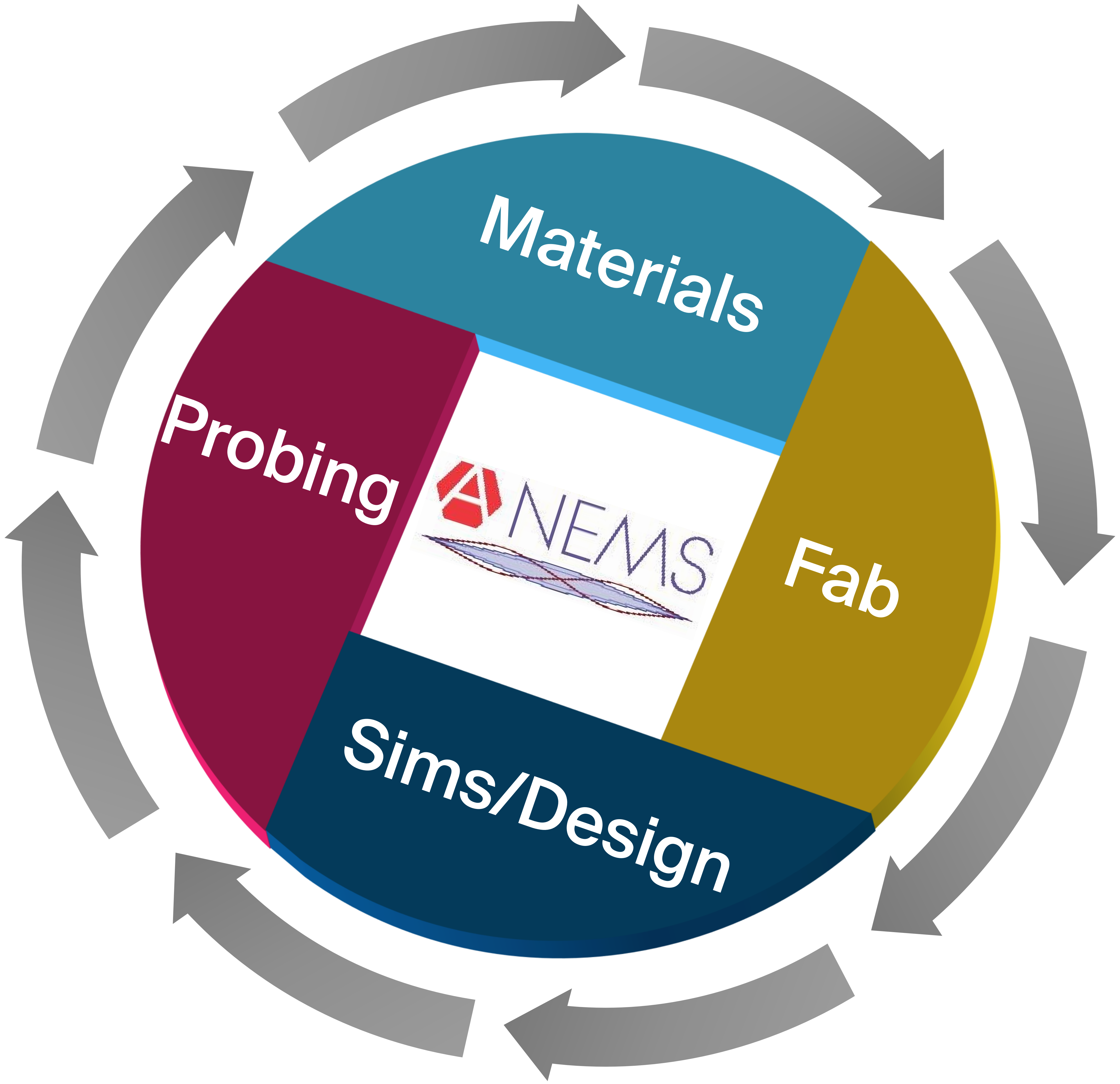
- Small footprint
- Good performance
- Reliability
- Easy** to produce



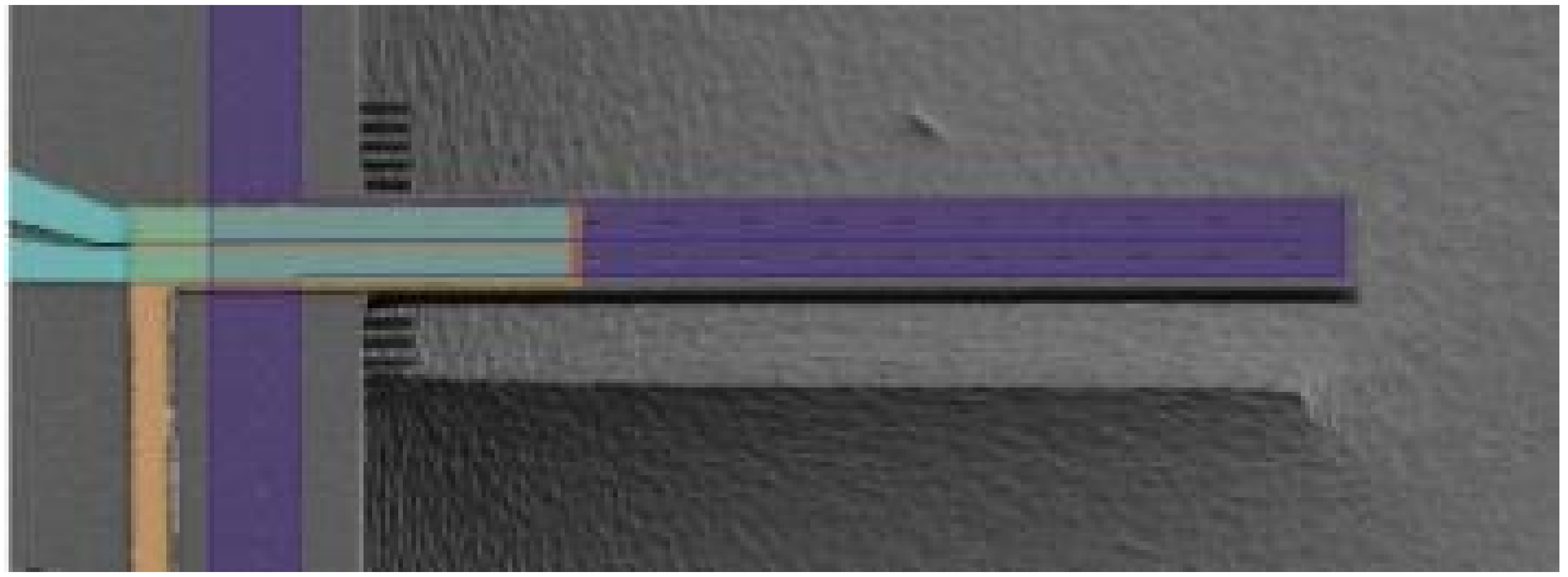
Our Research
(MEMS Resonators)


Materials
robing
s/Design

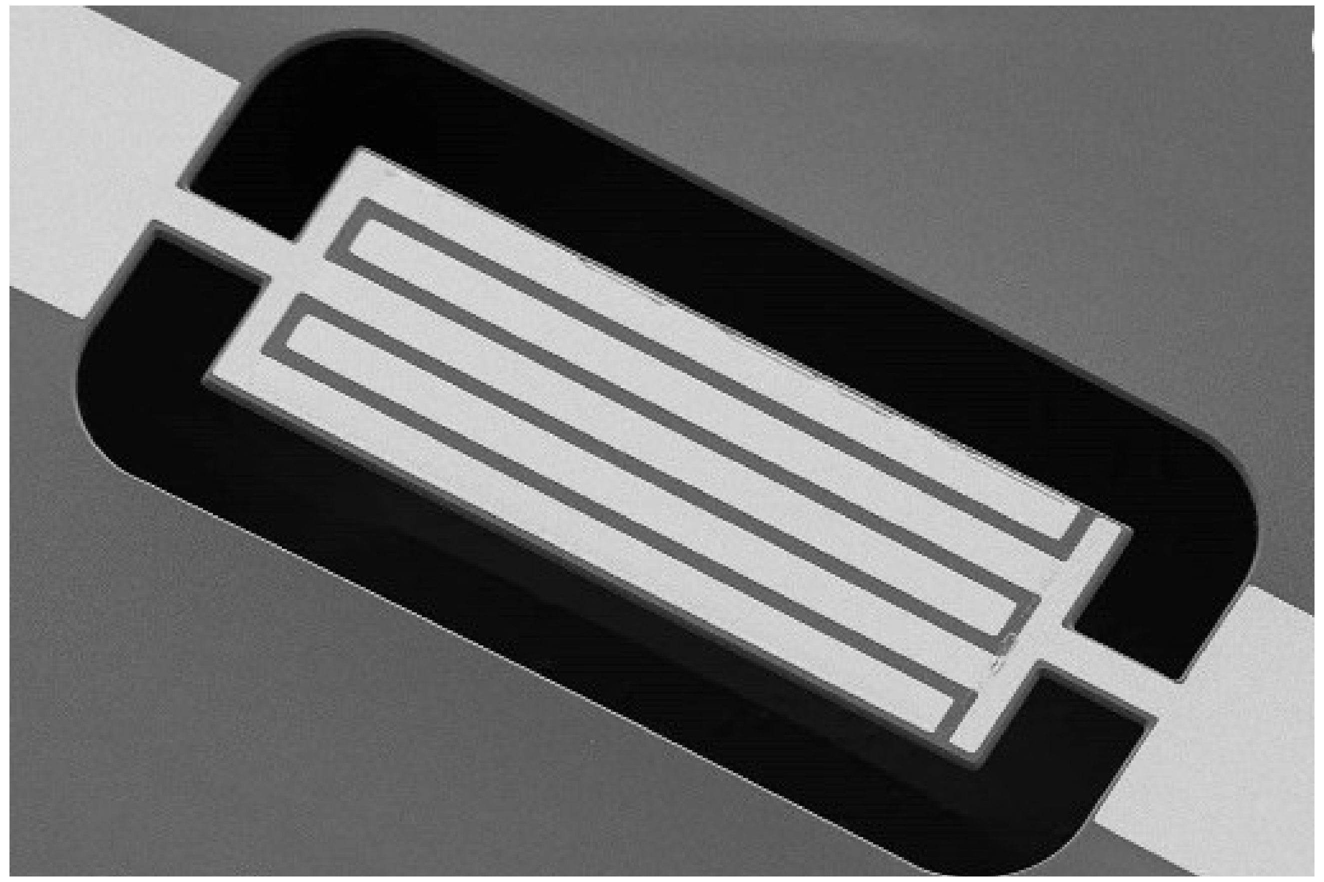
Our research



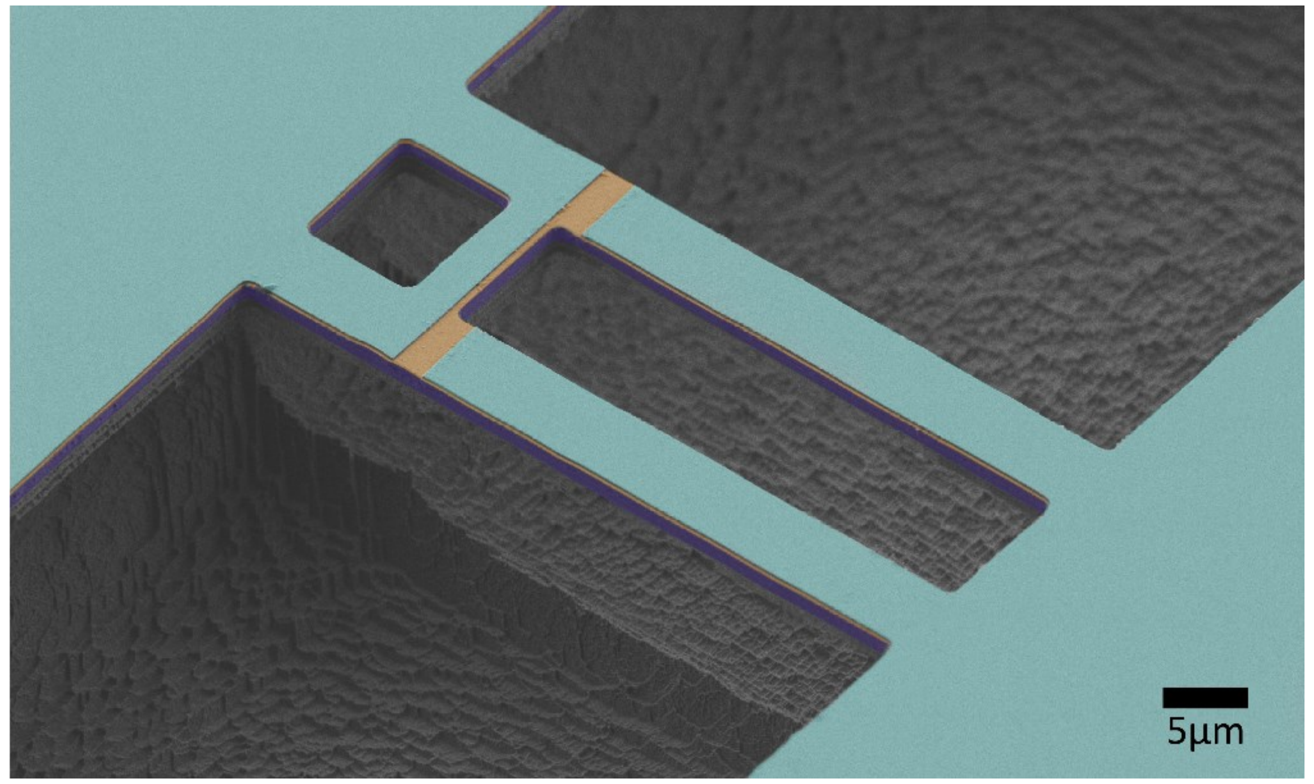
Our research



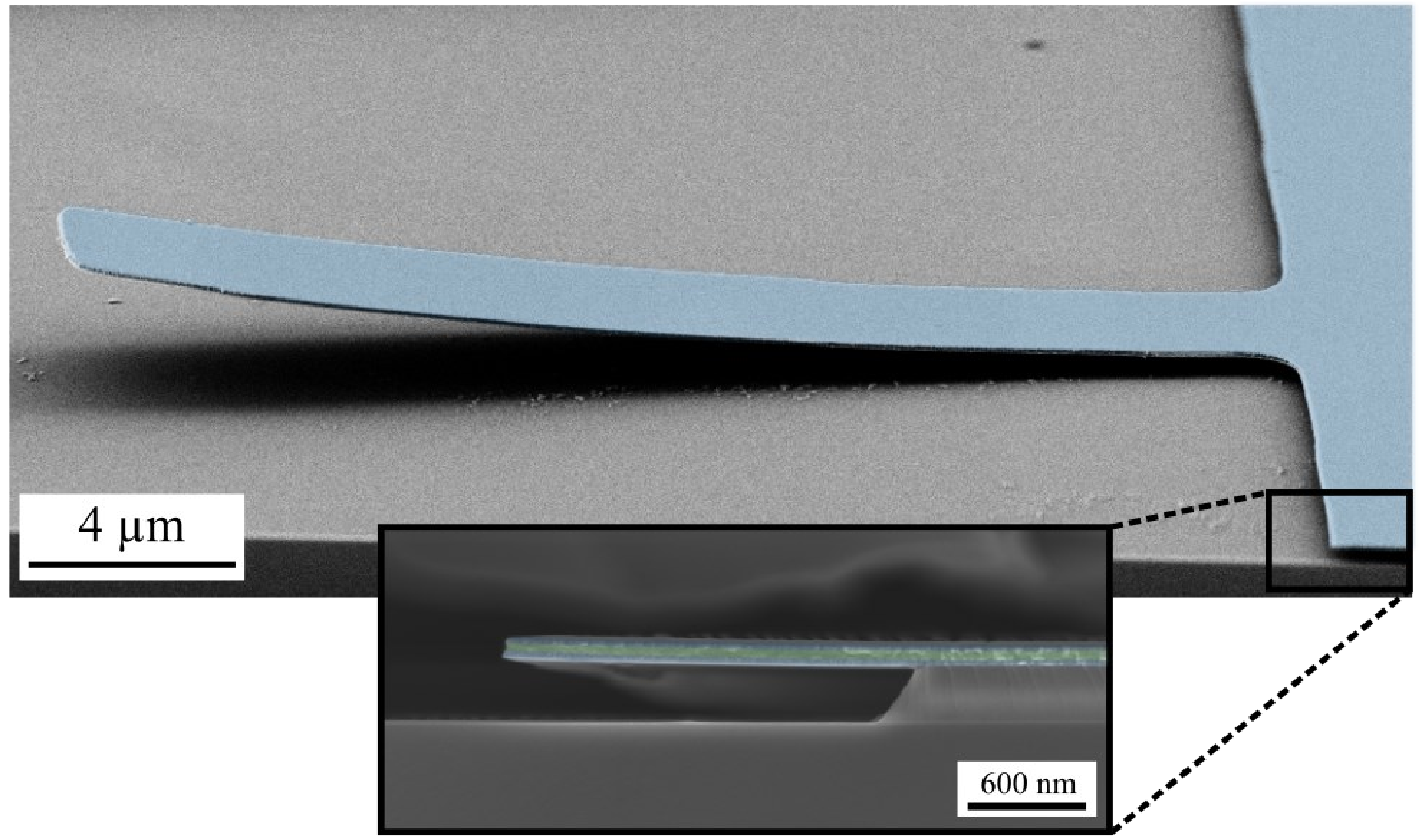
Biosensing Devices



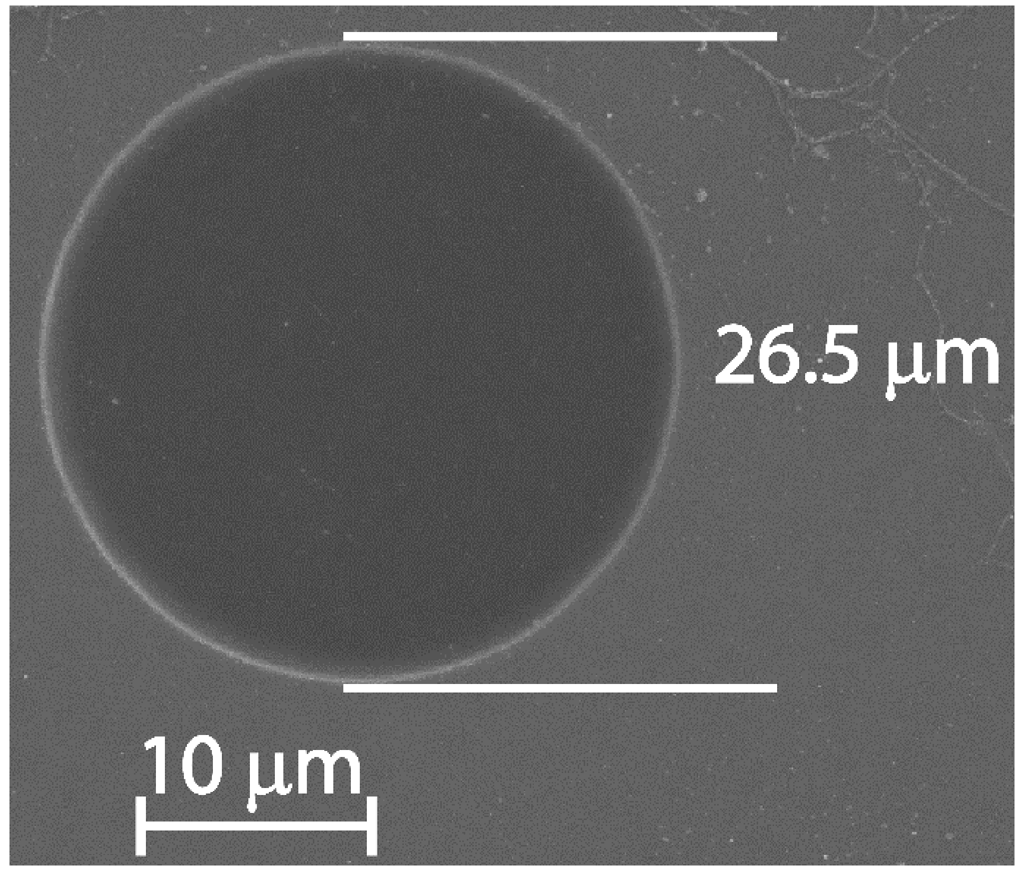
Filters and Oscillators



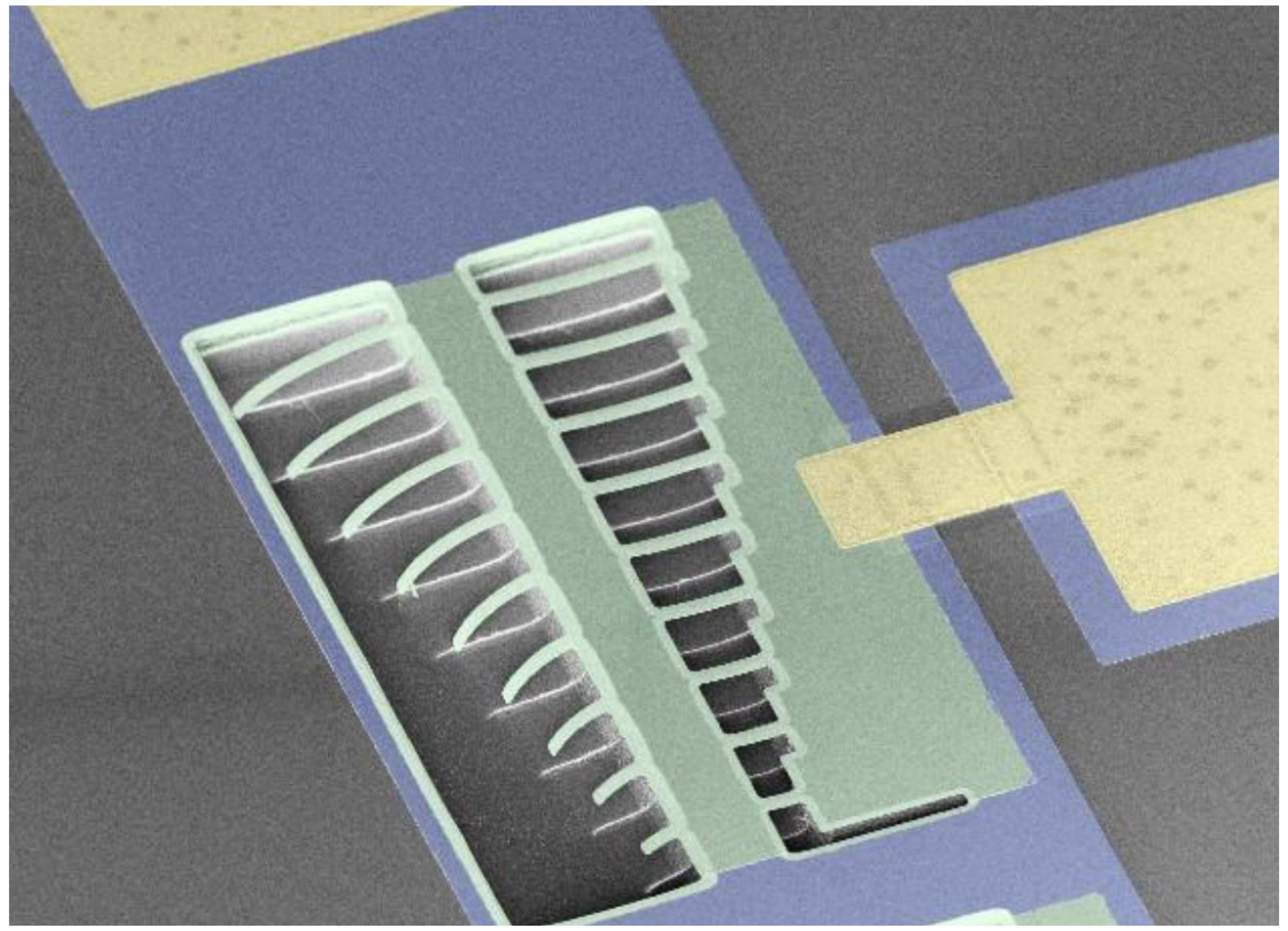
Coupled Dynamics



Flexoelectric Devices



Graphene Devices



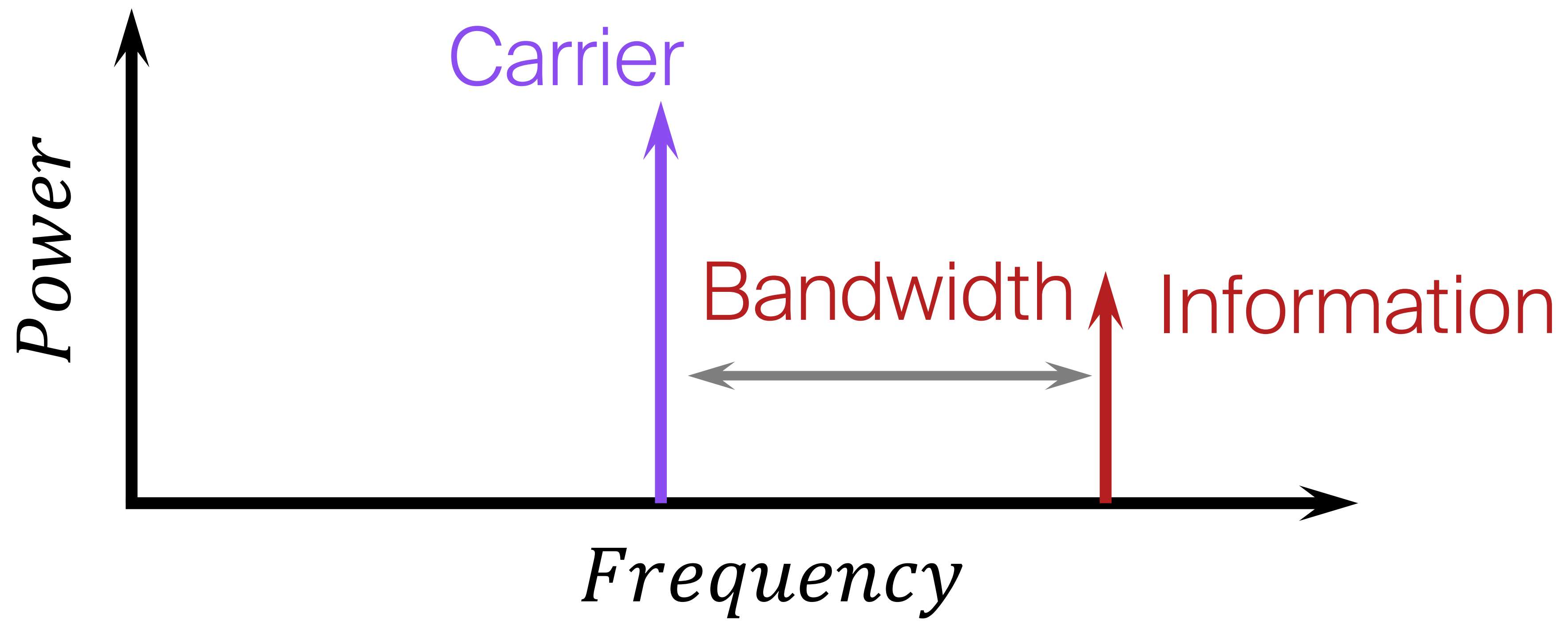
Nonlinear Dynamics

- Piezoelectric MEMS resonators for 5G filters

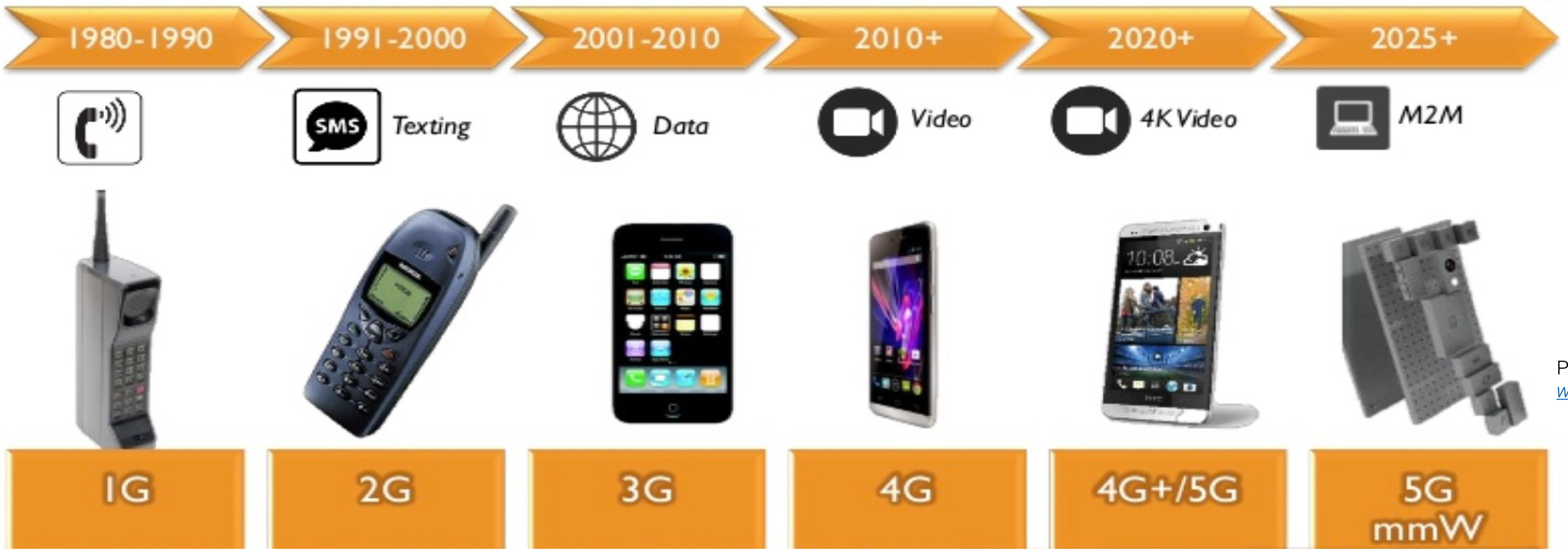
Resonators for Communications

Evolution in mobile communications

- More bandwidth
- Higher frequencies



- More bands



1G	2G	3G	4G	4G+/5G	5G mmW
30 kHz	0.9-2 GHz	1.6-2 GHz	2-4 GHz	3-4 GHz	3-30 GHz
2 kbps	64 kbps	2 Mbps	100 Mbps	1 Gbps	>1 Gbps

Picture from *Yole Developpement*
www.yole.fr

“Our” Goal

- Commercial challenges

Band	Frequency Range	Bandwidth	Fractional Bandwidth	**Resonator Coupling**
n77	3.3-4.2 GHz	900 MHz	24%	**65%**
n78	3.3-3.8 GHz	500 MHz	14%	**37%**
n79	4.4-5.0 GHz	600 MHz	12%	**31%**
Wifi 6E	5.9-6.4 GHz	500 MHz	9%	**25%**
n28	703-748 MHz	45 MHz	7%	**20%**

- **Coupling!!!**
- **Frequency!**
- **Q** – now 500, 2000 in some years
- **Reduction of spurious modes**

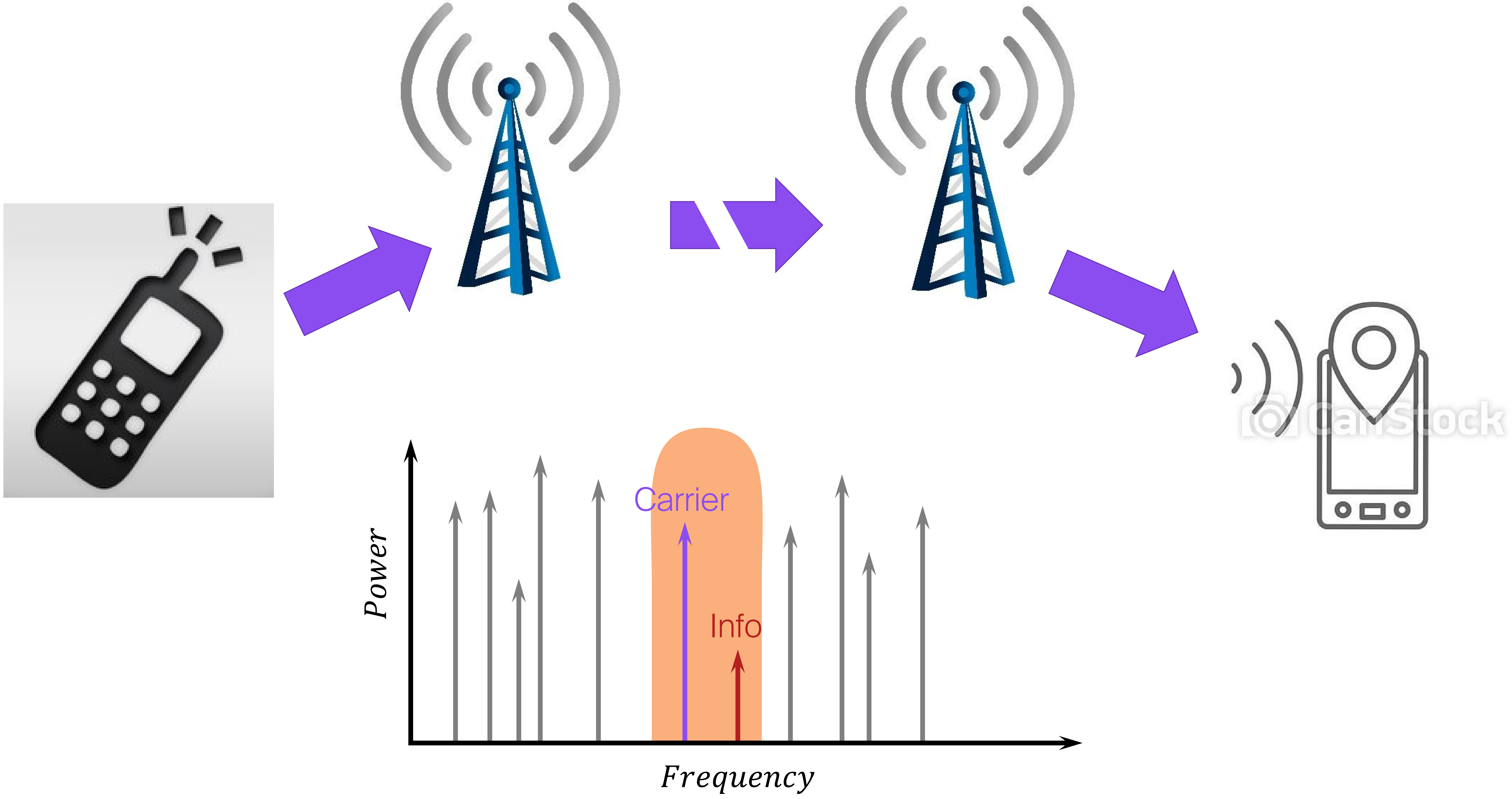
- Material ($Al_xSc_{1-x}N$ and $LiNbO_3$)
- Fab Technology
- Design (optimizing acoustic boundaries)

Brief overview

- AlScN Resonators

- LiNbO3 Resonators
  - S0
  - SH0
  - A1 (XBAR)
  - SH1 (YBAR)

Cell phones



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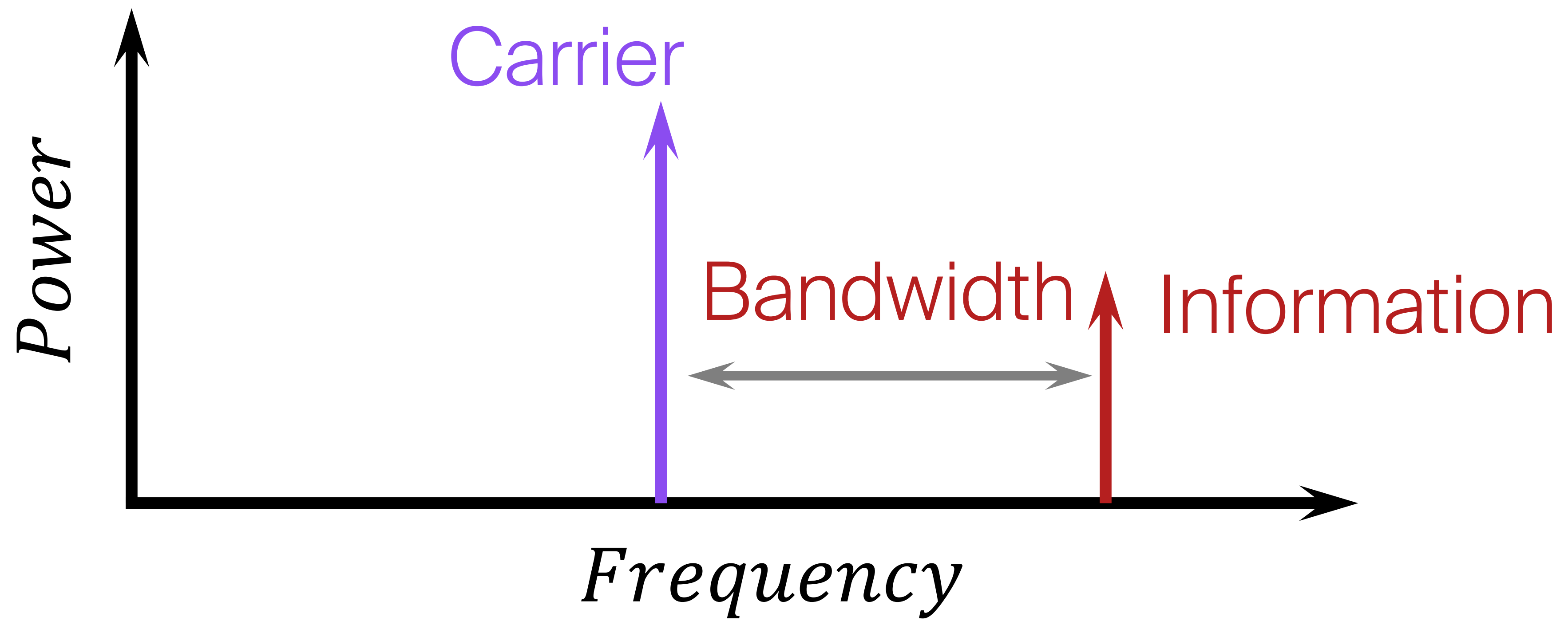

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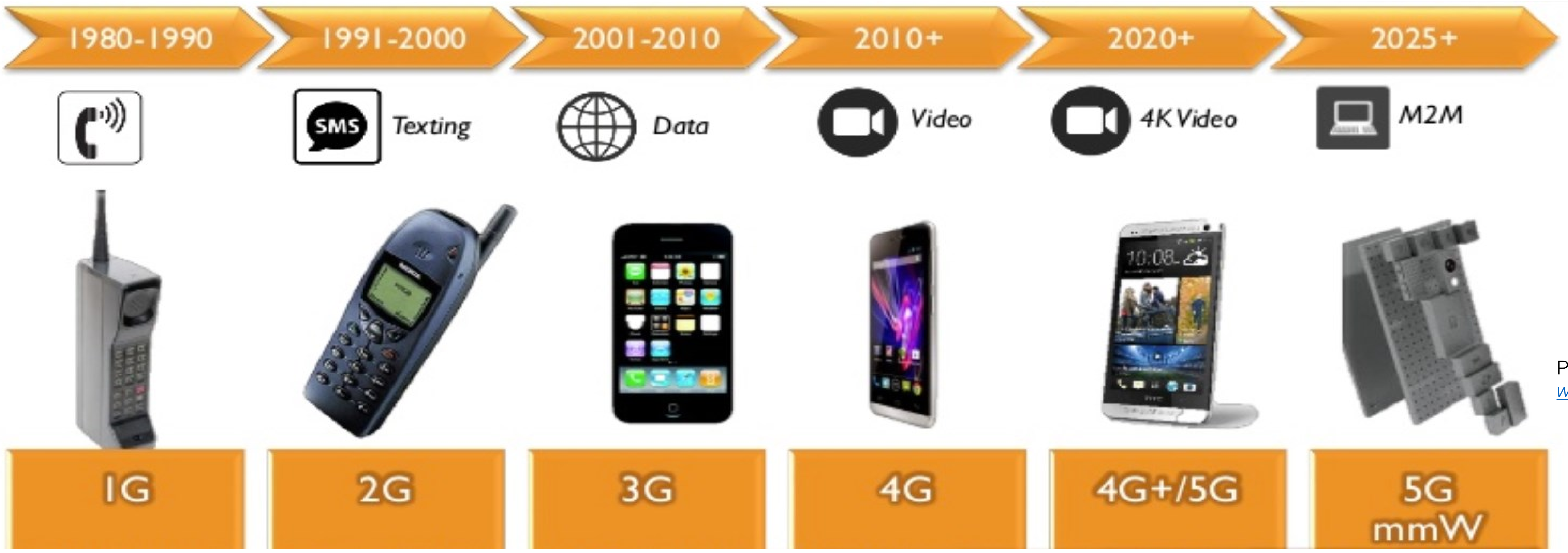

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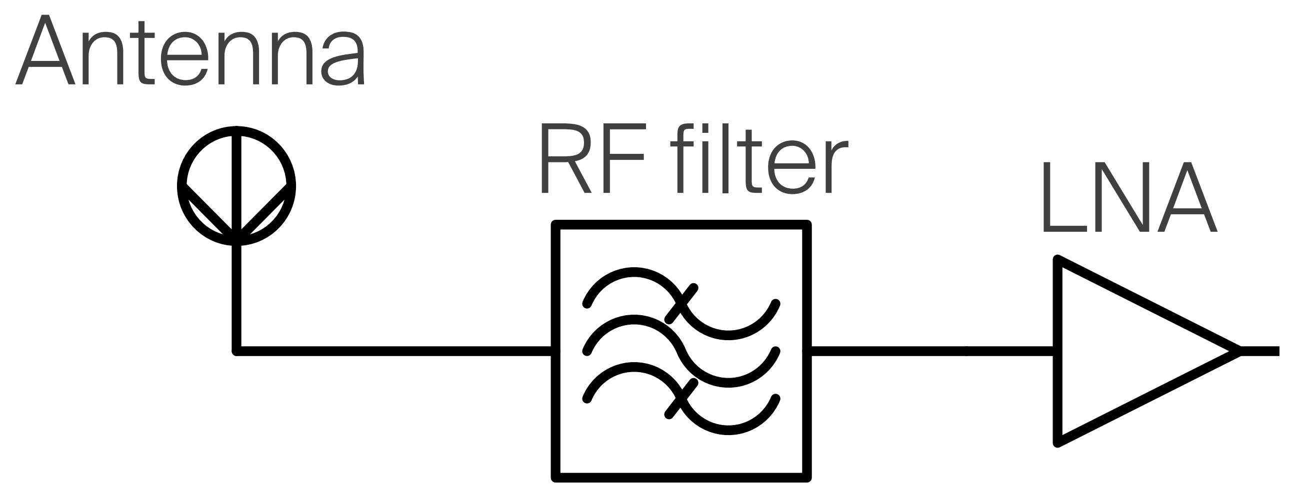
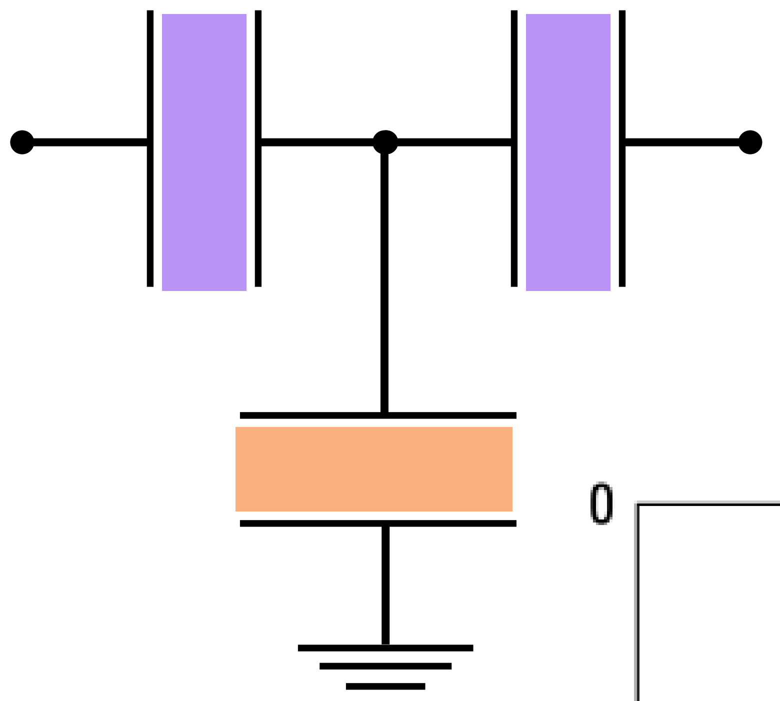
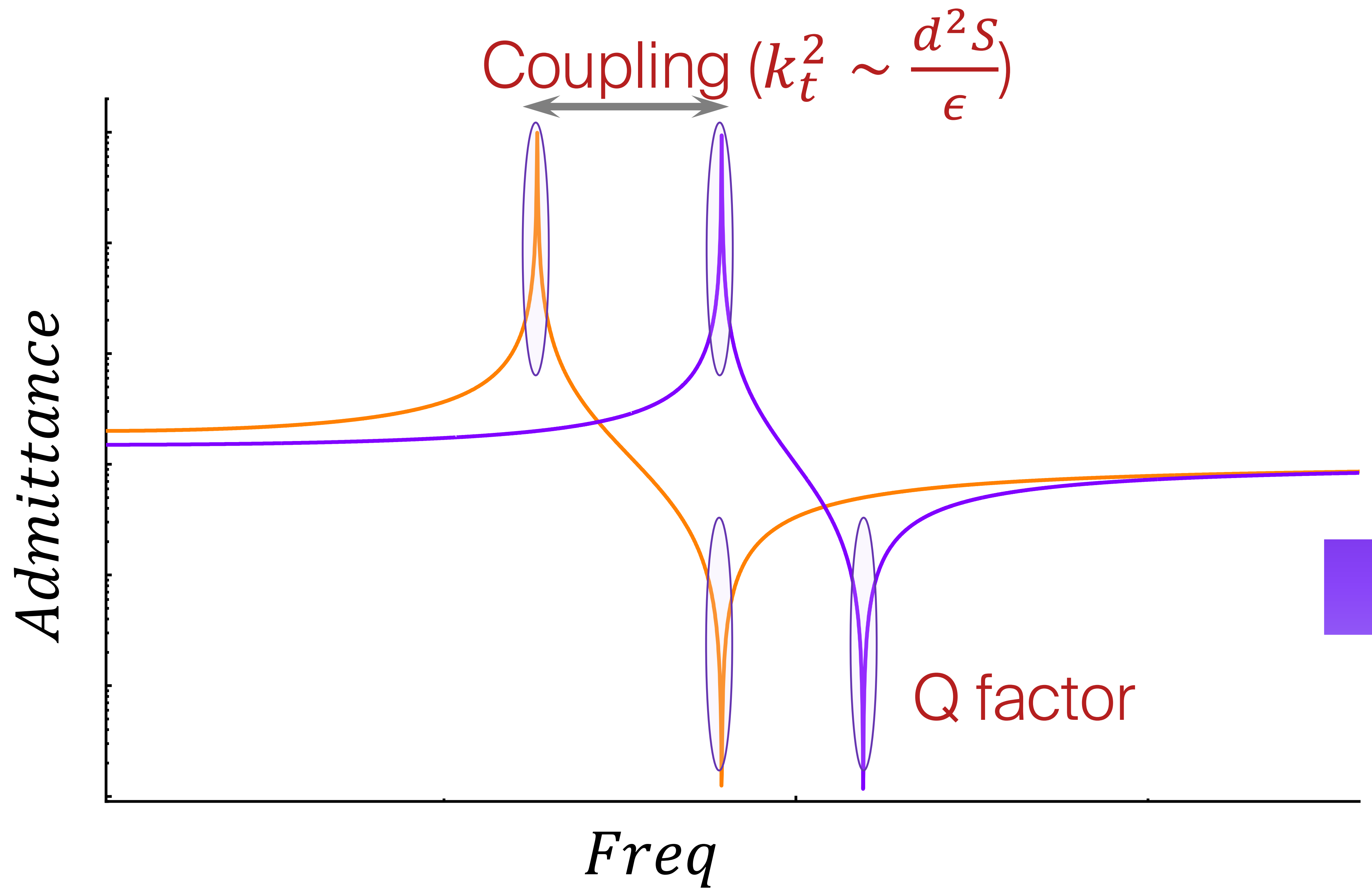
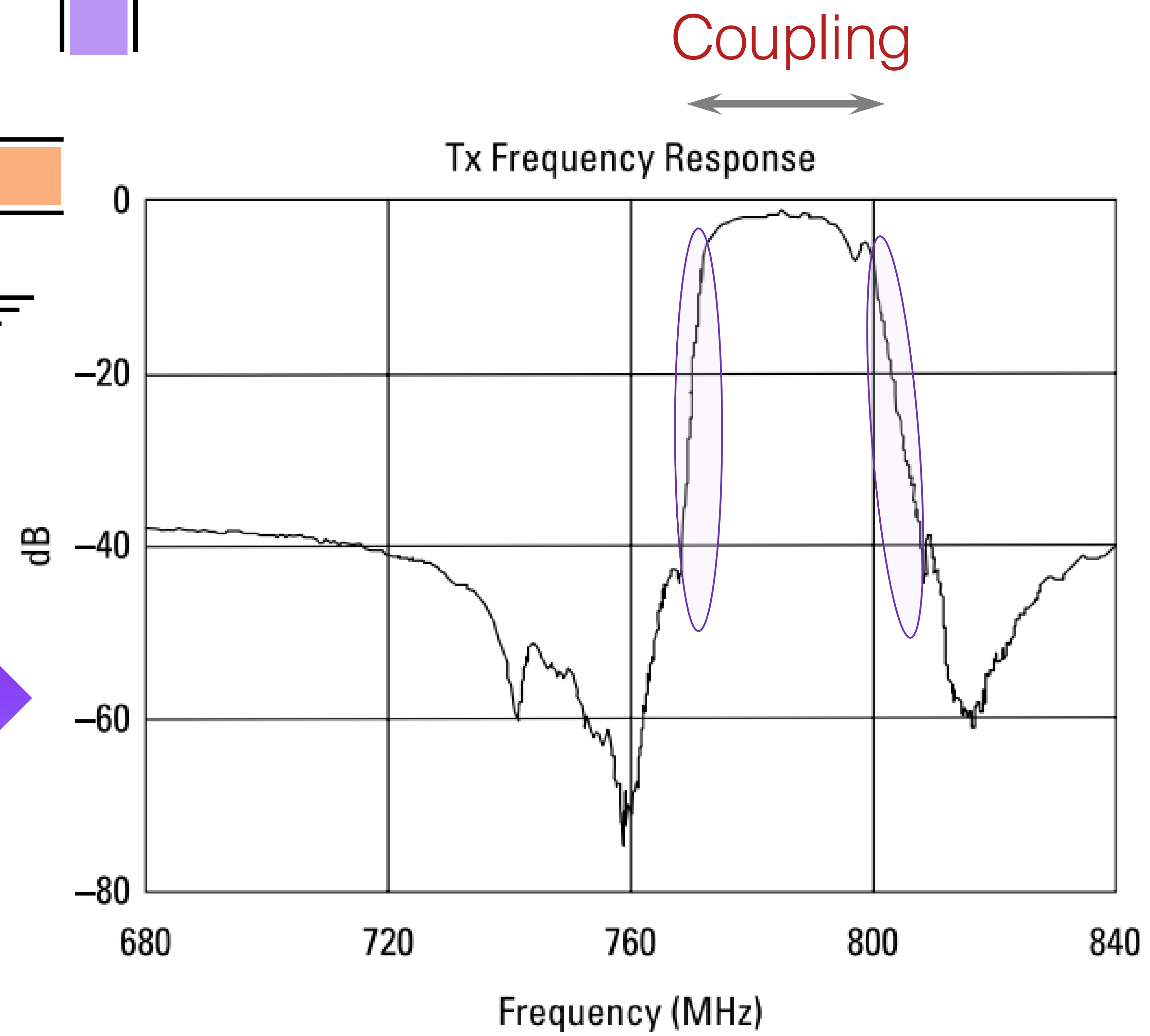
Making a filter – Ladder topology

- Combining 3 resonators
  - Two "in series"
  - One "shunted" to ground









Solutions in the market

SAW

Dominate below 1 GHz

+ Crystalline material
+ Many frequencies on same wafer
- Moderate k_t^2 (surface waves)
- Metal losses reduce Q

Classic
< 1 GHz

IHP
< 2.5 GHz

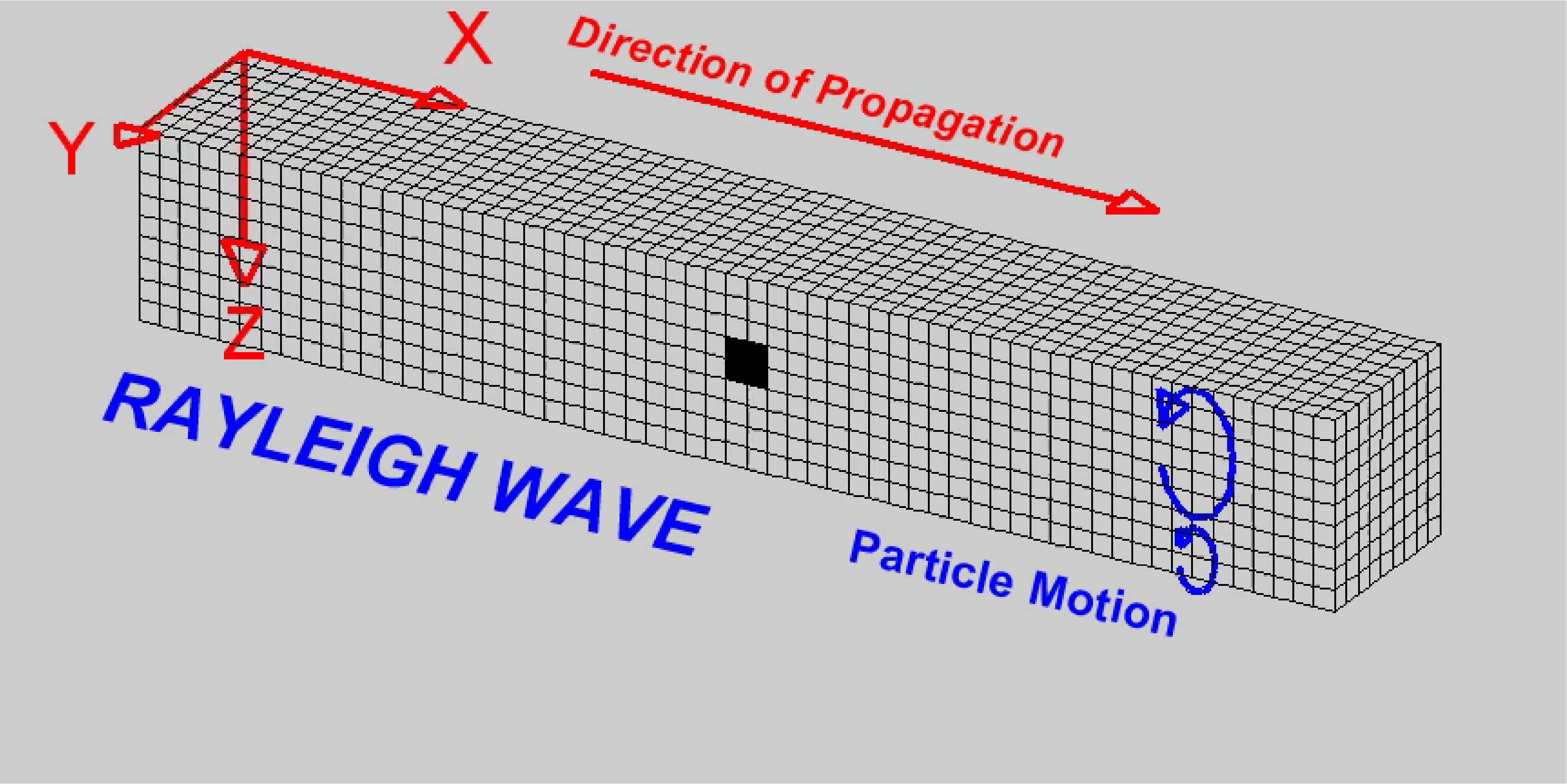
BAW

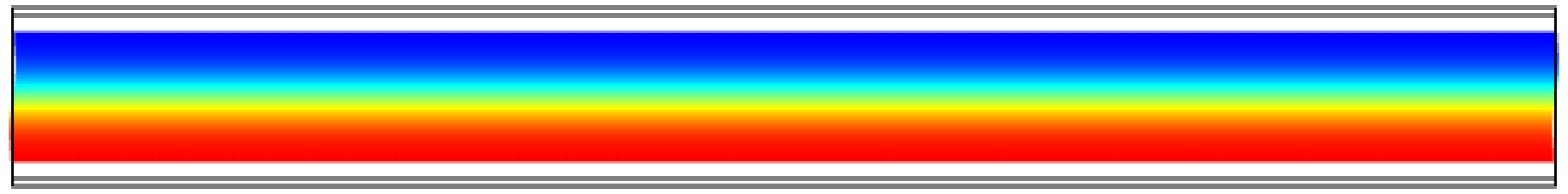
Dominate above 1 GHz

+ Thickness defined frequency
+ Higher frequencies easily attained
- Poly-crystalline material (lossier)
- Moderate k_t^2

SMR
Bragg reflector

TF
Power handling





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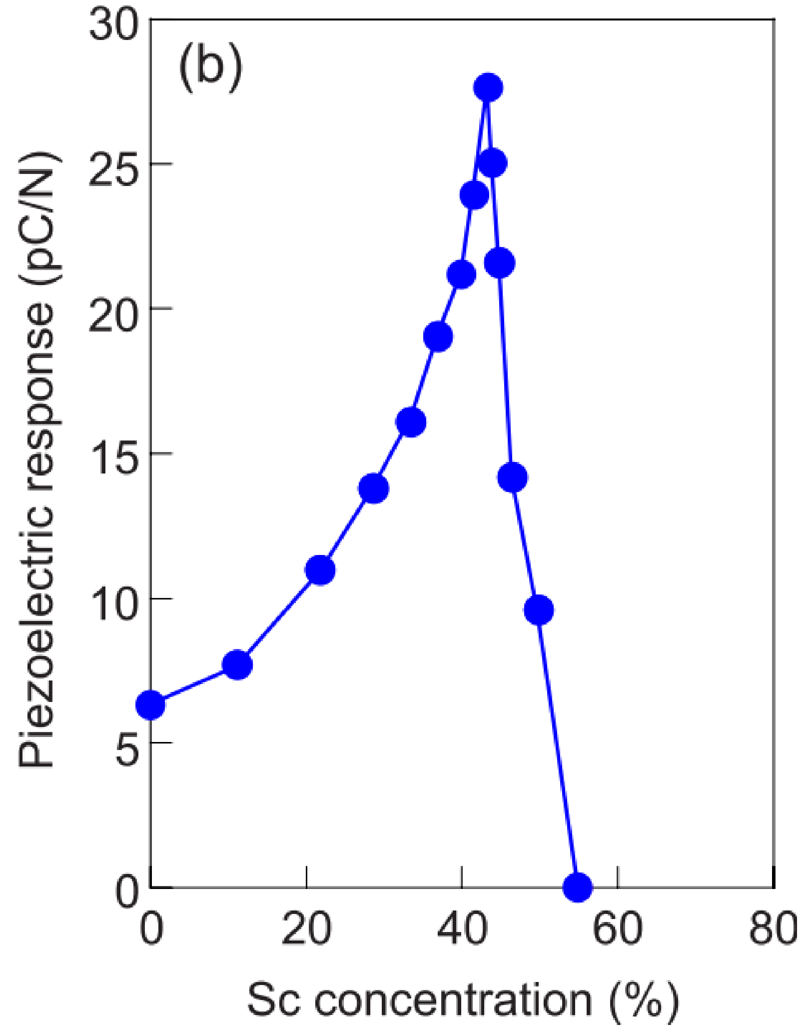
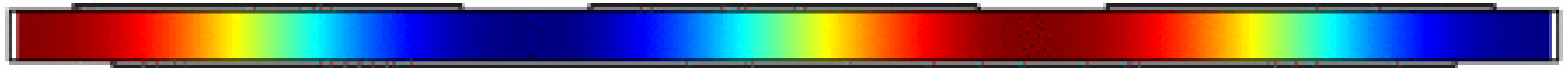
EPFL

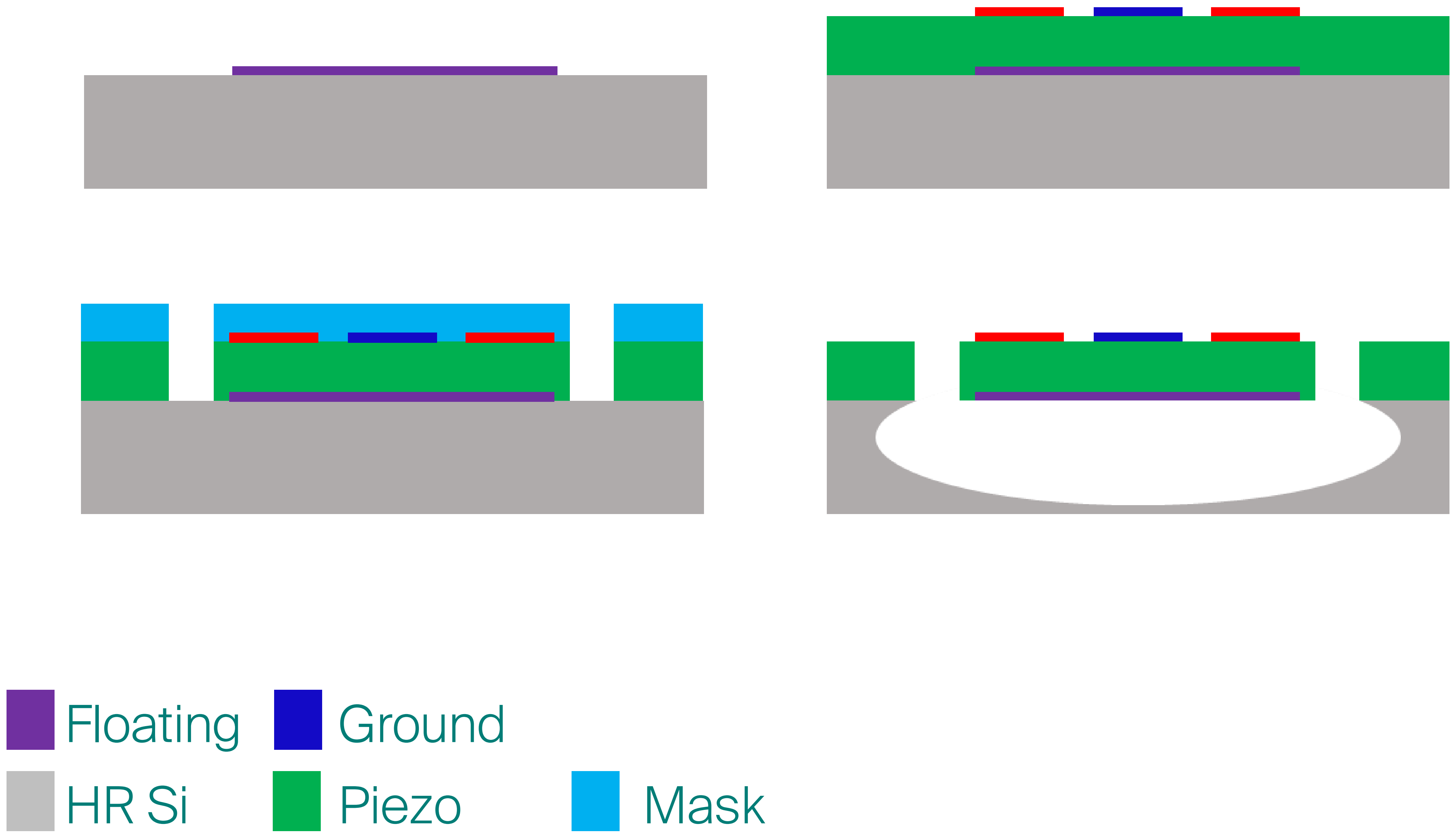
AlScN resonators

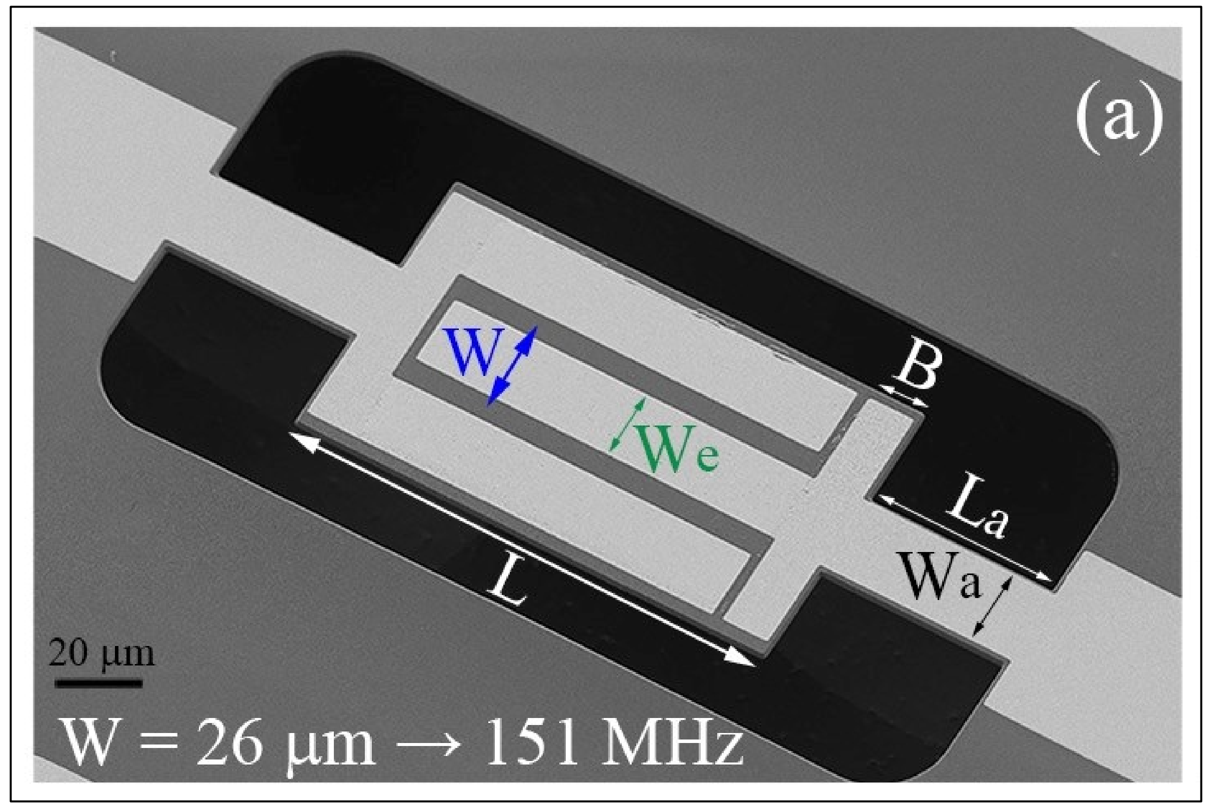
#1 – AlScN Resonators

- AlN and AlScN can be deposited via sputtering (<400°C)
- Doping it with Scandium increases piezoresponse
- Fabrication of S0 resonators







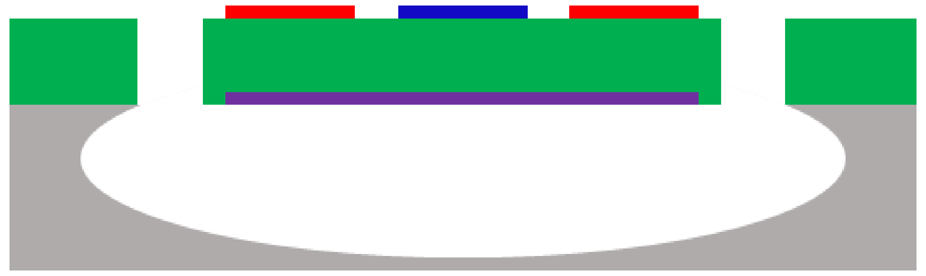


* Lozzi et al, TUFFC, 2018

Special Thanks to Prof. P. Muralt

- Piezoelectric MEMS resonators for 5G filters

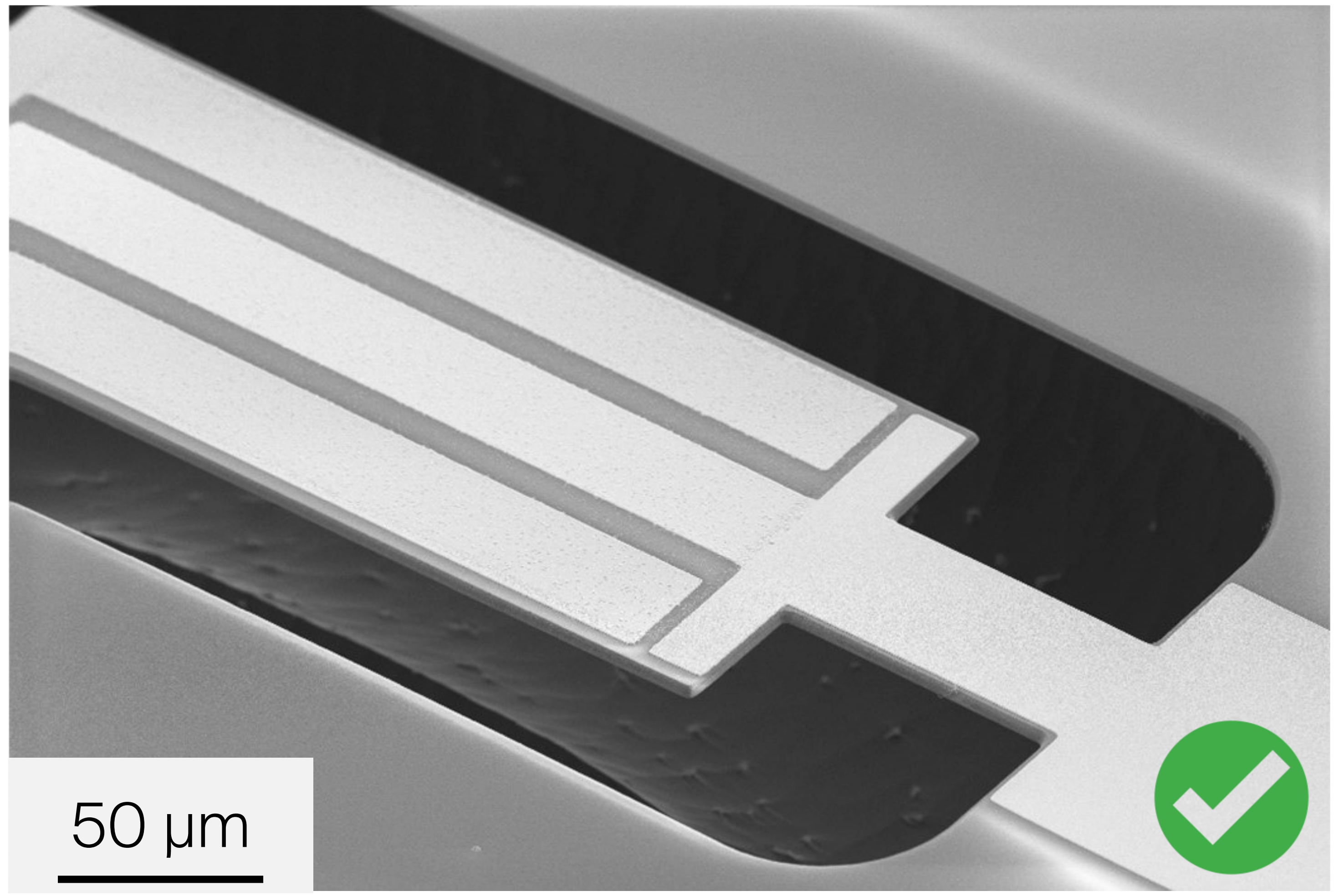
In-depth Fab

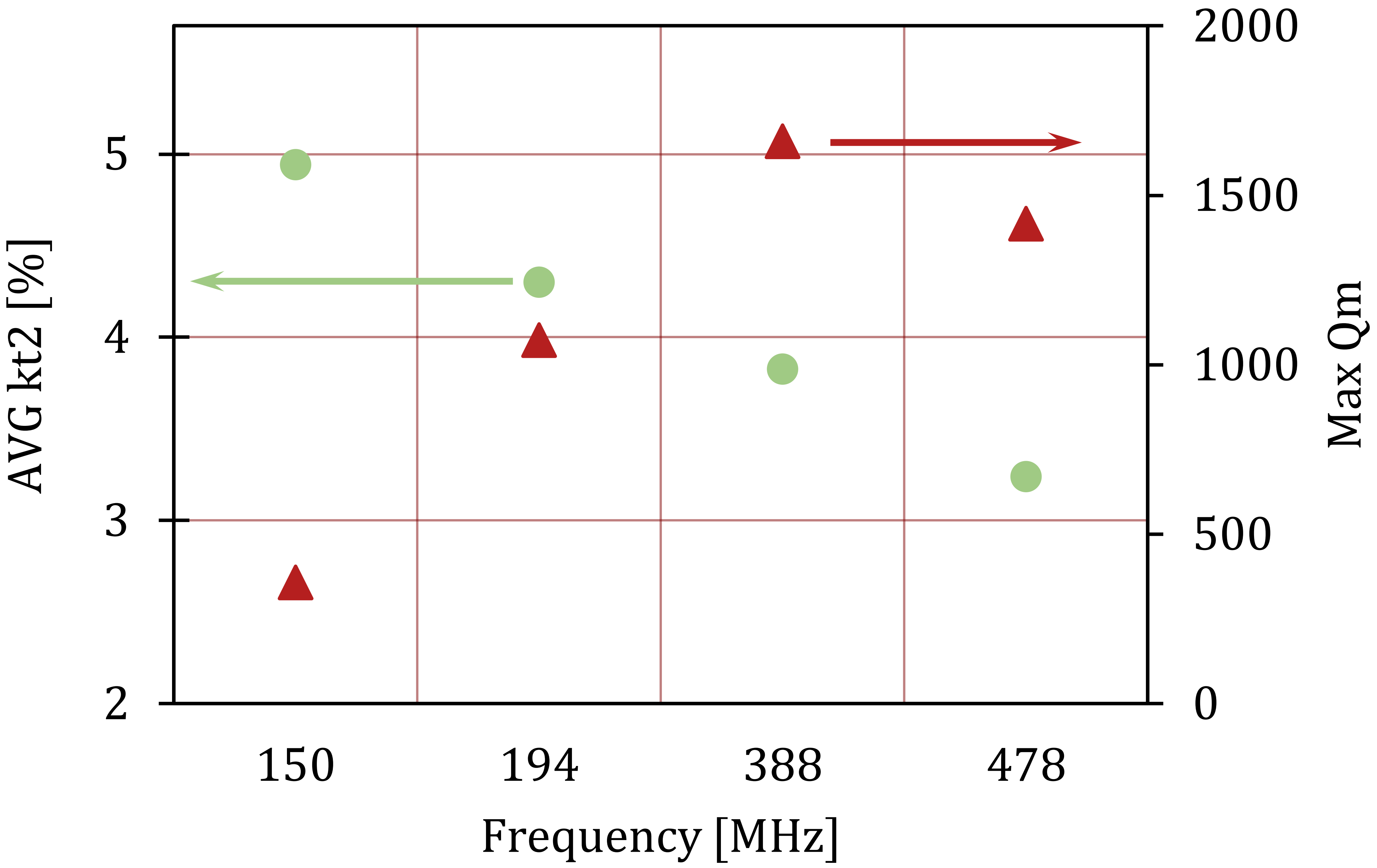


In-depth Fab

EPFL #1 - AlScN resonators

- First S0 devices with 17.5% Sc in AlN



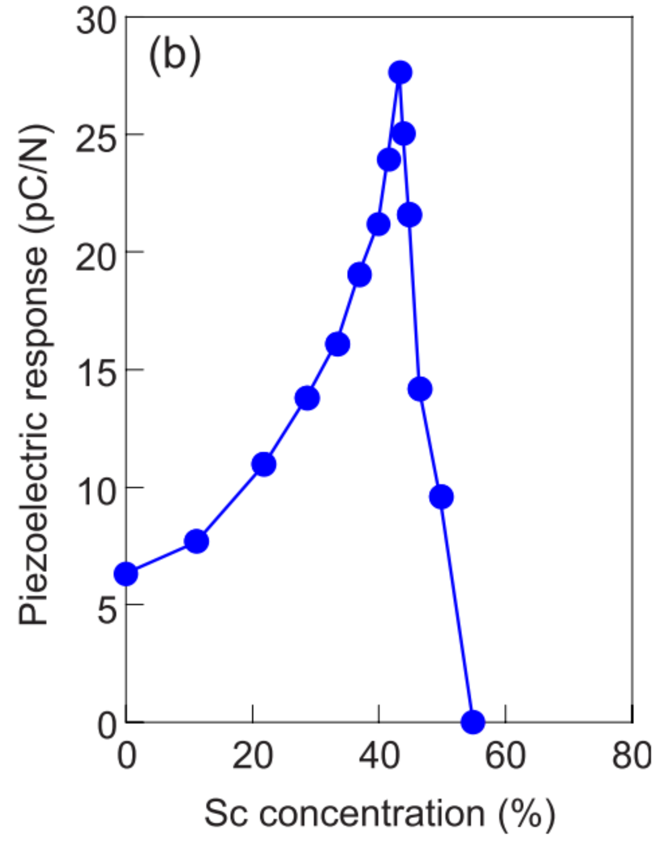


- Average $k_t^2 = 4.4\%$ @ 194 MHz
- Average $k_t^2 = 3.3\%$ @ 478 MHz
  - (spurious modes)
- 2x more coupling than AlN

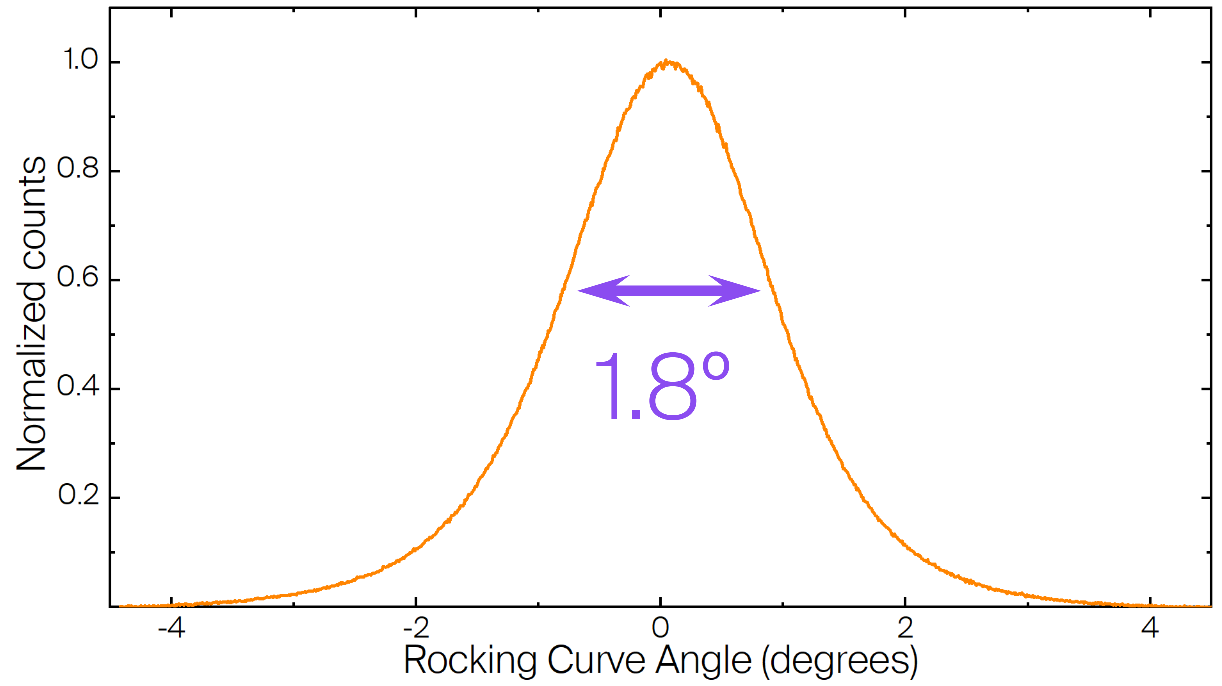
* Lozzi et al, TUFFC, 2018

Special Thanks to Prof. P. Muralt

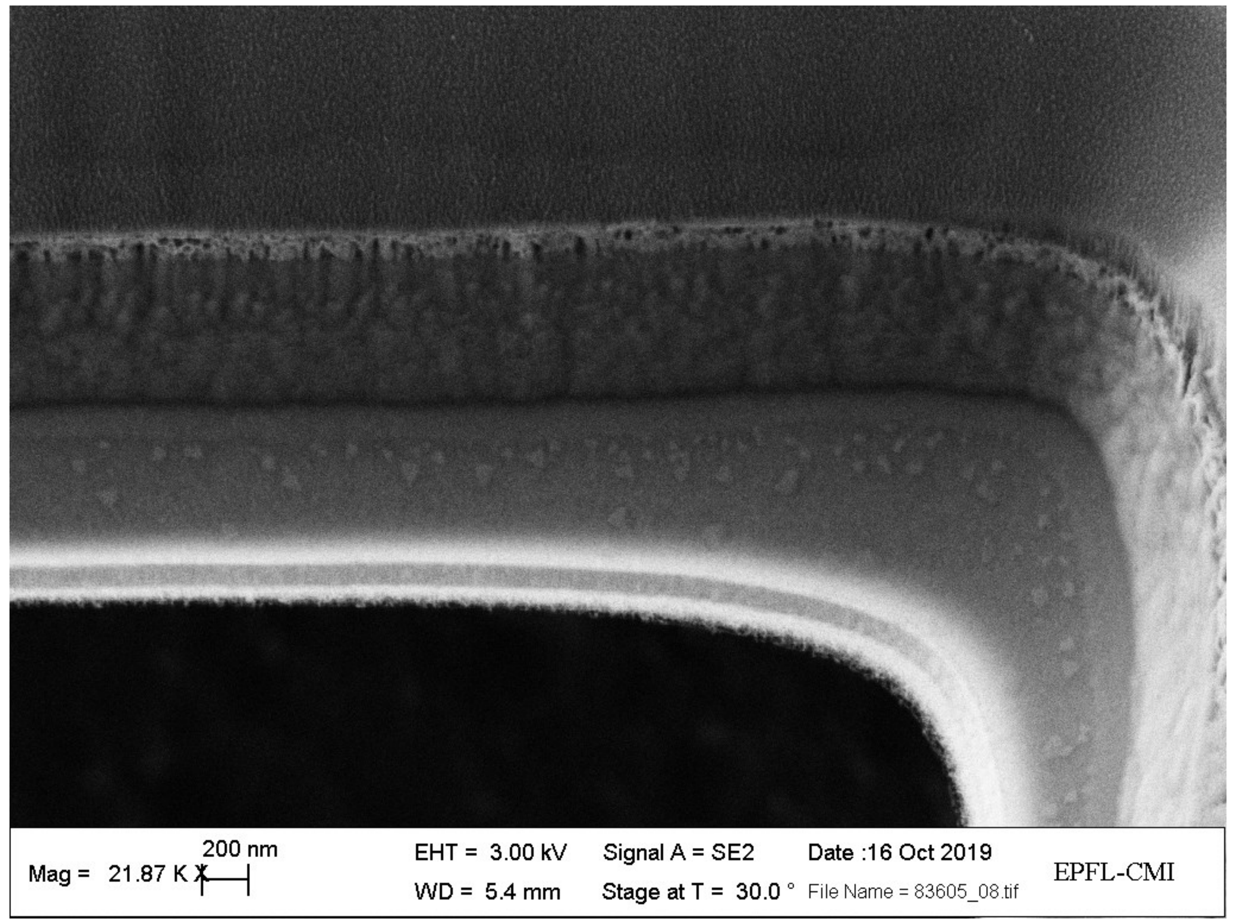
#1 - AlScN resonators

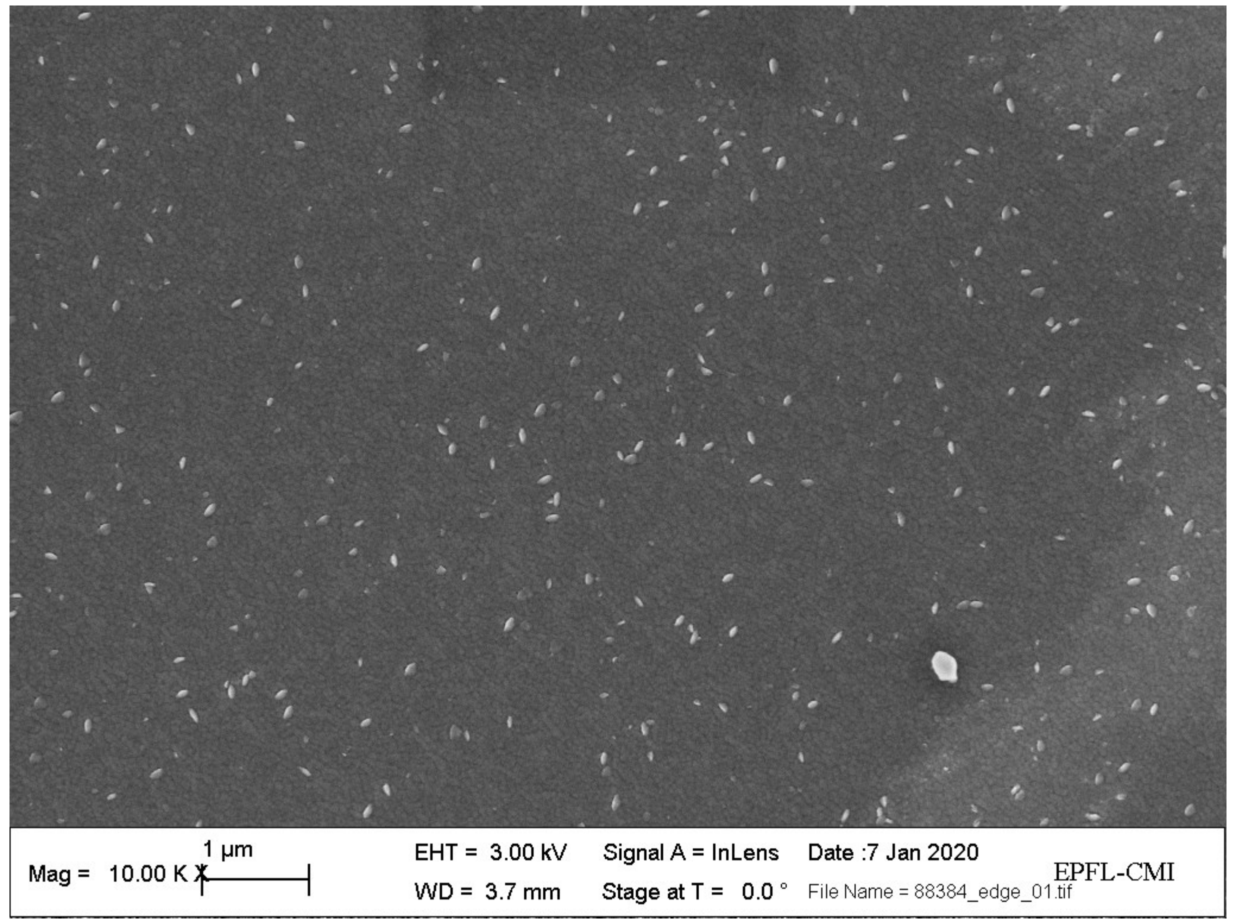


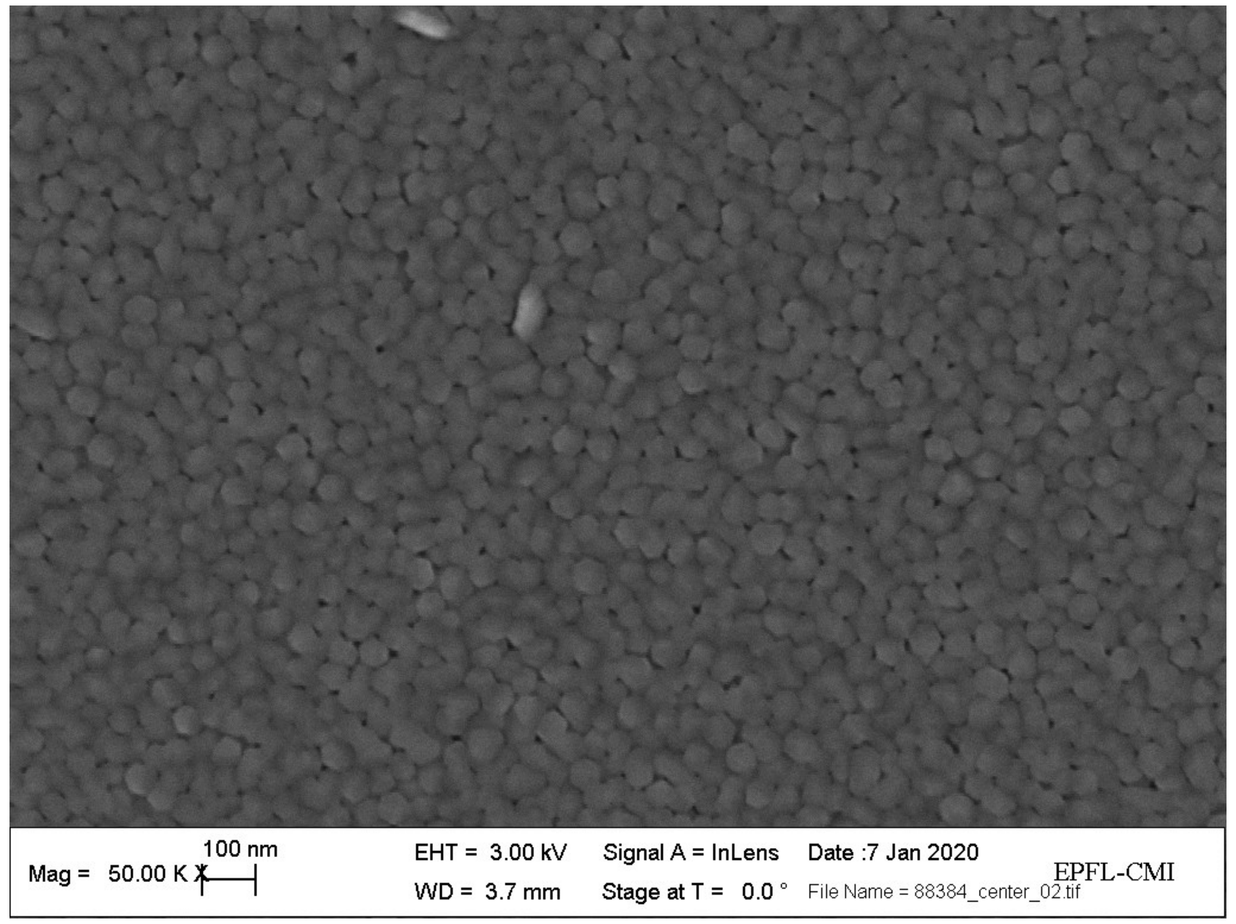
- Currently we are increasing concentration up to 40% Sc
  - Slightly below the phase transition



- Challenges:
  - Etching → around 70° sidewalls are obtained
  - Growth → minimizing abnormal grains



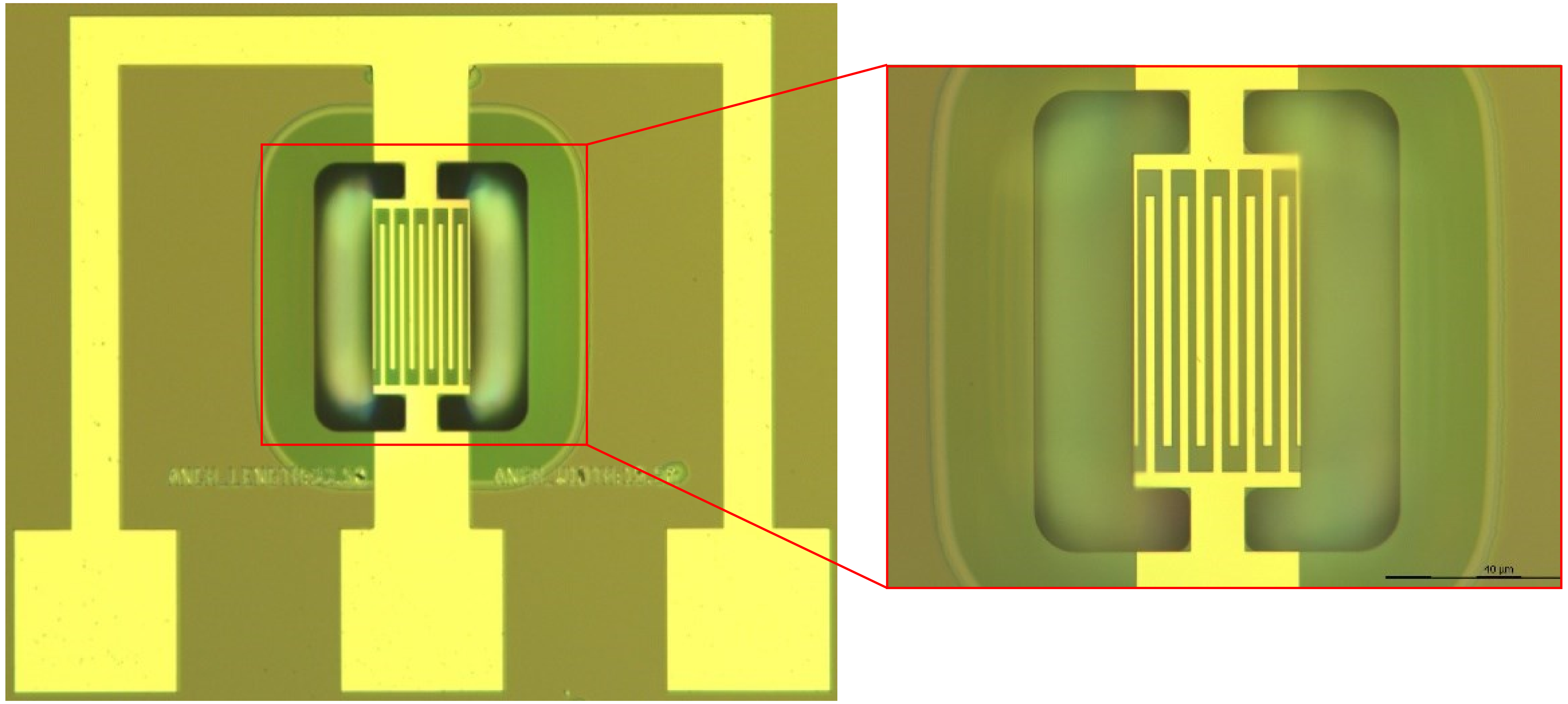




$LiNbO_3$ Resonators (S0 and SHO)

#2 – $LiNbO_3$ S0&SH0 resonators

- $LiNbO_3$ also broadly used – its properties depend a lot on orientation
- We use (X-cut) LiNbO3 thin films on oxide or Si
  - Substrates available since 2012



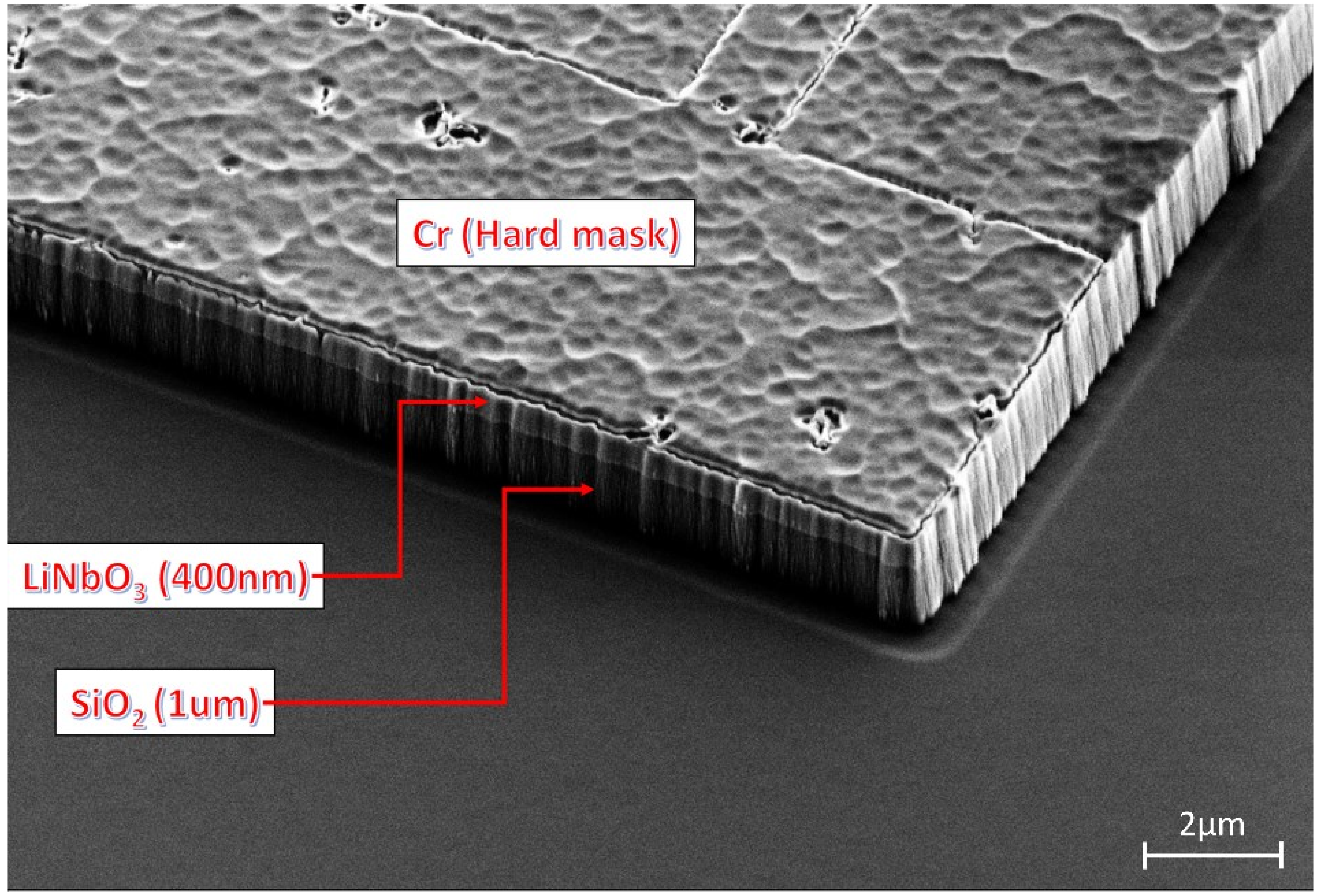
In-depth Fab

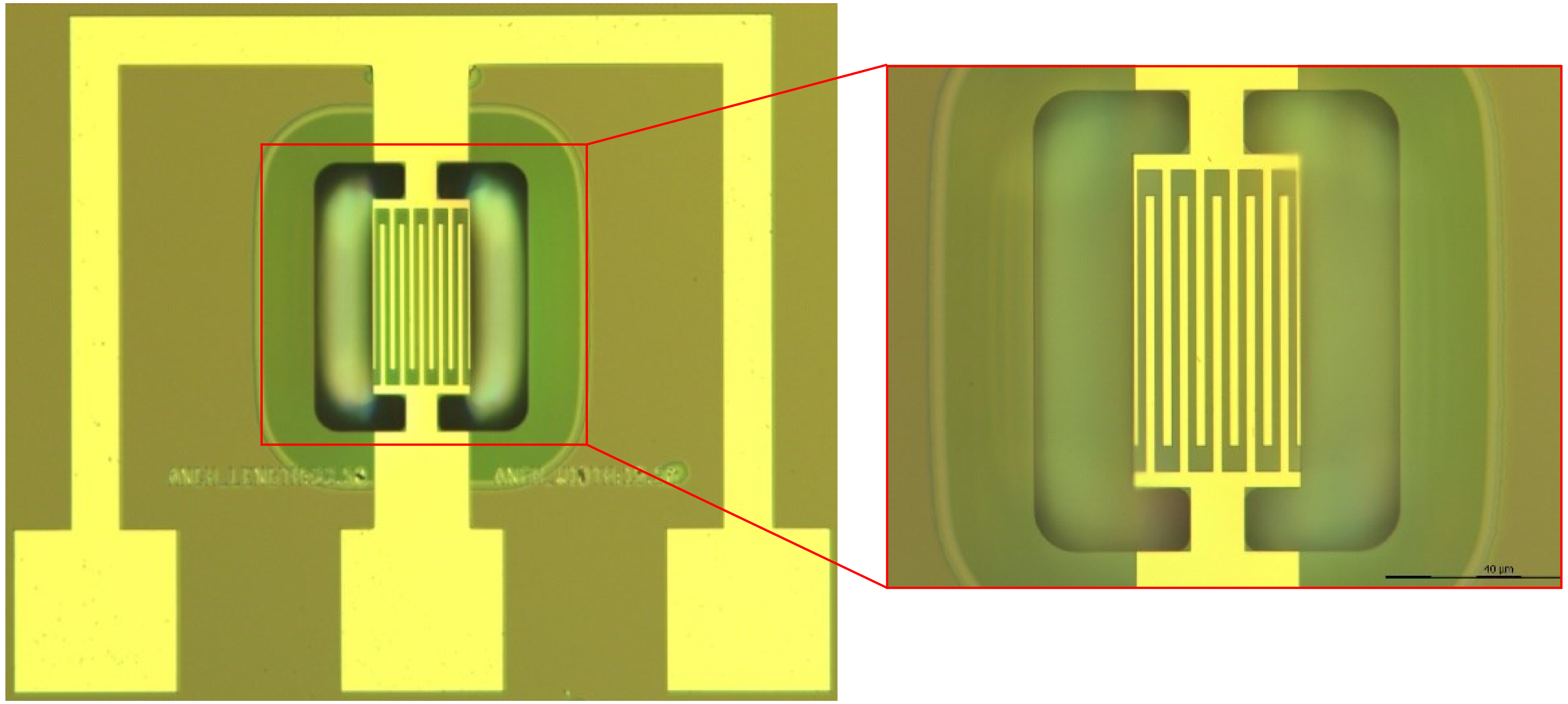
In-depth Fab

#2 – $LiNbO_3$ S0&SH0 resonators

- Challenge:
  - Sidewall angles close to 80°
  - Lateral roughness in the order of 50nm
- Process scalable up to 4-5 GHz

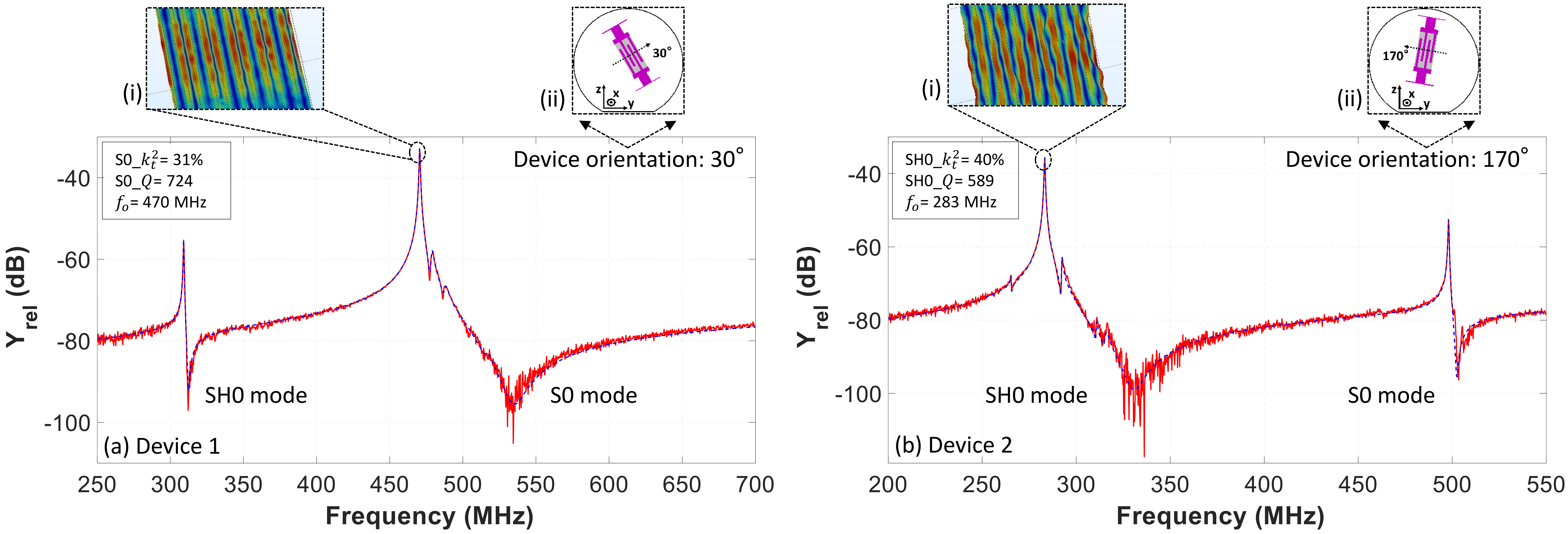
$$f_r = \frac{V_{SO}}{\lambda} = \sqrt{\frac{E_{eq}}{\rho_{eq}}}\frac{1}{pitch}$$





#2 – $LiNbO_3$ S0&SH0 resonators

- In the same wafer, we could fabricate optimized S0 and SH0 devices
- k_t^2 is 30% (S0) or 40% (SH0)
- Loaded Q (average) was 650 in our first run

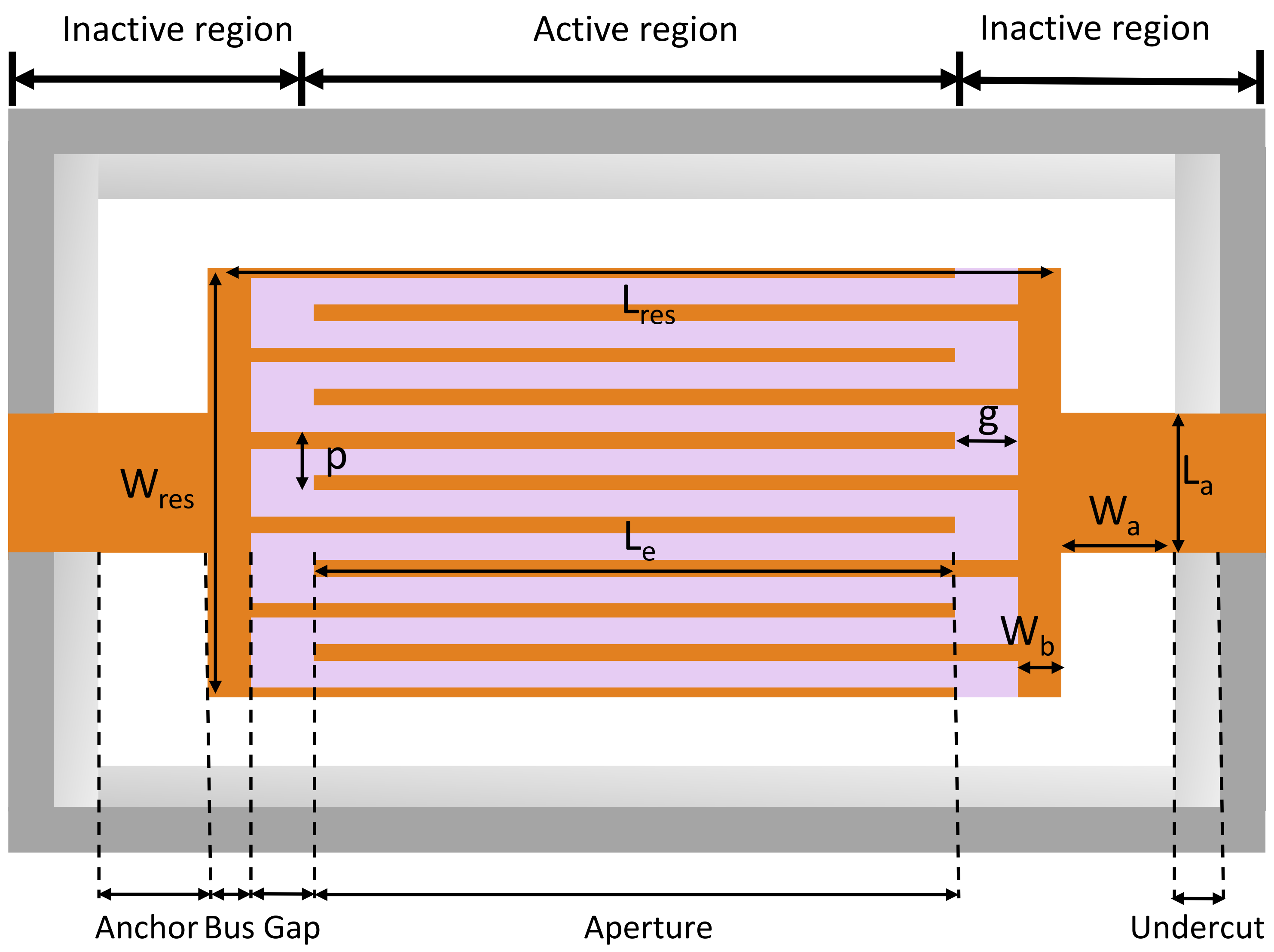


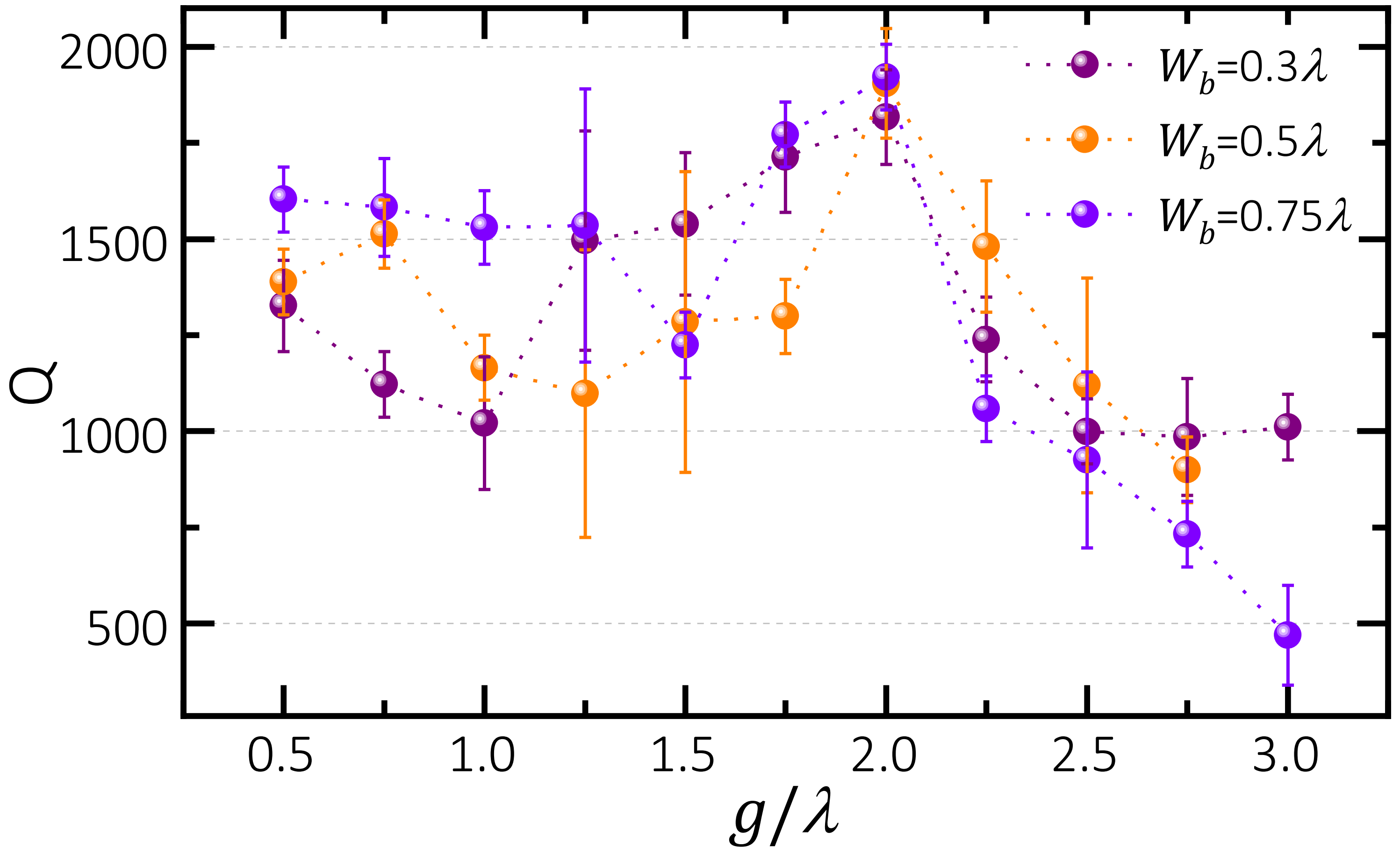
#2 – $LiNbO_3$ S0&SH0 resonators

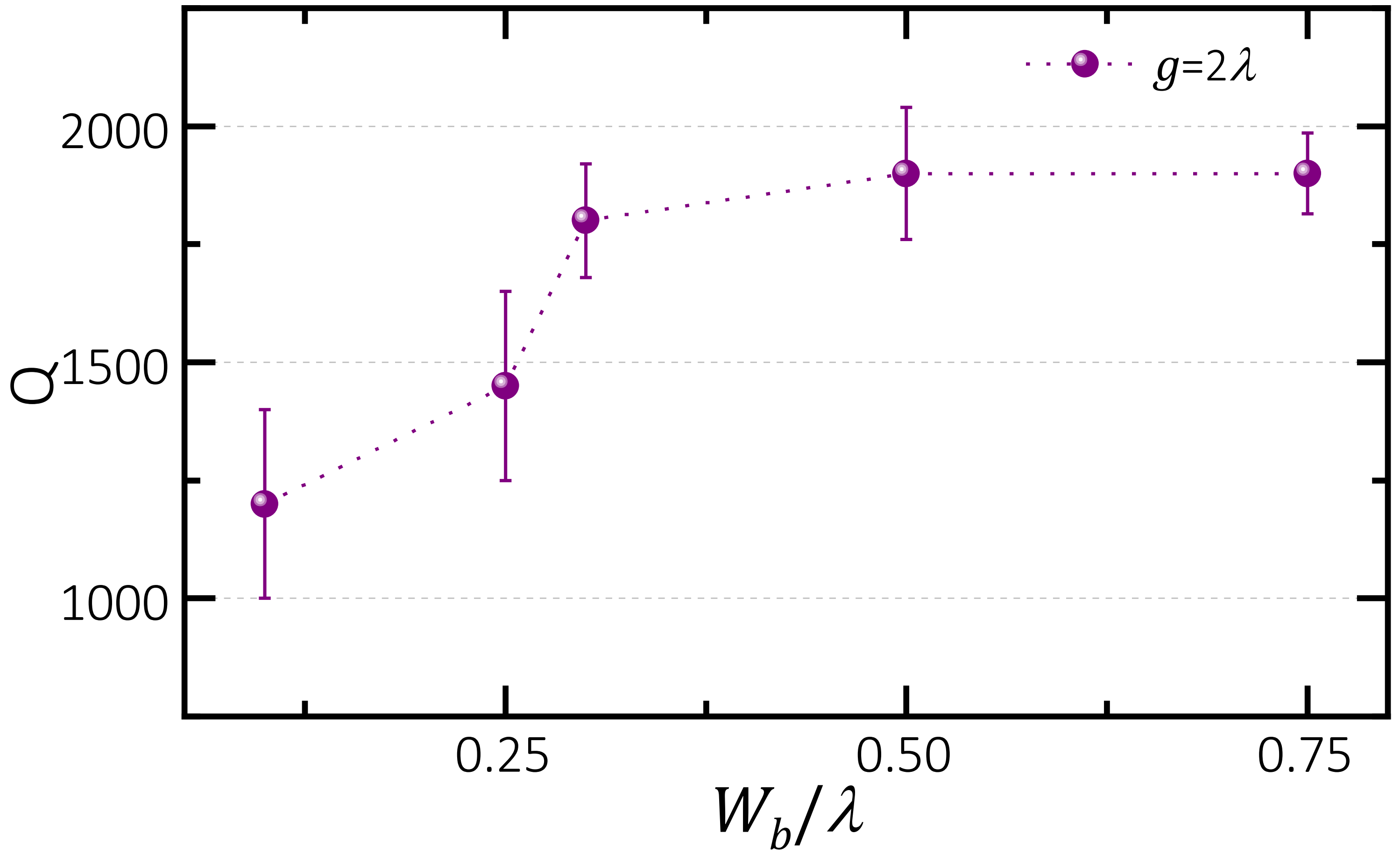
- Design optimization – tweaking inactive regions

- Coupling was maintained
- Q improved 3x

$$Q = 1900 \ @ \ 290\text{MHz}$$
$$k_t^2 = 41\%$$

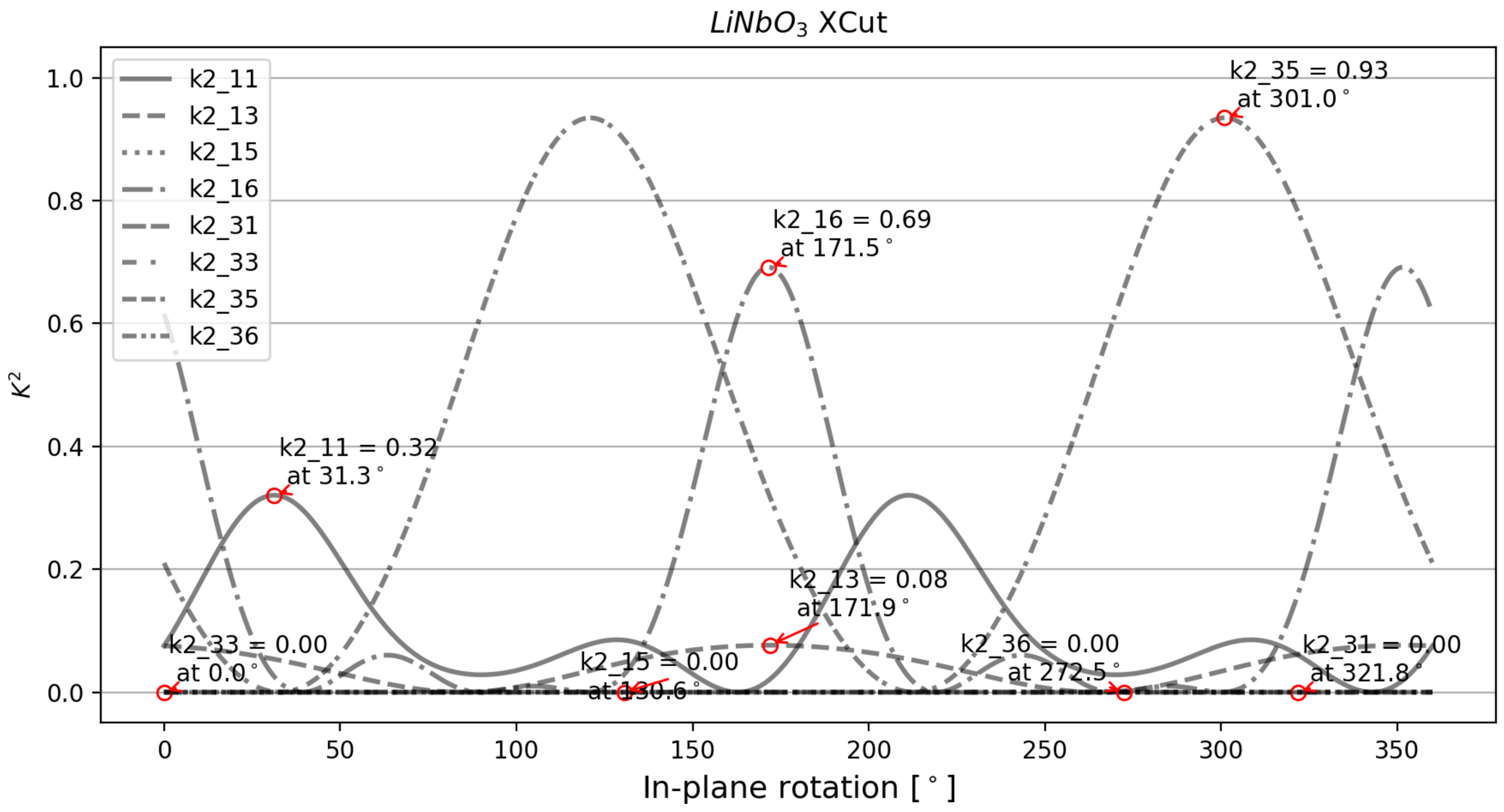


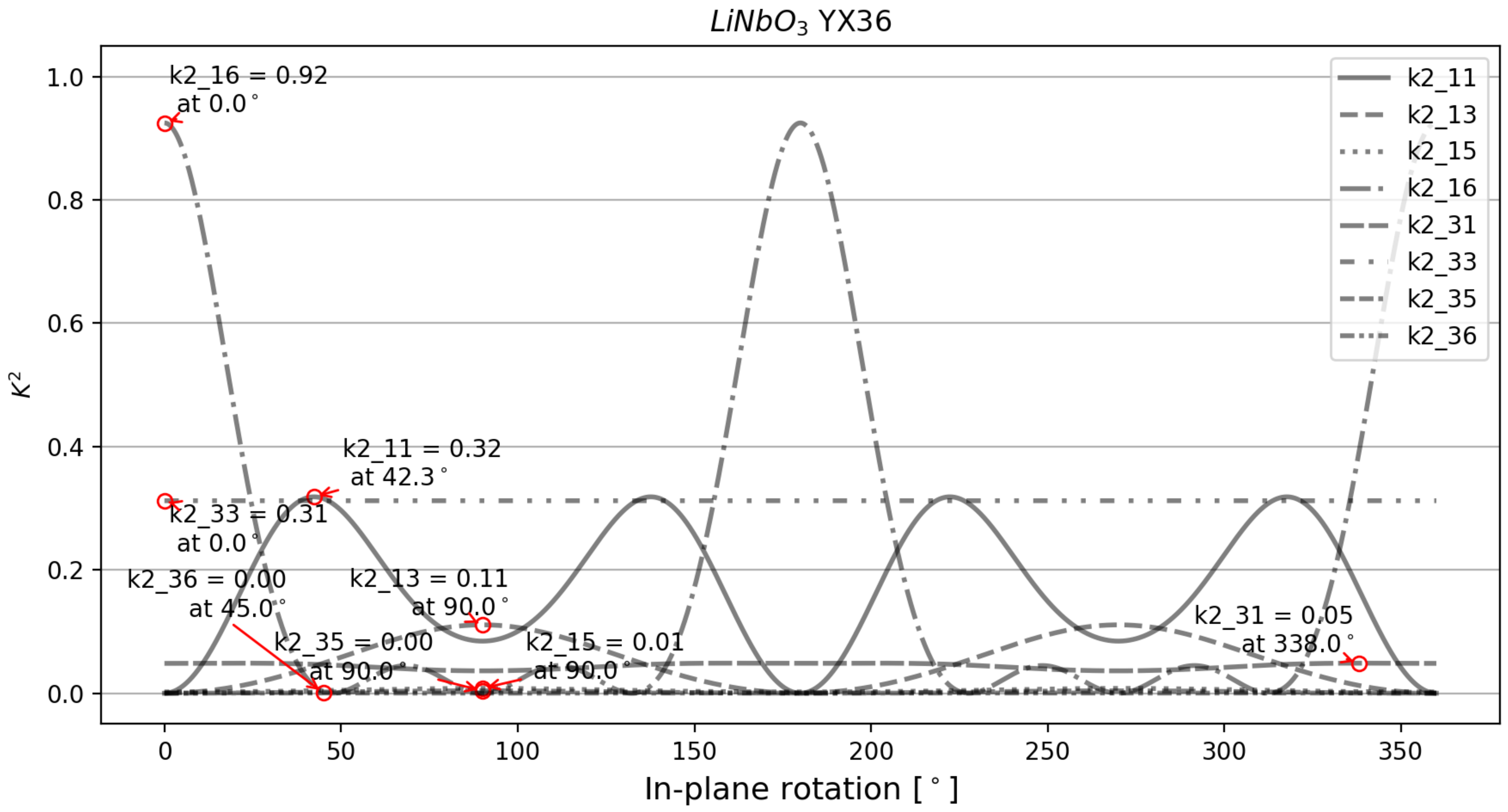




#2.1 – SH0 resonators in XY36

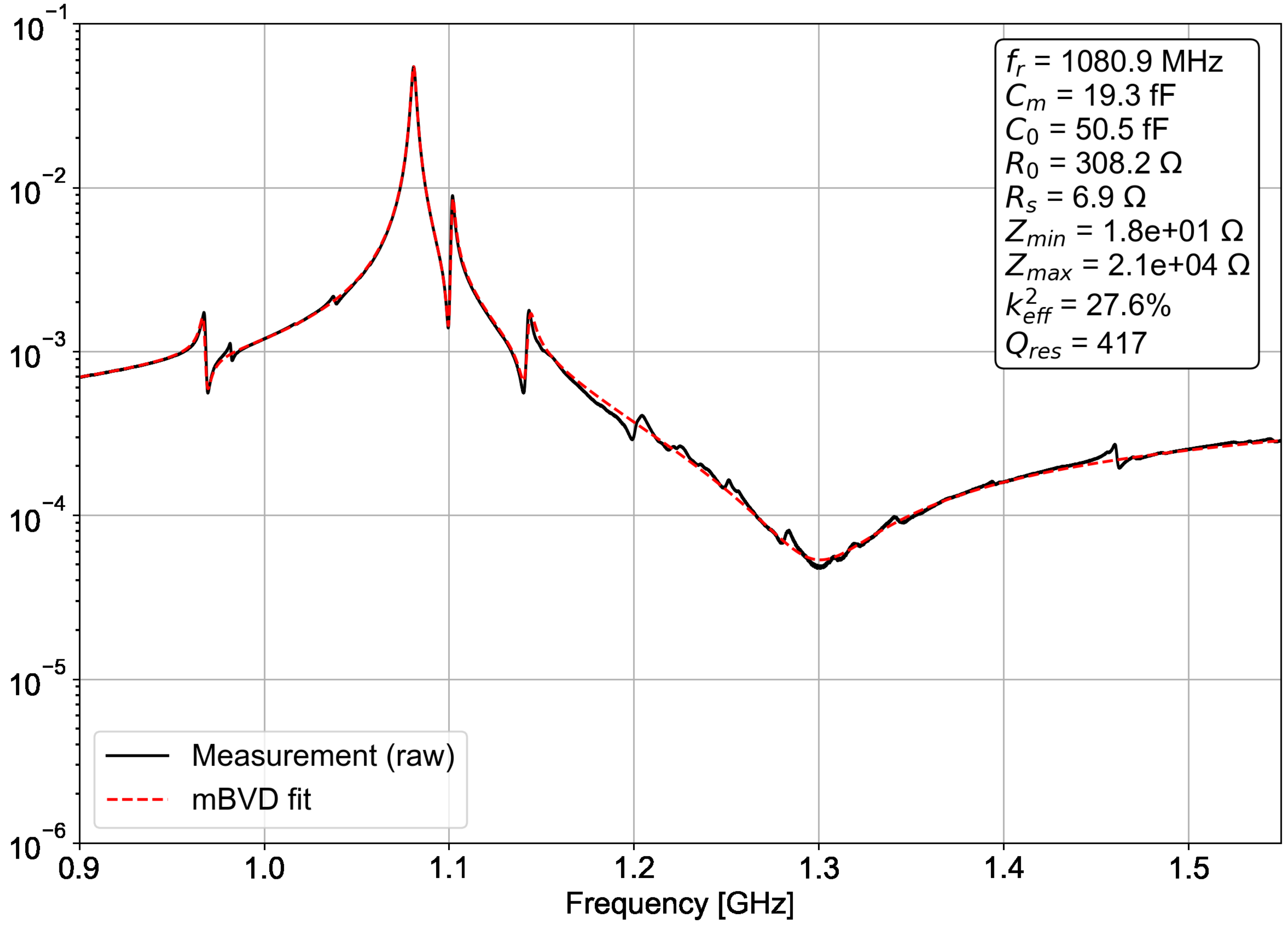
- Search for larger coupling
- Removing major spurious (S0)

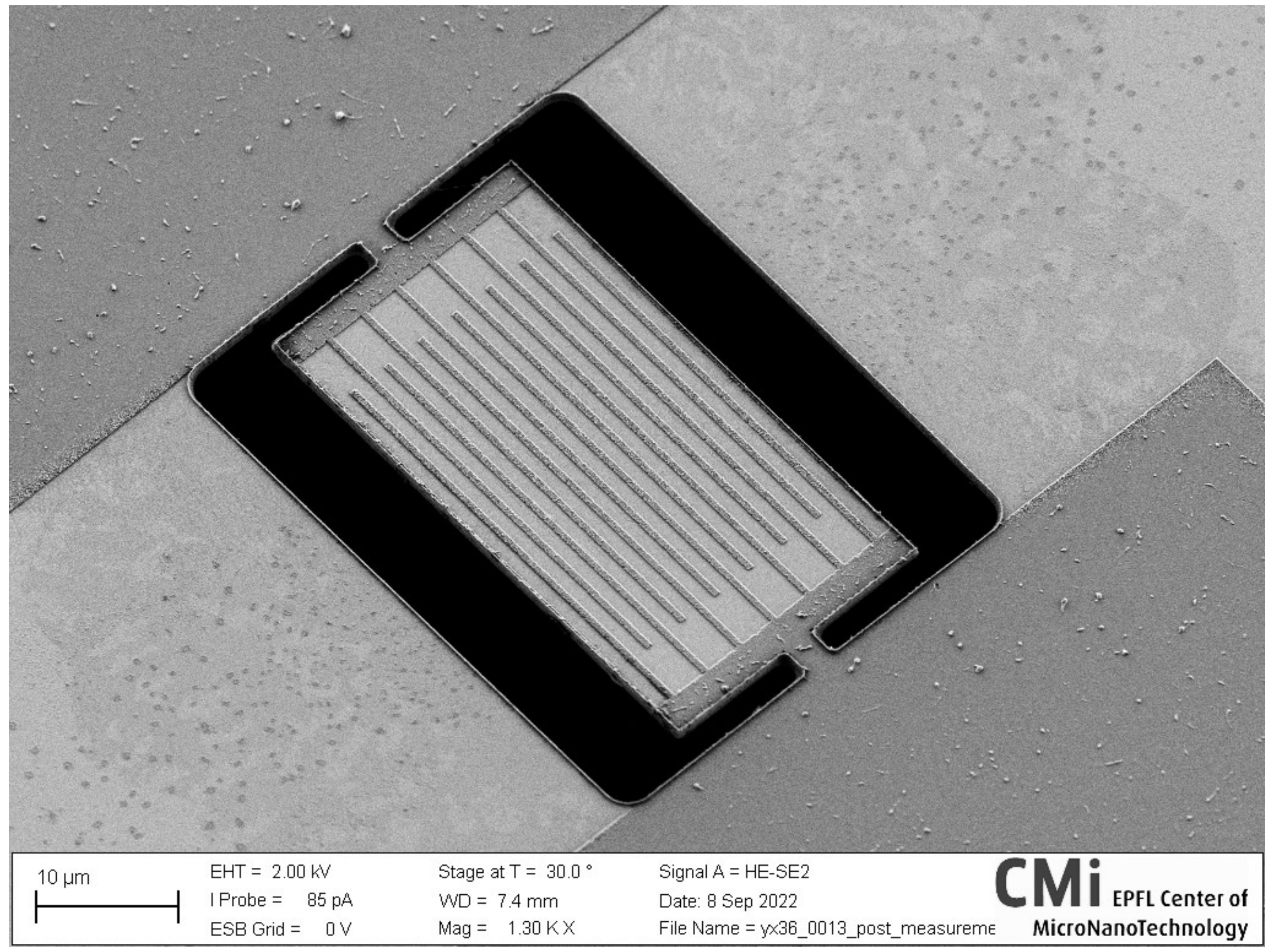


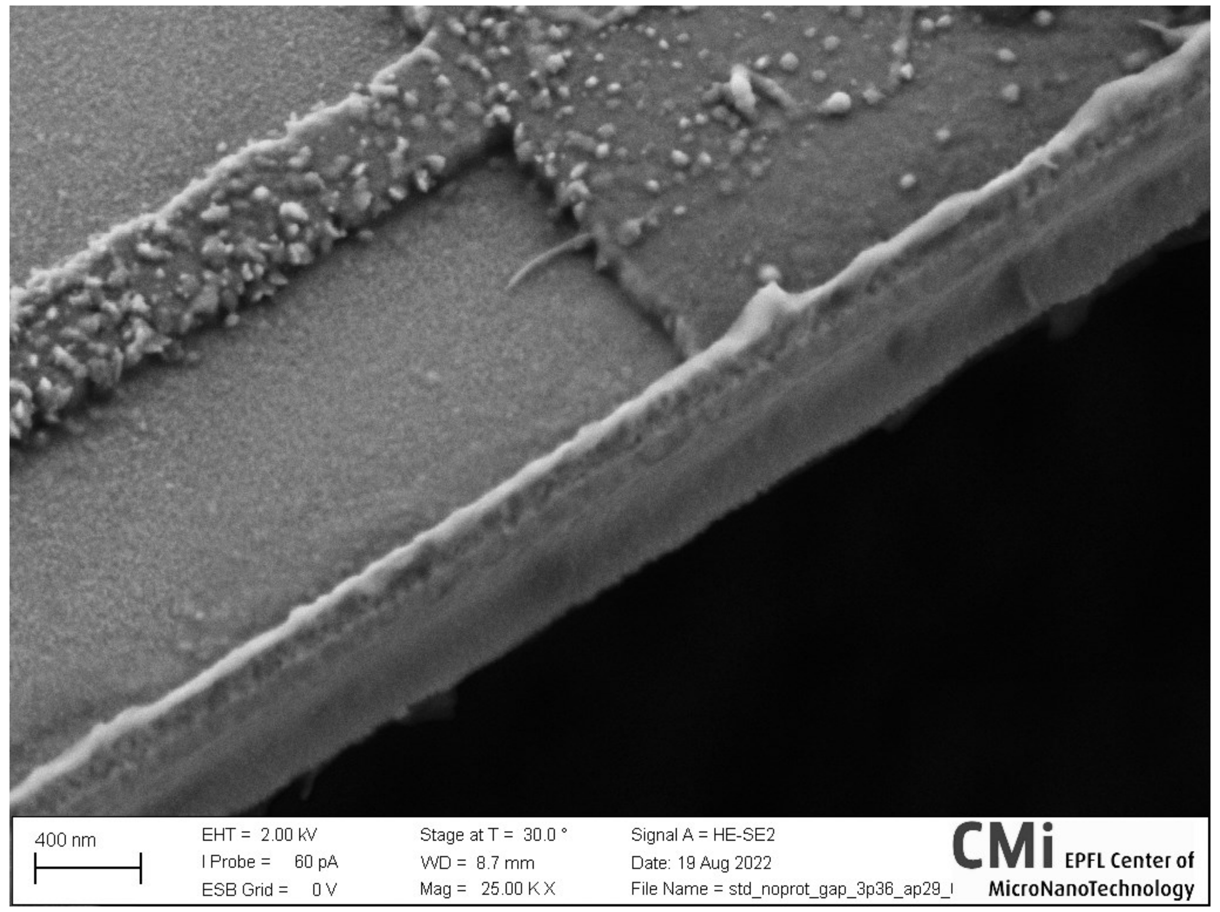


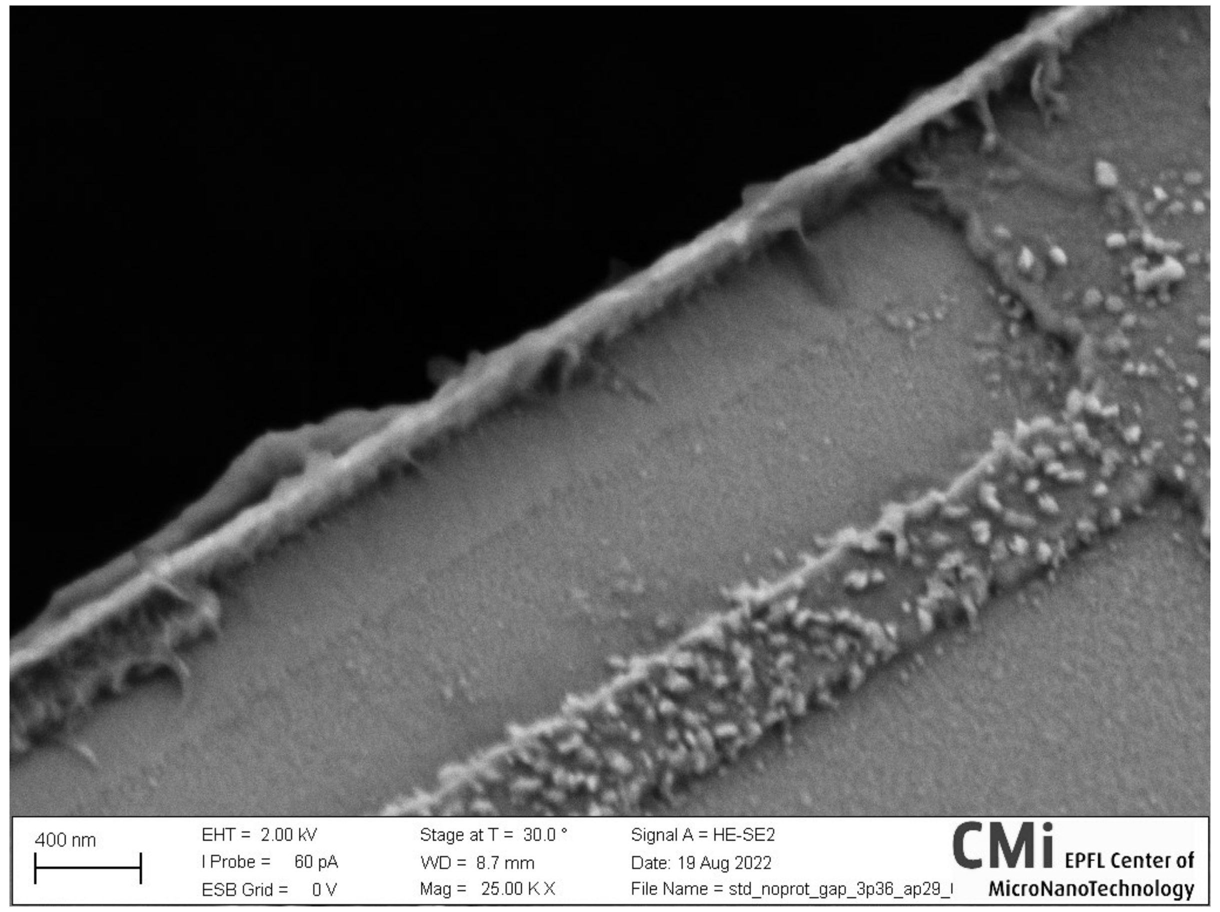
EPFL The Devil is in the Details

- 1st round of fabrication – Anti-Resonance heavily suppressed









* Stettler et al, IUS 2022, Venice

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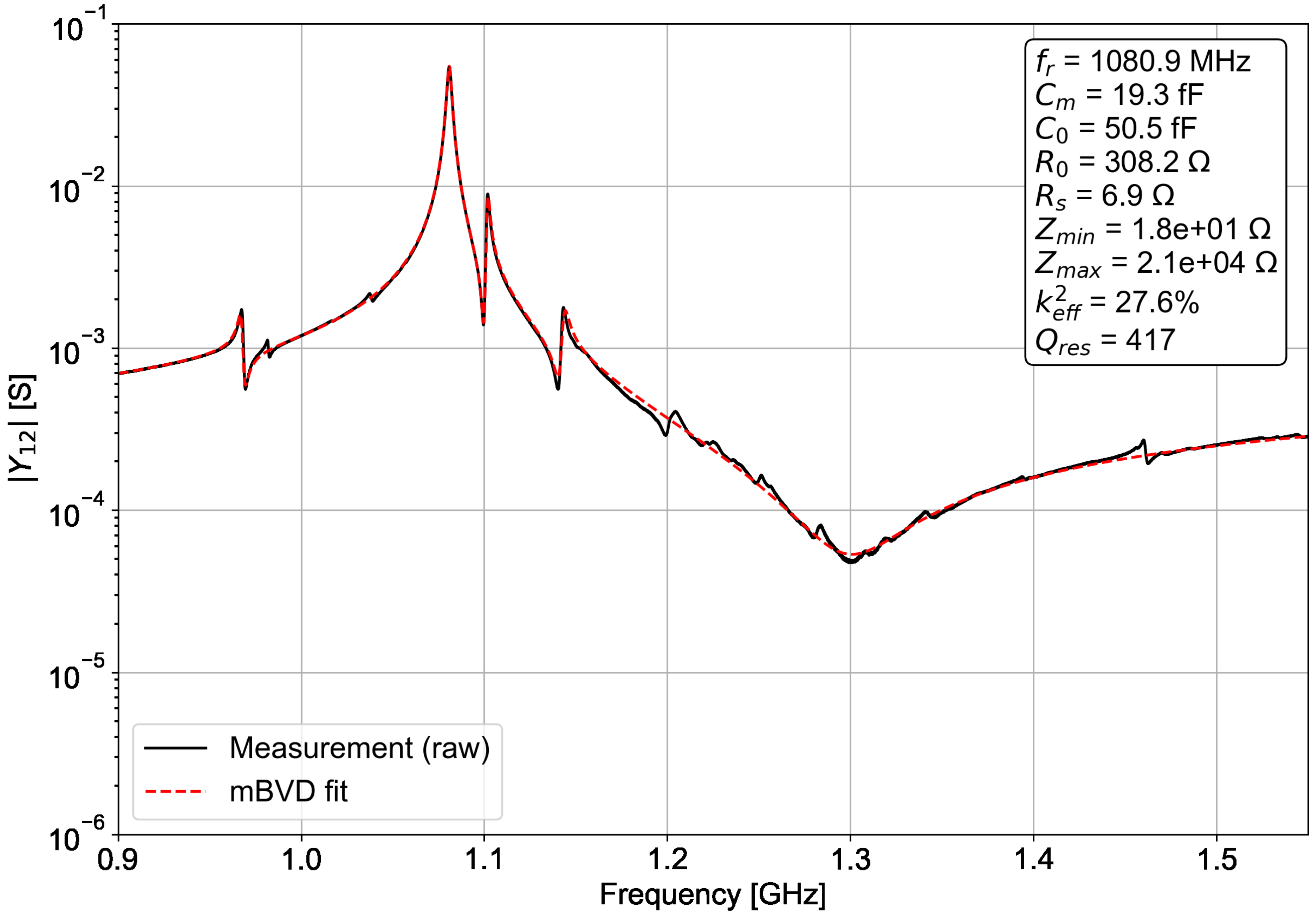
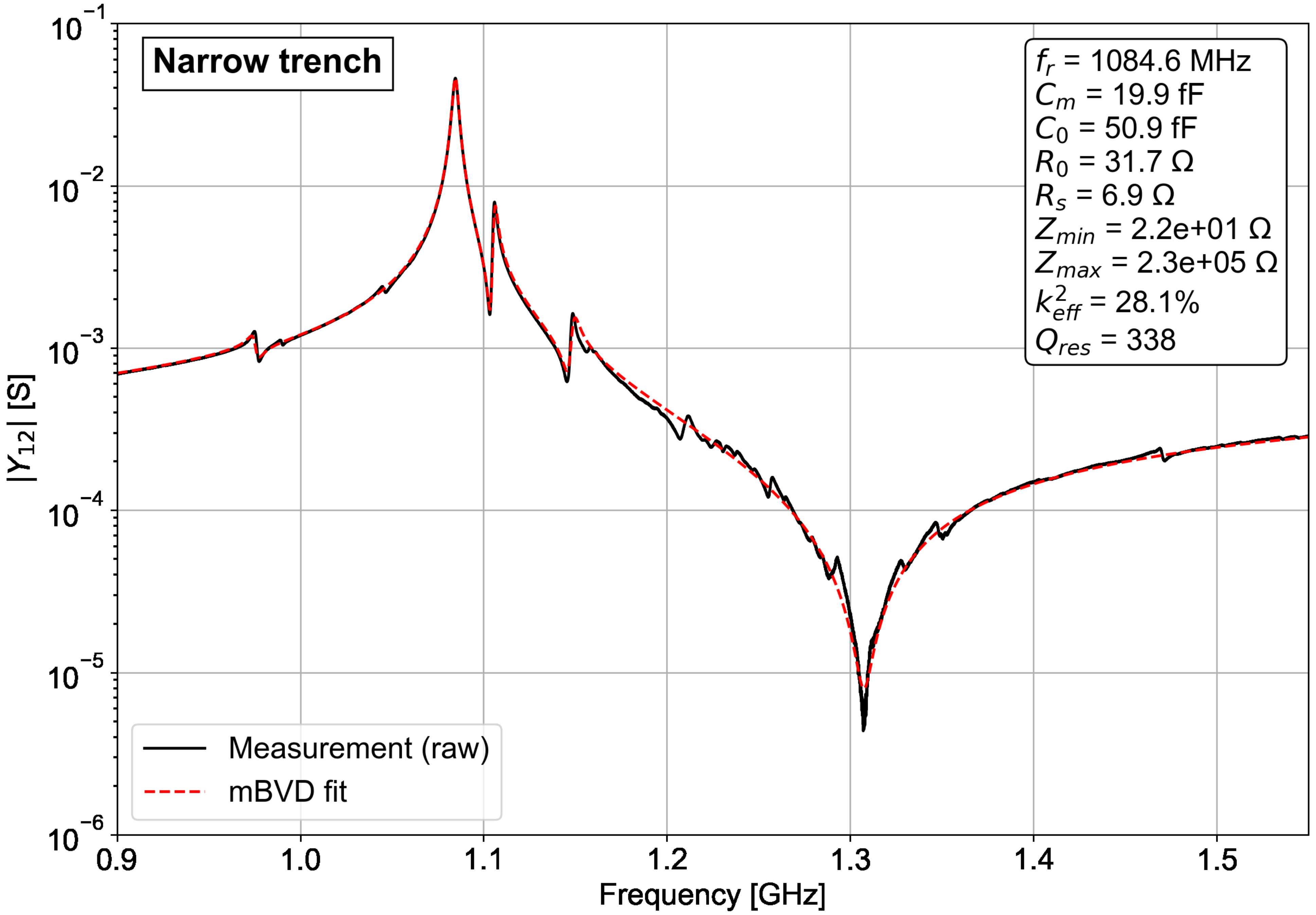
- 2nd round – Defining resonators via a narrow trench ($R_0 \sim 30\ \Omega$)





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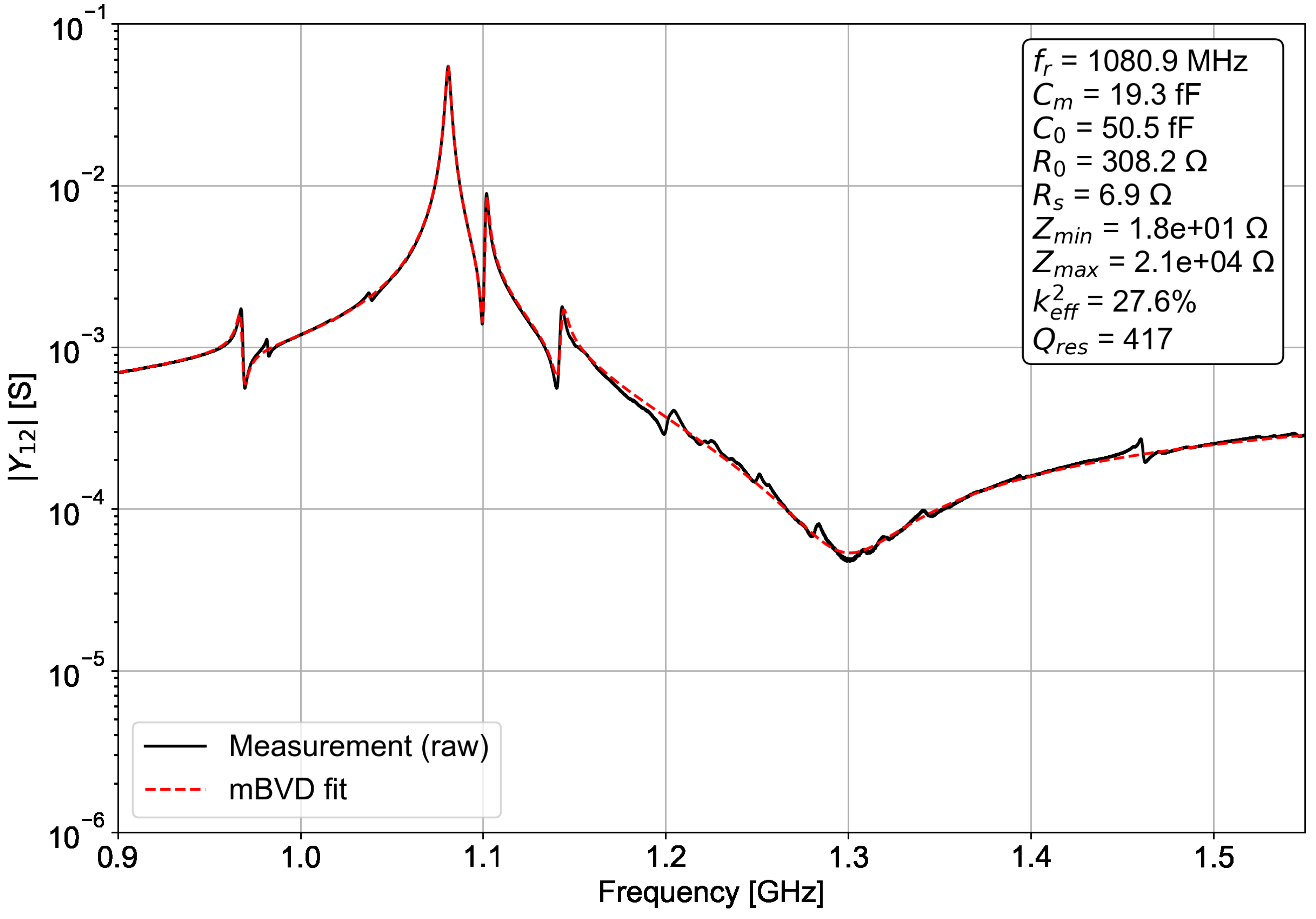
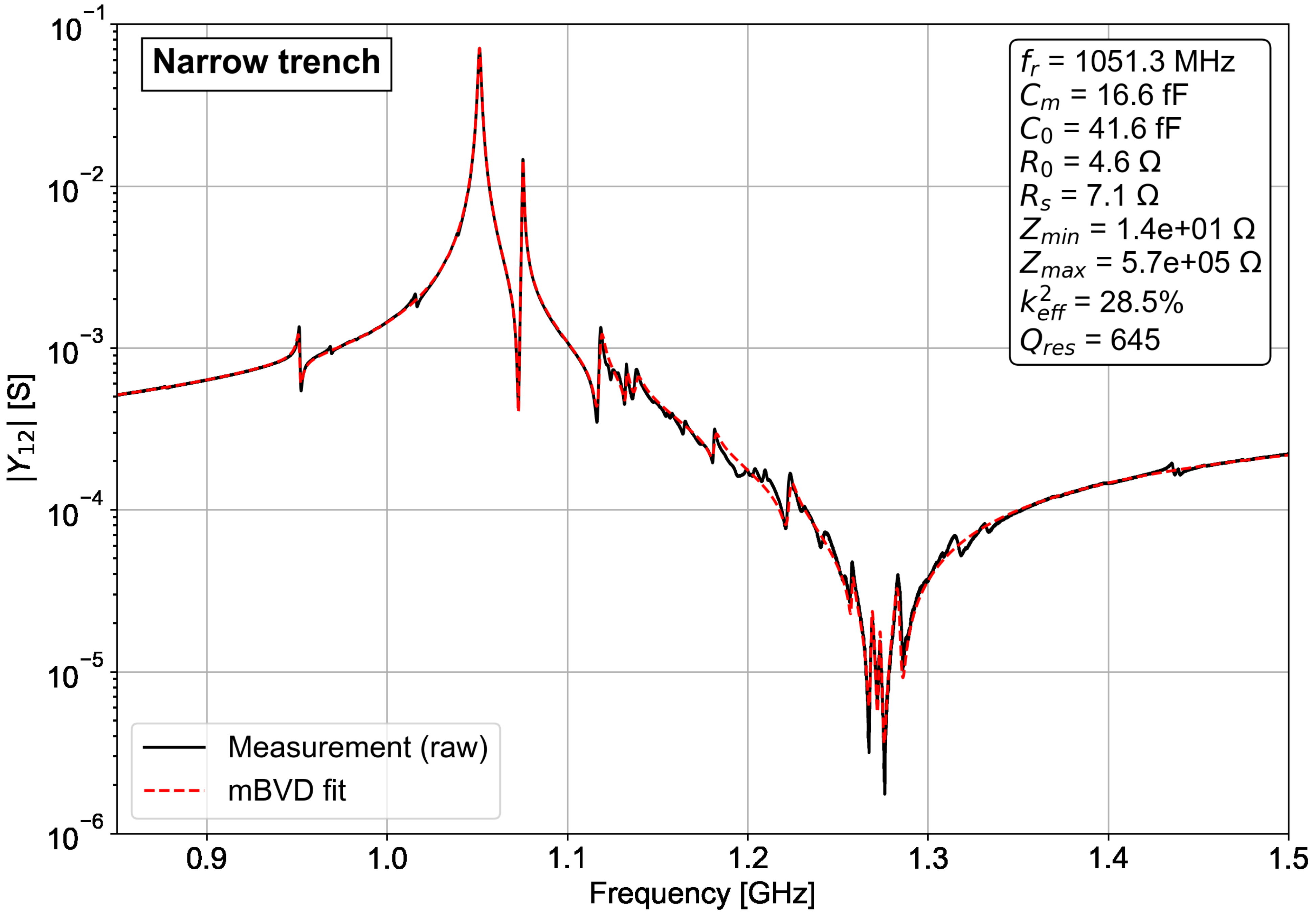
The Devil is in the Details

- 1st round of fabrication – Anti-Resonance heavily suppressed ($R_0 \sim 300\ \Omega$)
- 2nd round – Defining resonators via a narrow trench ($R_0 \sim 30\ \Omega$)
- 3rd round – Narrow trench + Controlling the resist sidewall ($R_0 \sim 5\ \Omega$)





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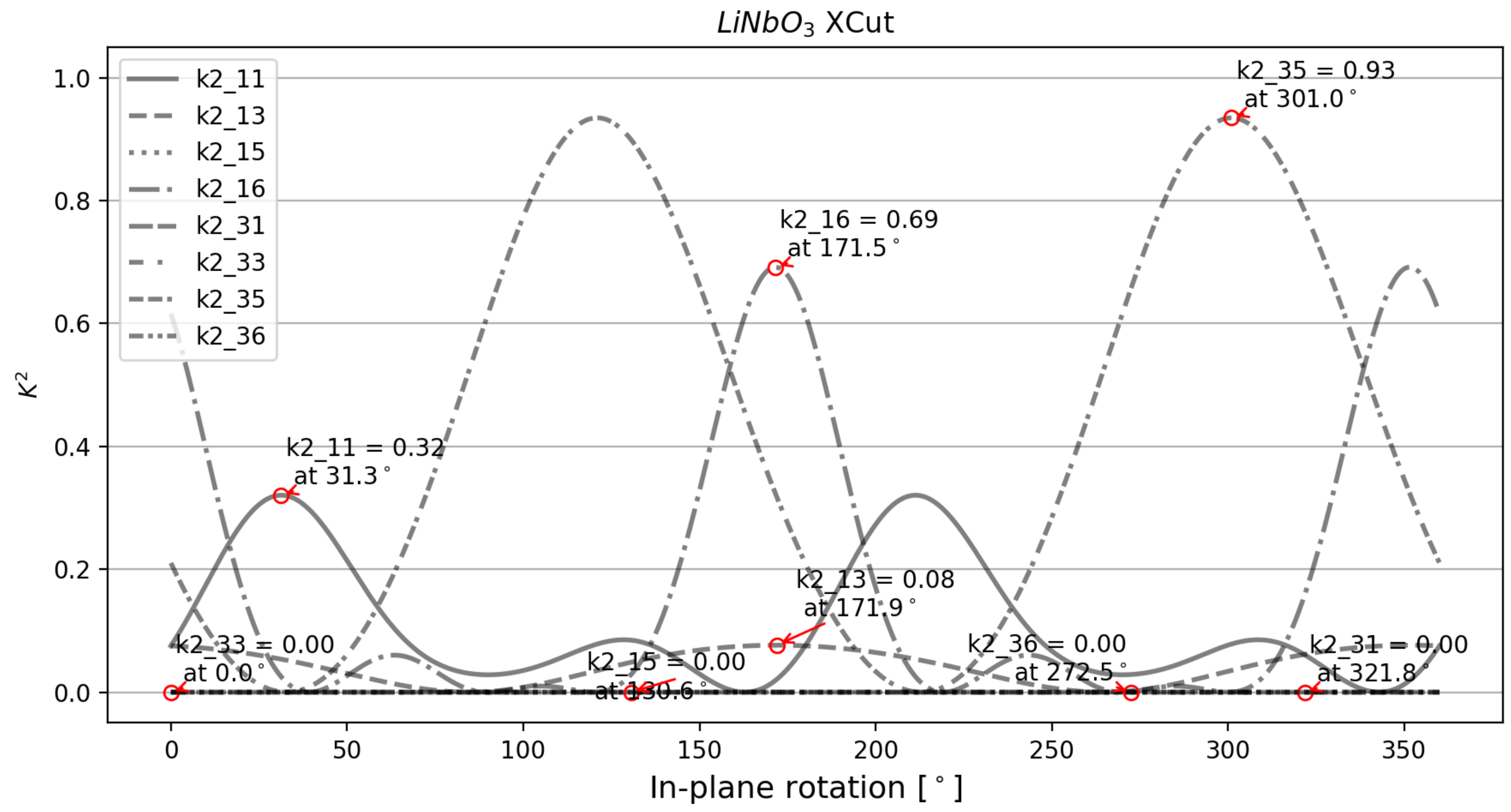
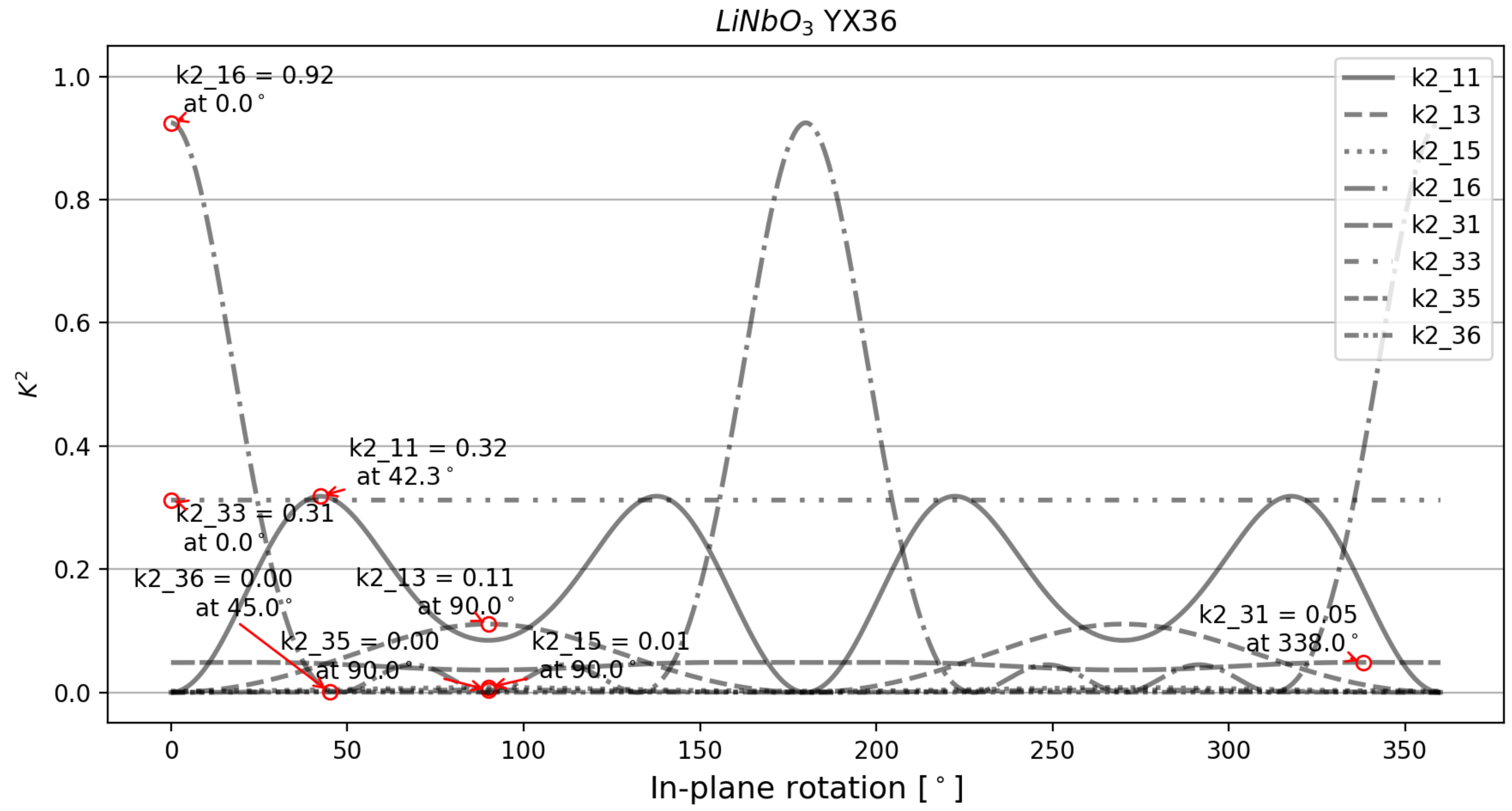
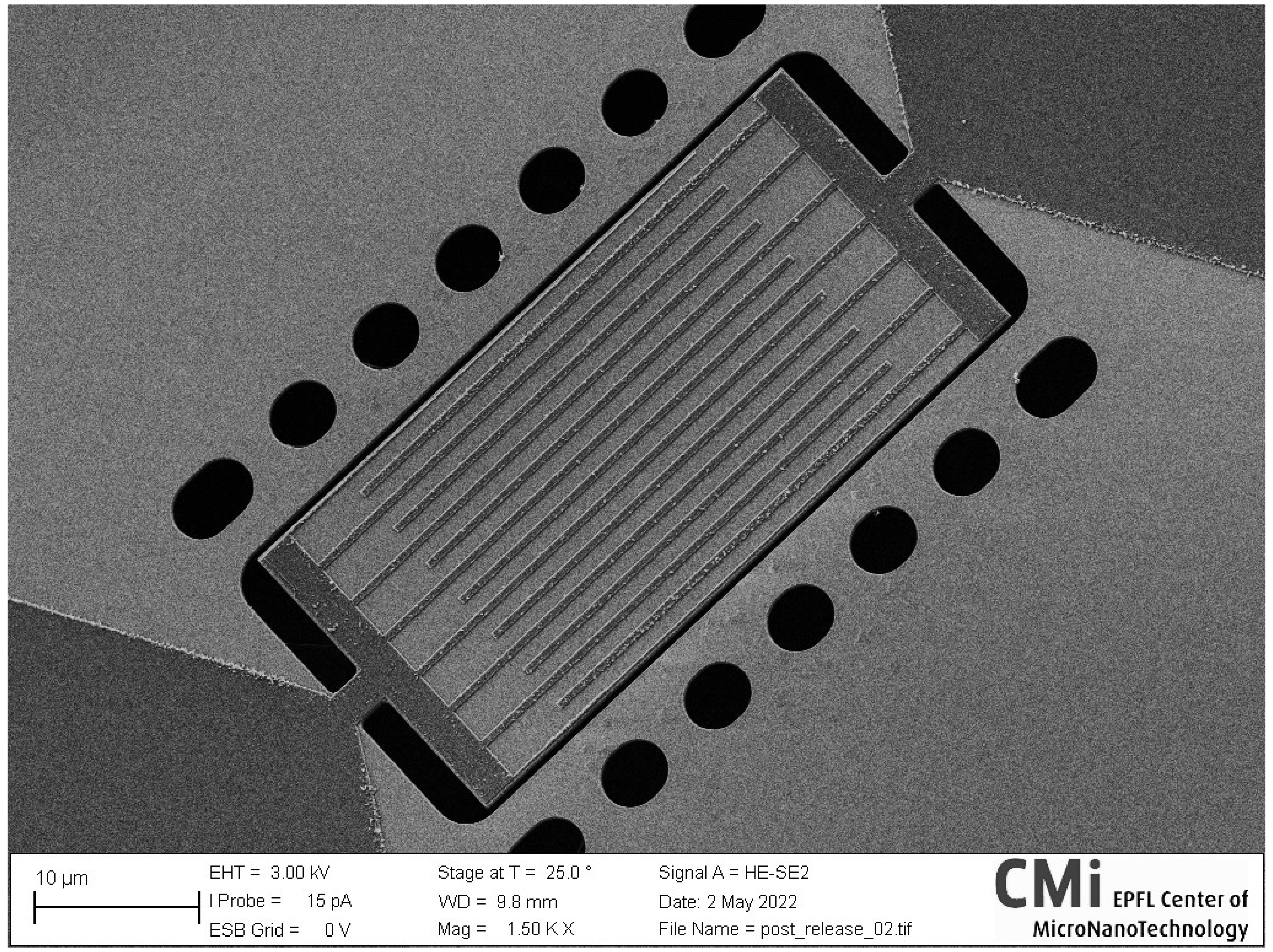


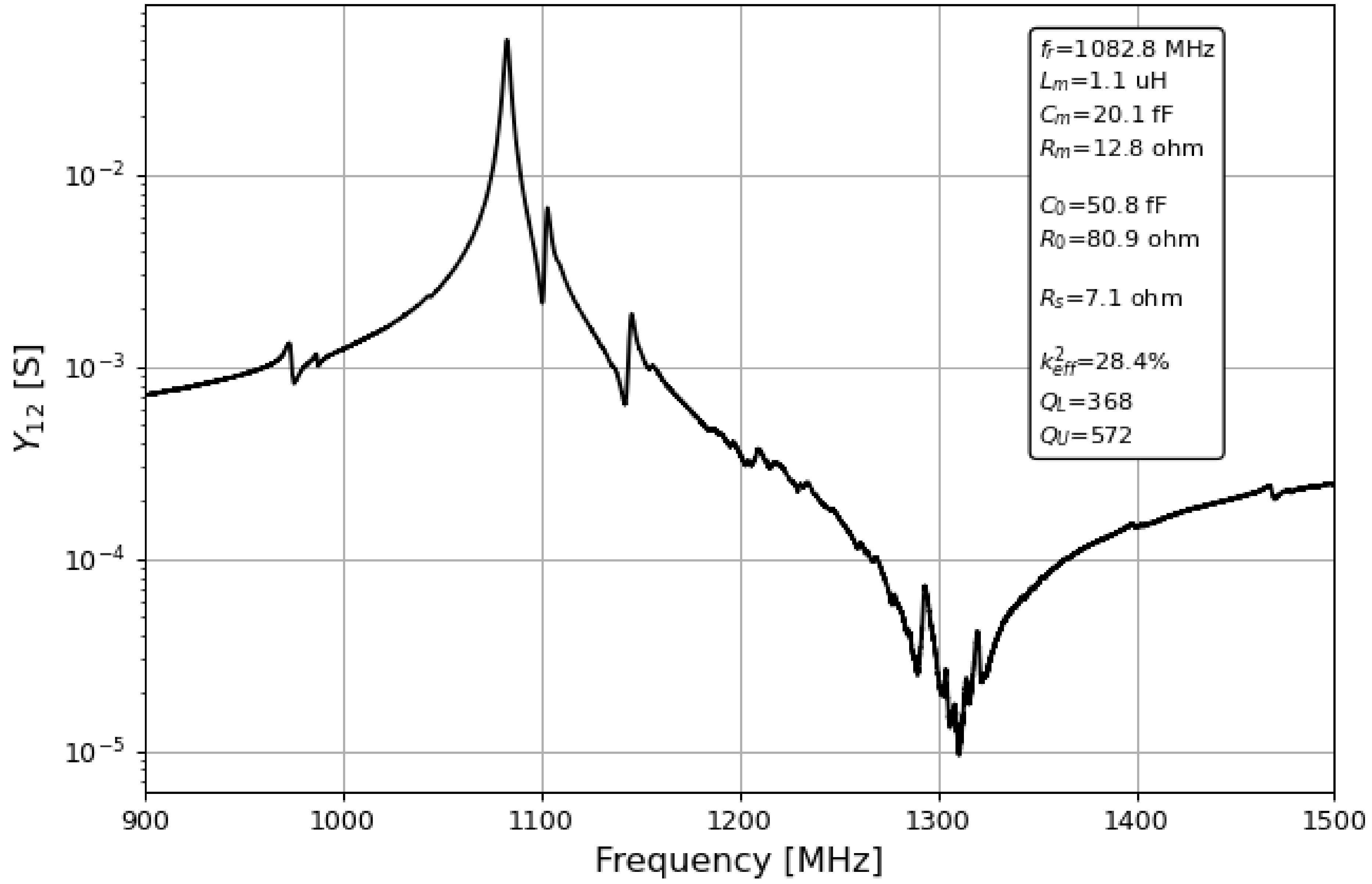


#2.1 – SH0 resonators in XY36

- 300 nm thick suspended platelet
- Al IDT transducer
- f_r 300 MHz or 1.1 GHz

Performance:
- Up to RaR of 16%
- Loaded Q factor
  - 350 @ 1.1 GHz
  - 1000 @ 280 MHz

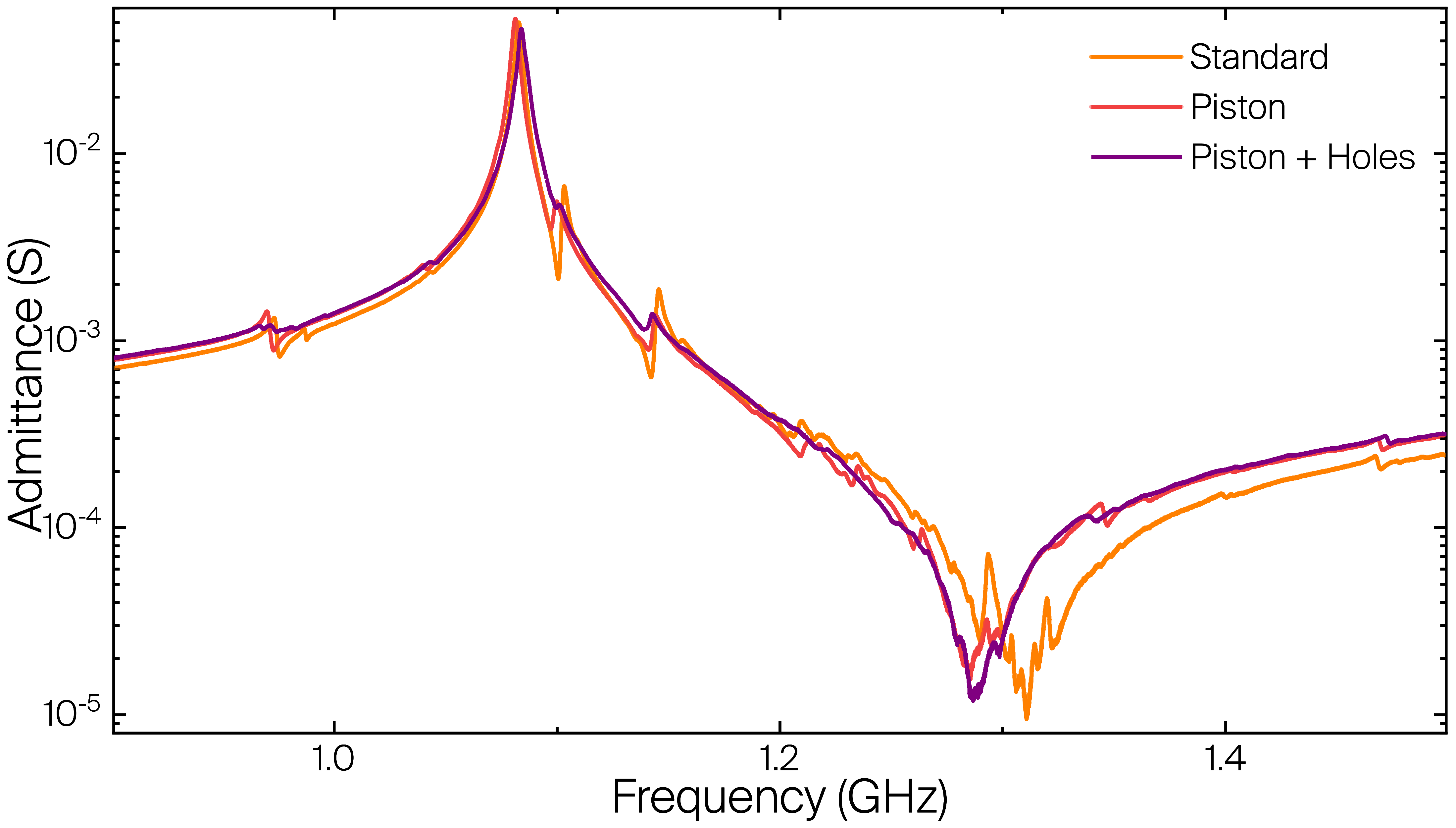




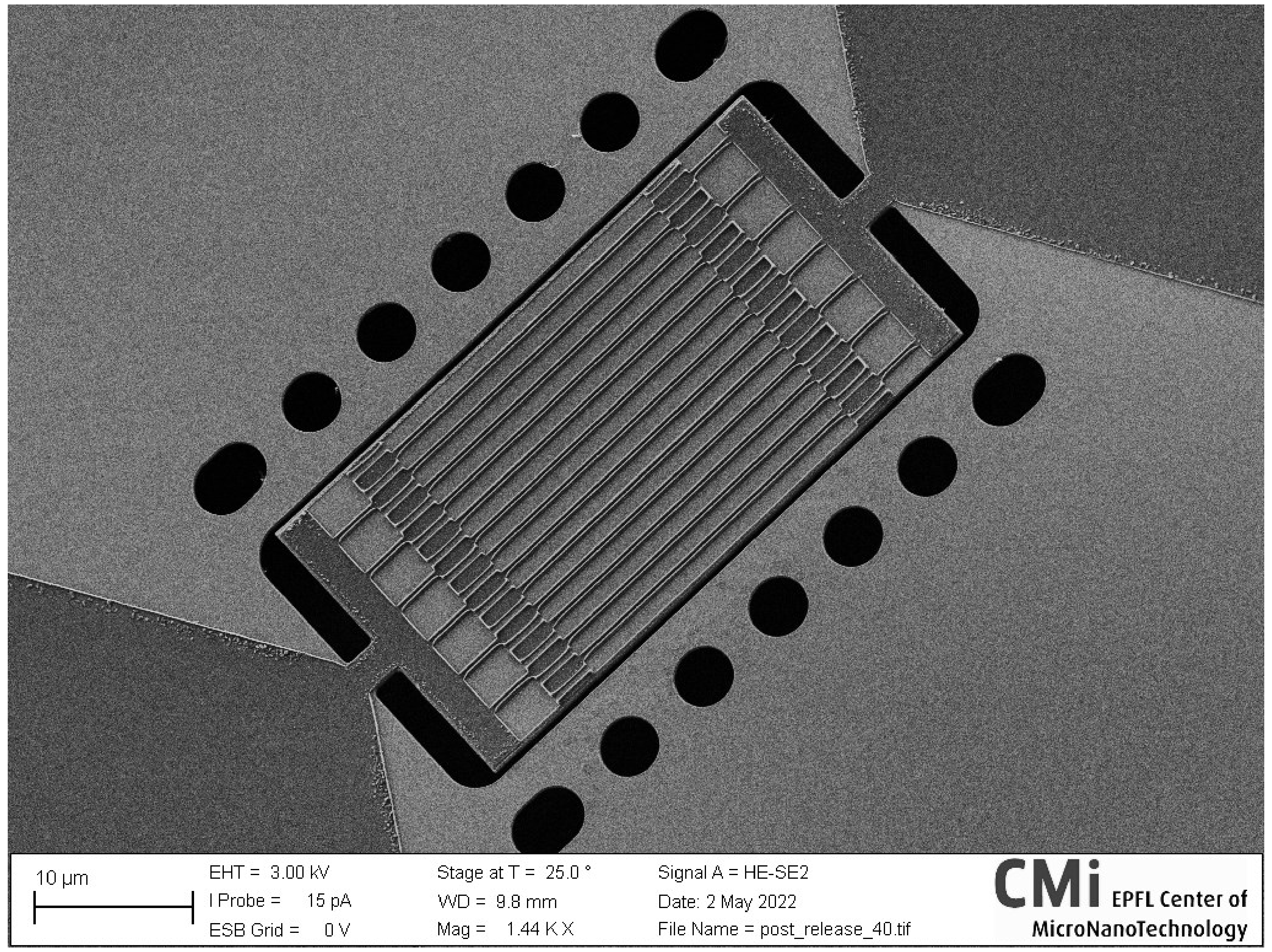
#2.1 – SH0 resonators in XY36

- 1st order correction: Suppression around f_r
- 2nd order correction: Suppression over entire band and RaR of 16%

- Piezoelectric MEMS resonators for 5G filters



Record Figure of Merit



* Stettler et al, JMEMS, *submitted*

#2.1 – SH0 resonators in XY36 – Next steps

- Increase Q factor
  - Optimizing boundary conditions
  - Minimizing fabrication residues
  - Changing electrode material

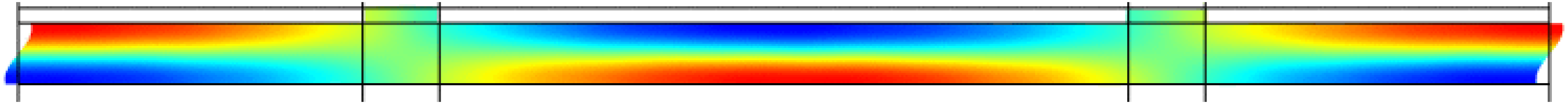
- Increase frequency
  - E-beam lithography allows it (also DUV)
  - Thinner layer of LNO → might cause extra losses and reduce Q

EPFL

$LiNbO_3$ Resonators (A1, XBAR)

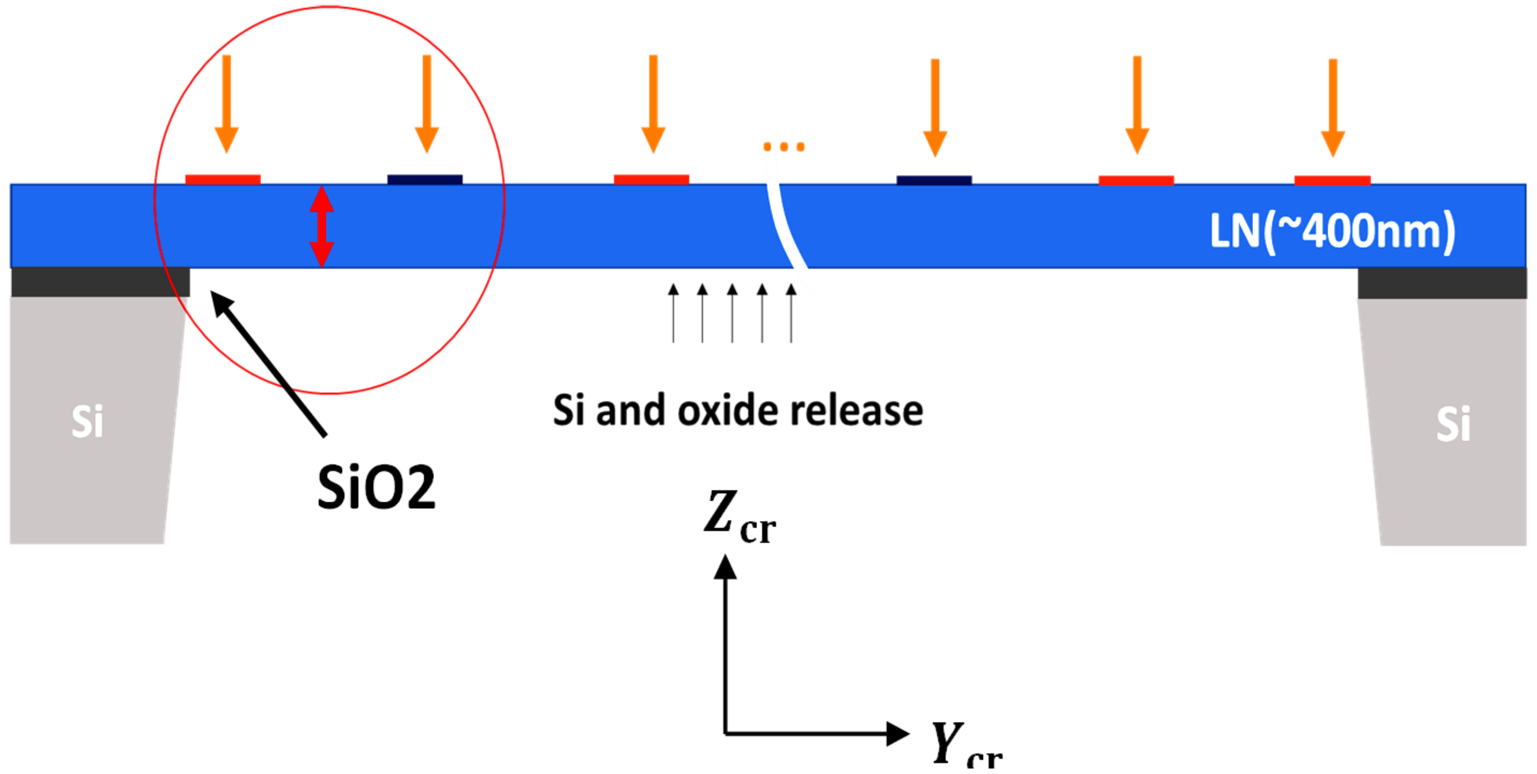
#3 – $LiNbO_3$ XBAR

- Shear A1-like mode



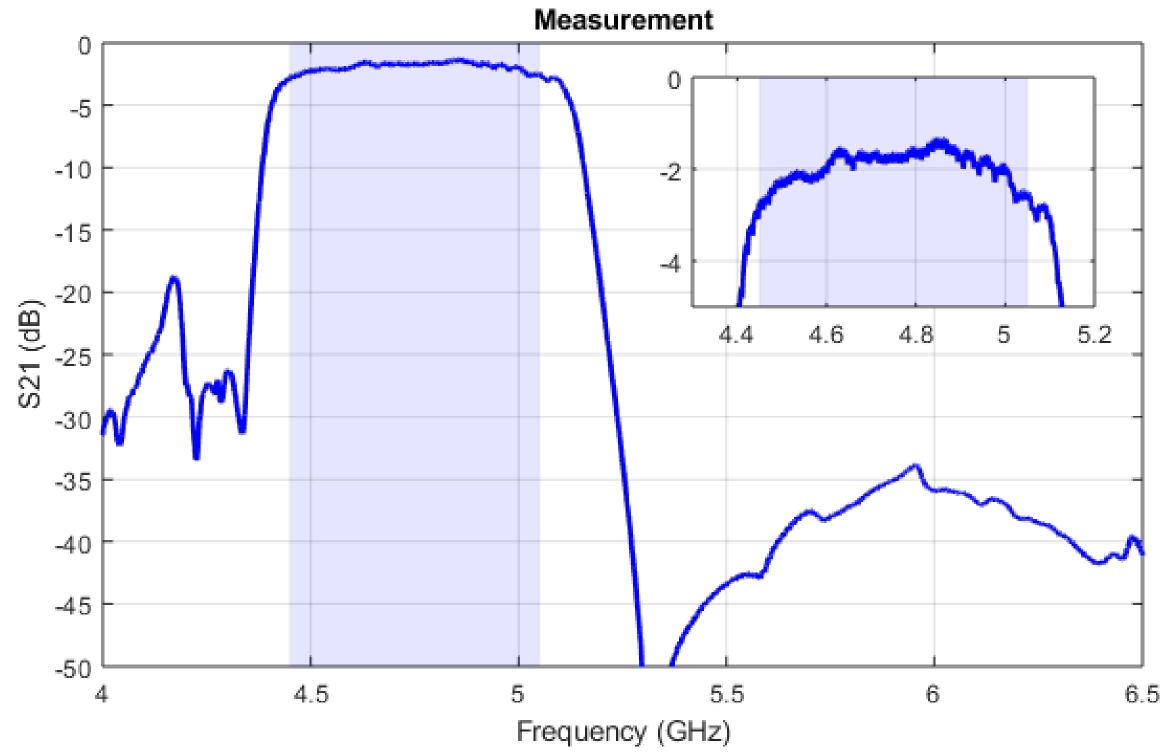
- Originally in z-cut (see later)
- Resonant frequency is predominantly thickness defined

$$f_r = \frac{V_{A1}}{\lambda} = \sqrt{\frac{E_{eq}}{\rho_{eq}}} \cdot \frac{1}{2t}$$



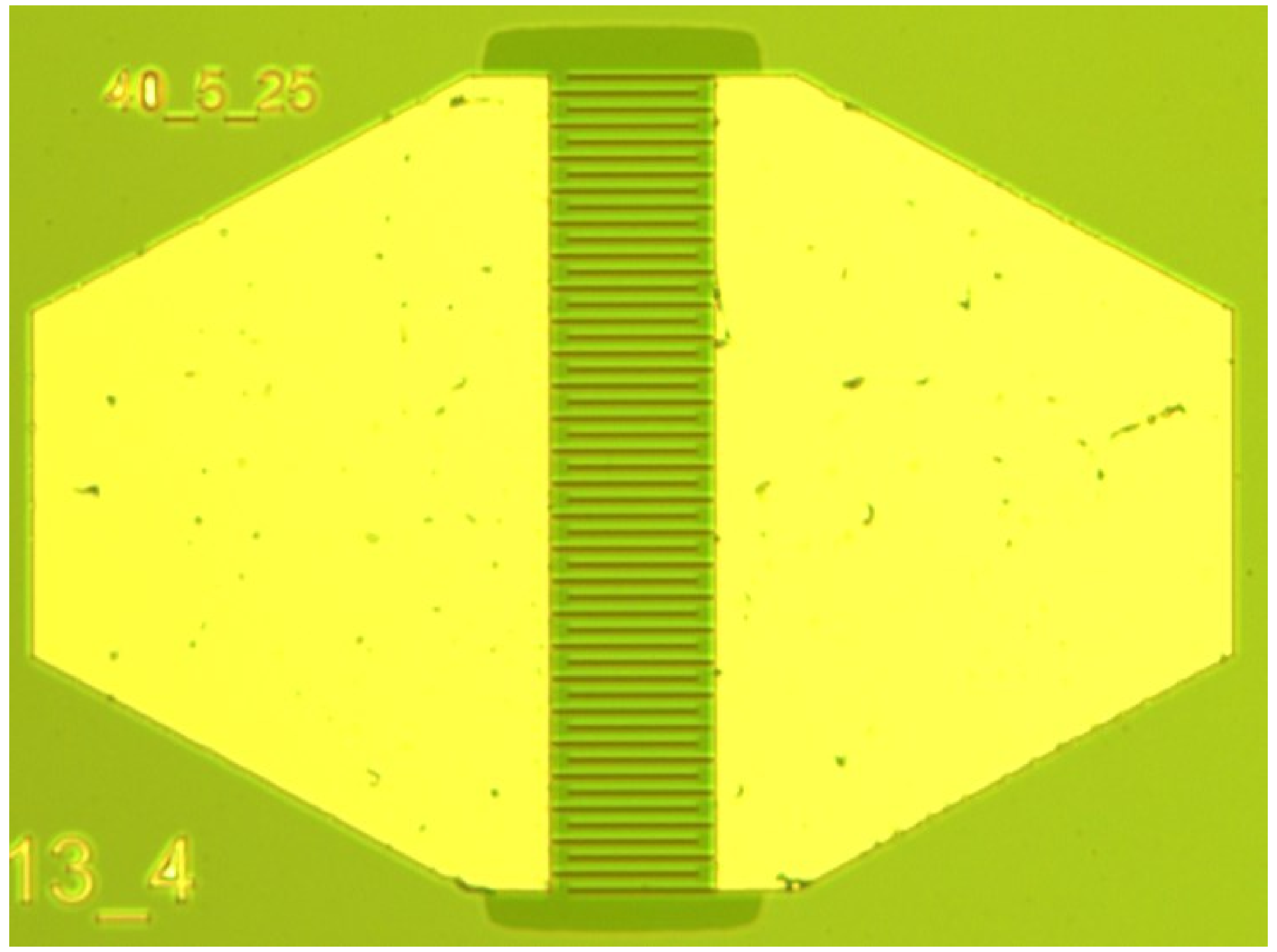
EPFL #3 – $LiNbO_3$ XBAR

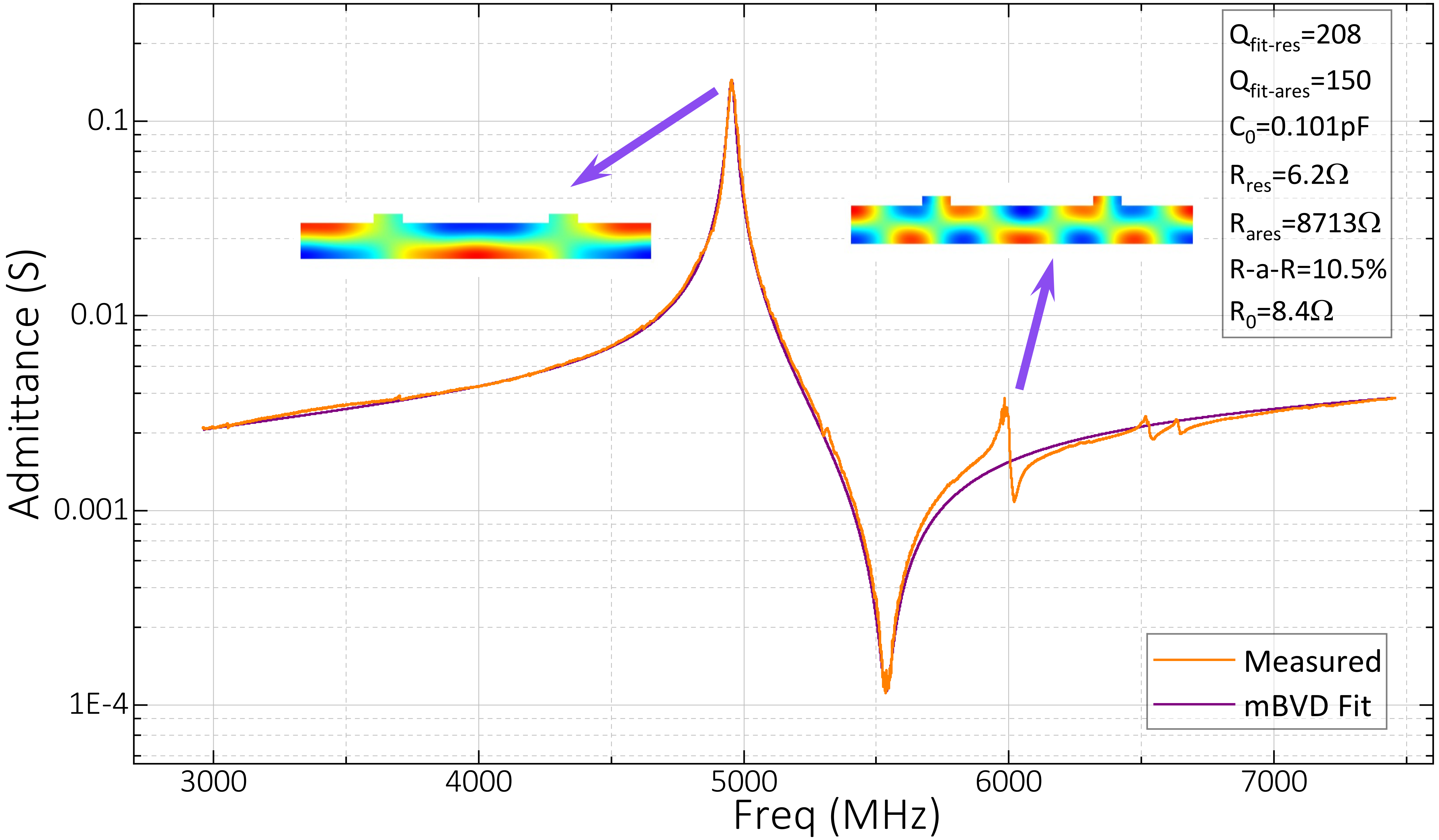
- Easily reaching 5GHz
- Few spurious modes (in z-cut)
- Coupling RaR of up to 10.5%



Good candidate for n79

- Piezoelectric MEMS resonators for 5G filters

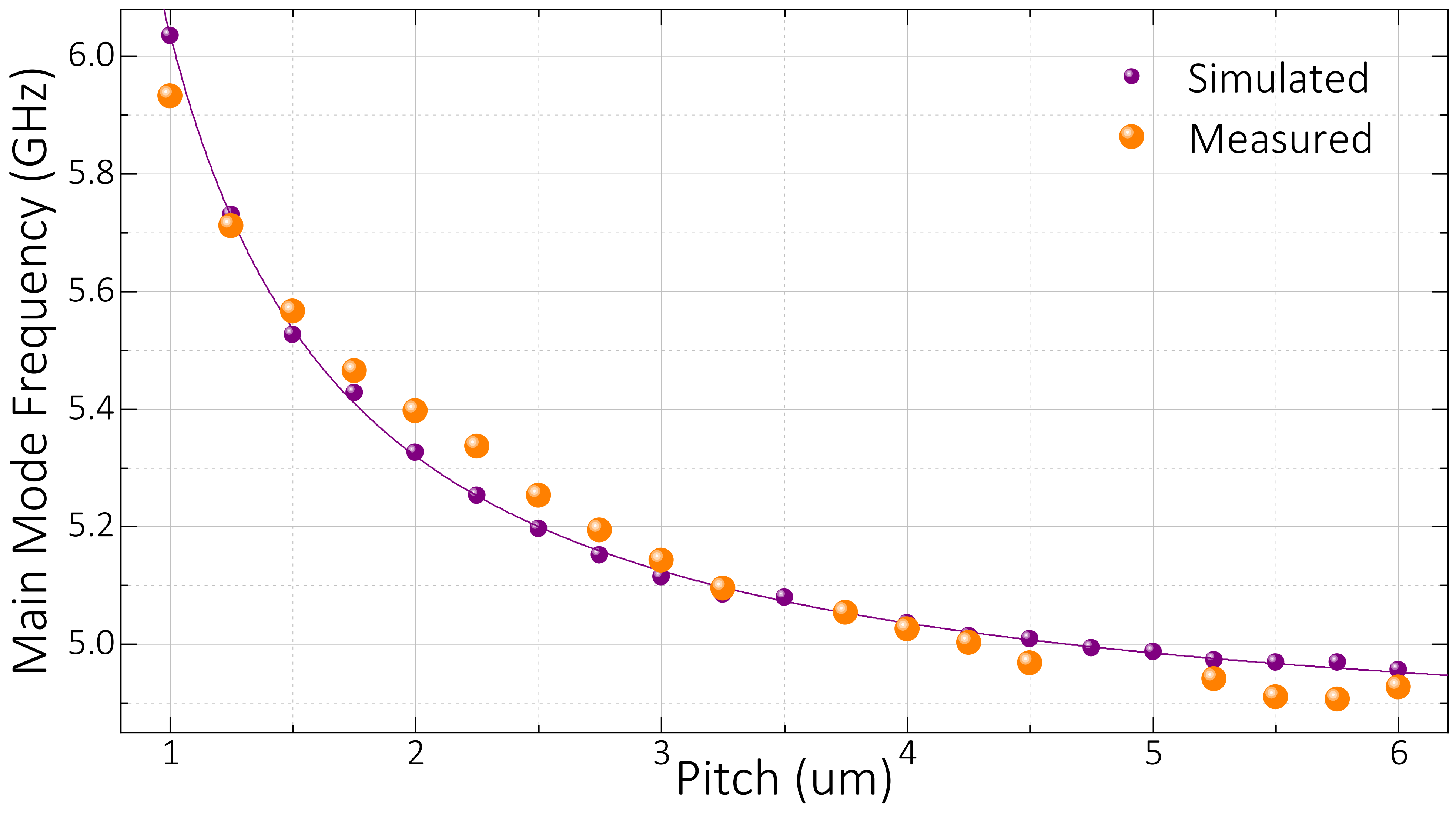


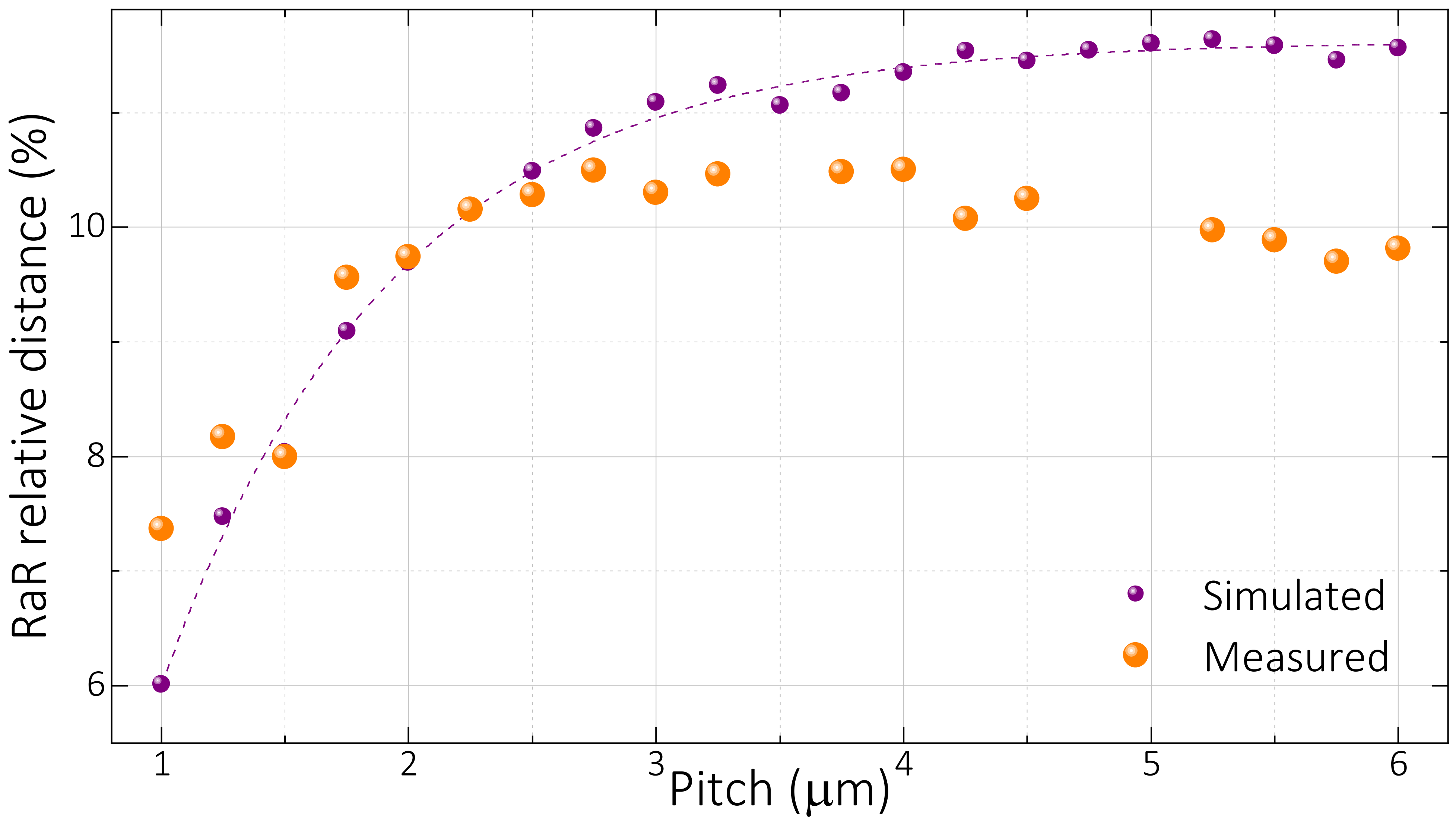


* Yandrapalli et al, JMEMS, *2022*

#3 – $LiNbO_3$ XBAR

- Frequency controlled by pitch when approaching thickness
- Coupling affected by pitch

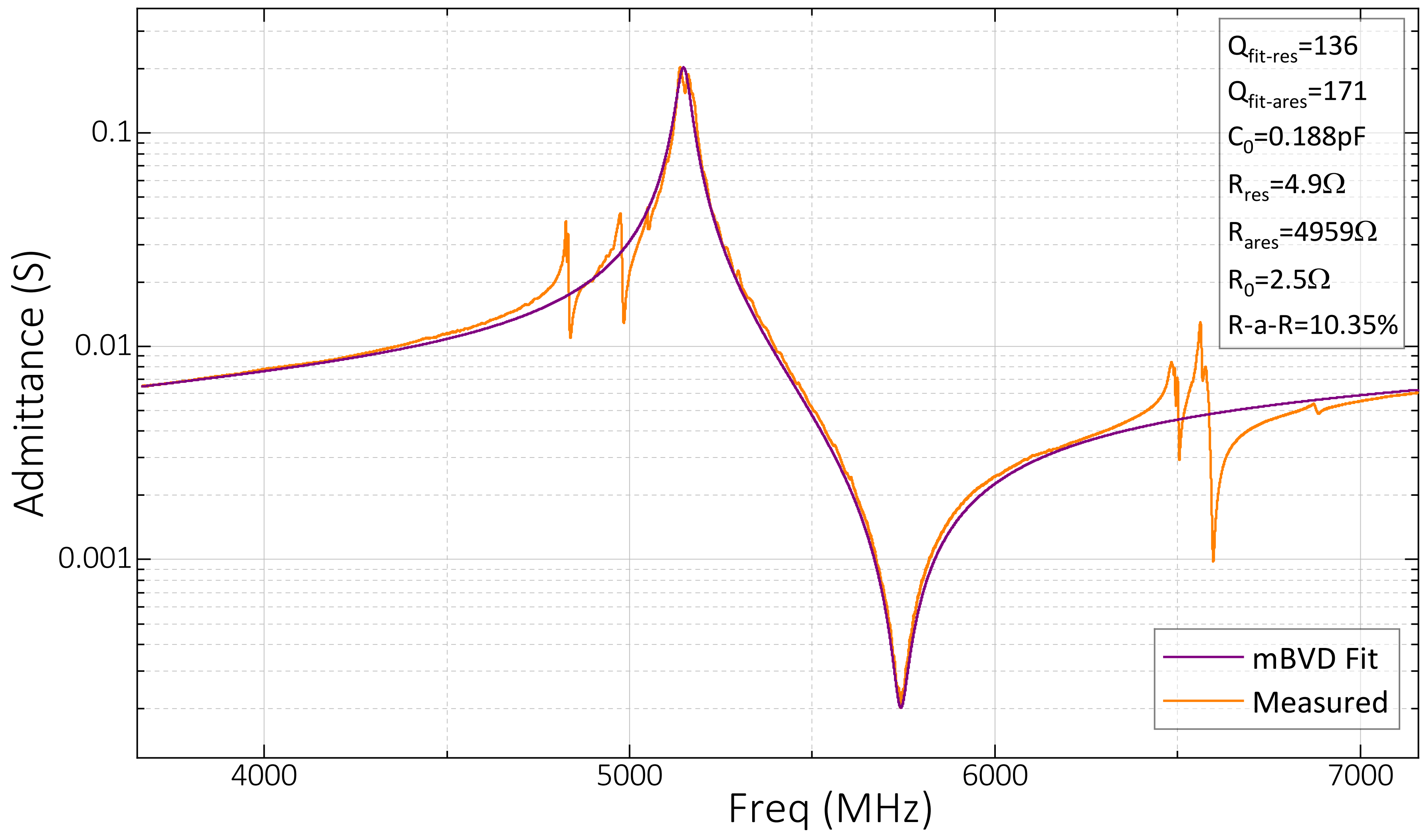




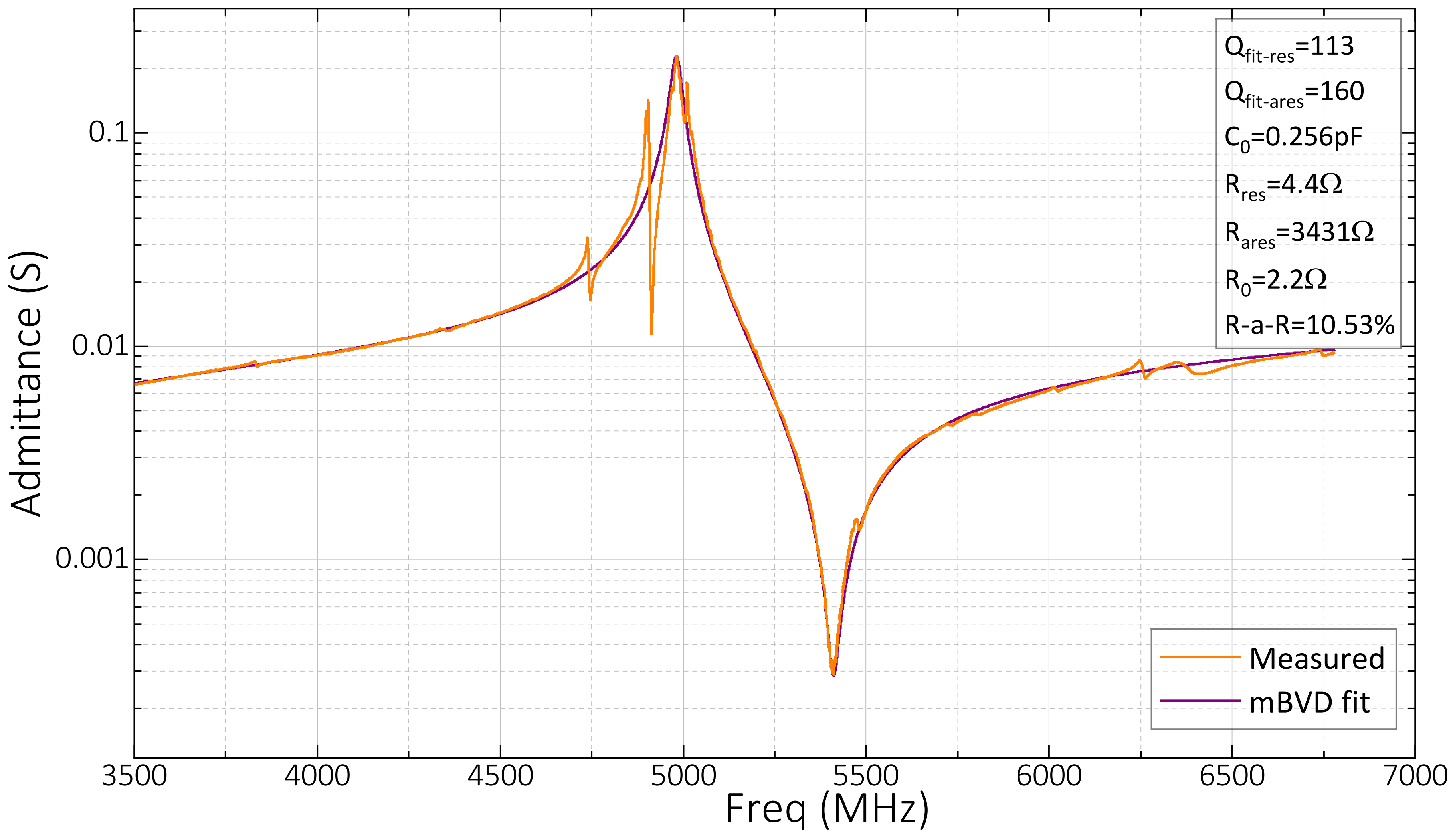
* Yandrapalli et al, JMEMS, *2022*

#3 – $LiNbO_3$ XBAR

- Frequency controlled by pitch when approaching thickness
- Coupling affected by pitch
- Spurious mode can be suppressed with the right metallization ratio



15% metallization ratio

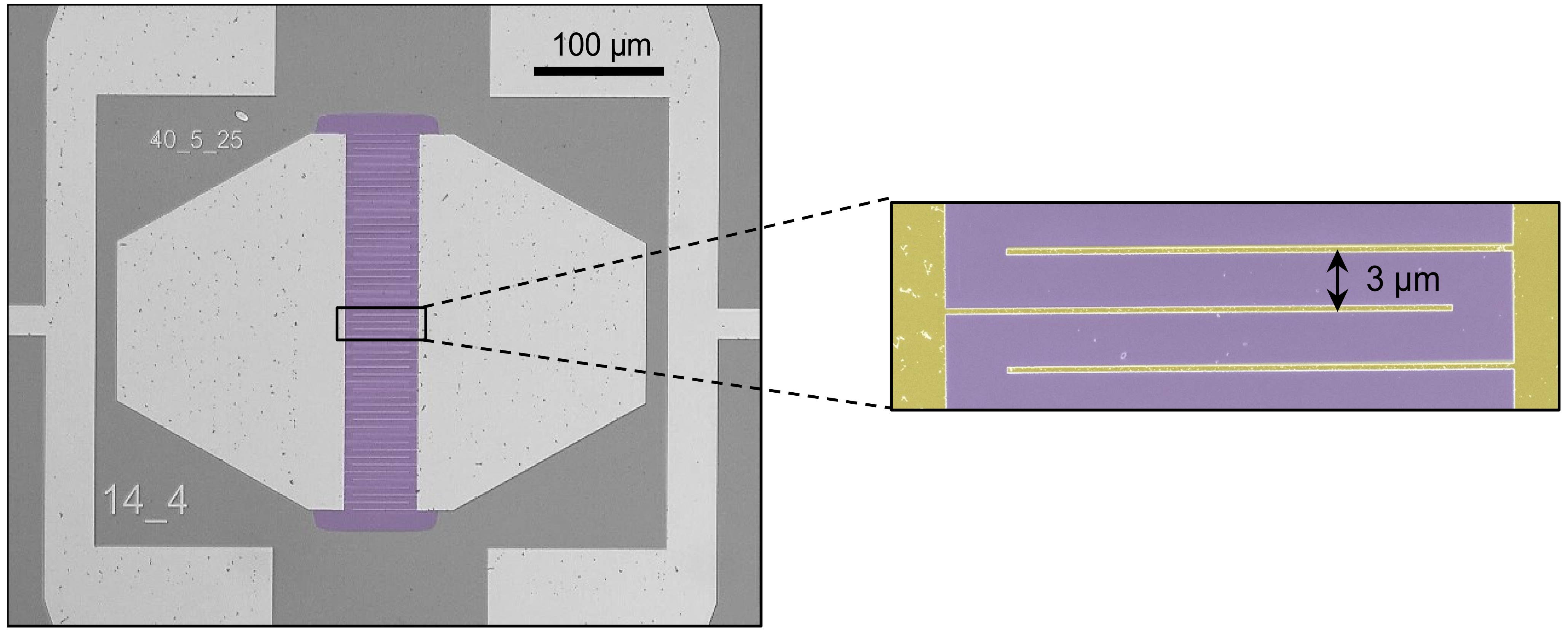


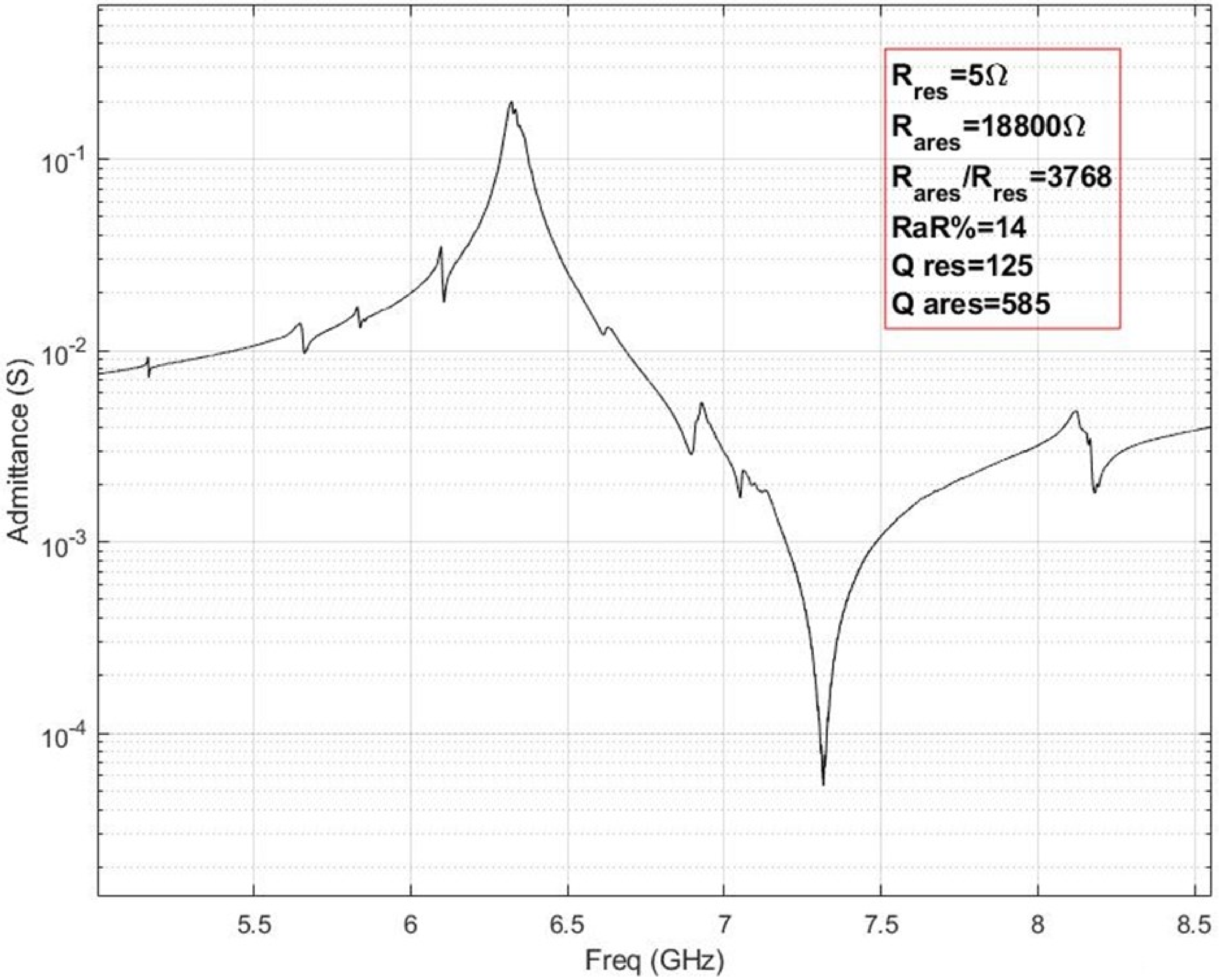
25% metallization ratio

* Yandrapalli et al, JMEMS, *2022*

EPFL #3.1 – LiNbO3 XBAR – XY128

- Increasing coupling going to XY128
- RaR up to 14%
- Bandwidth $1\ \mathrm{GHz}$ @ $6.3\ \mathrm{GHz}$
- More spurious appear compared to z-cut

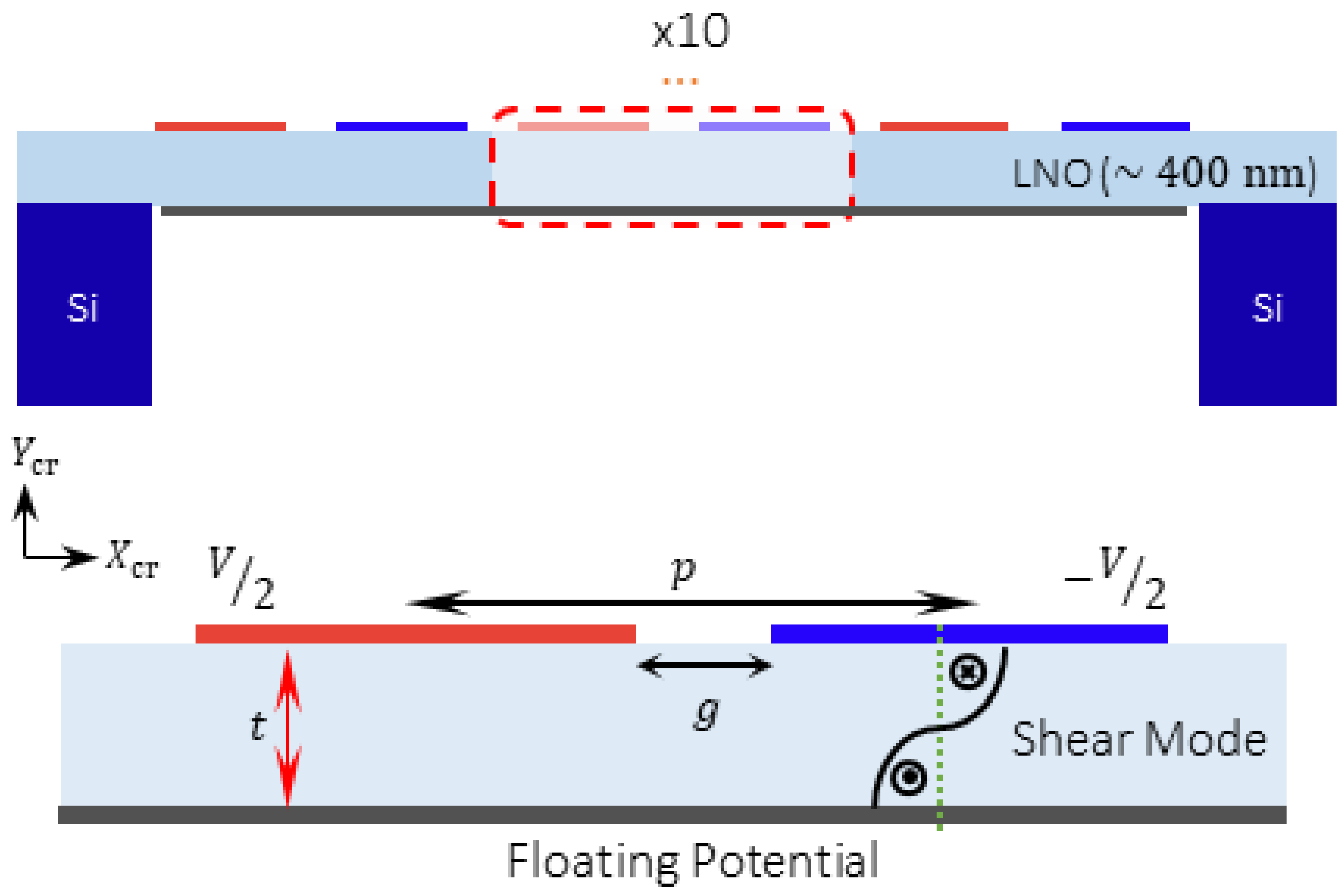




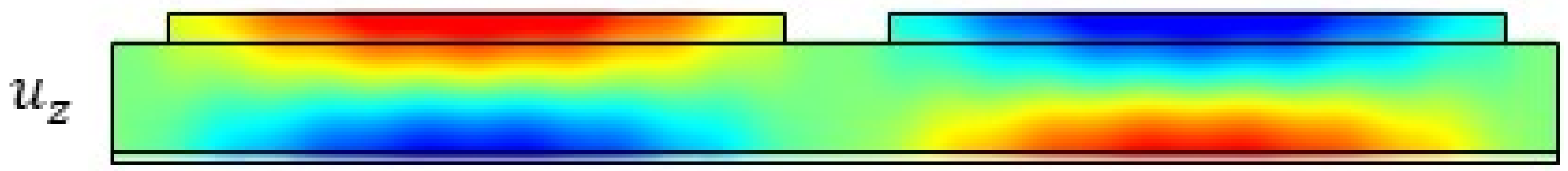
$LiNbO_3$ Resonators (SH1, YBAR)

#4 – $LiNbO_3$ YBAR

- Shear SH1 mode



- Originally in Y-cut



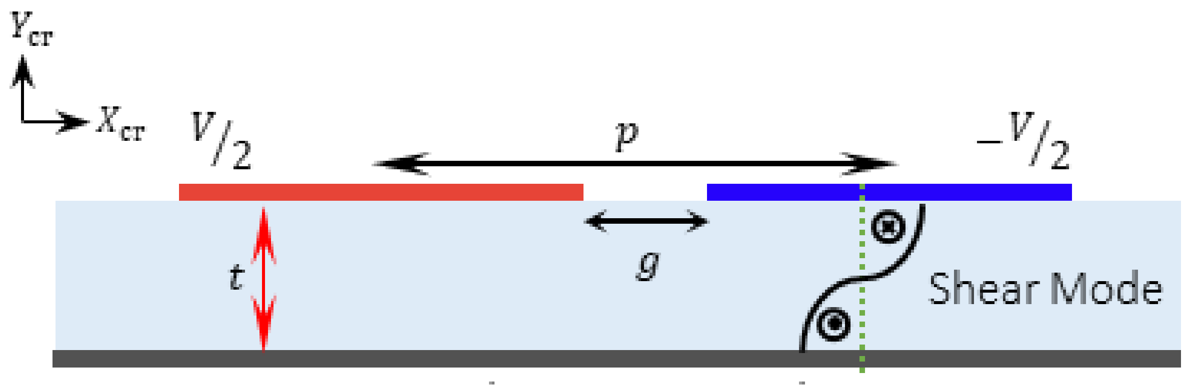
- Resonant frequency is predominantly thickness defined

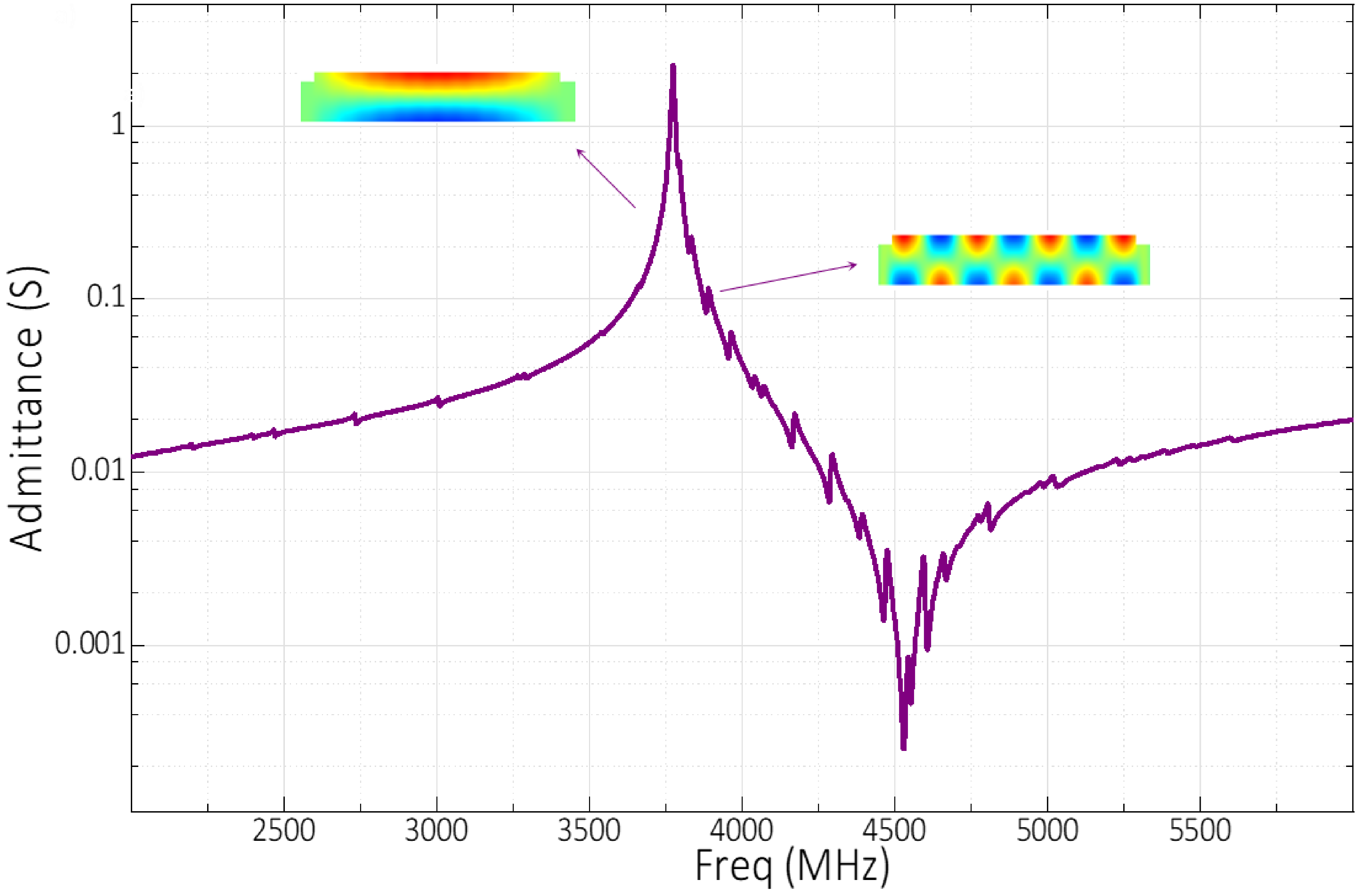
$$f_r = \frac{V_{A1}}{\lambda} = \sqrt{\frac{E_{eq}}{\rho_{eq}}} \cdot \frac{1}{2t}$$

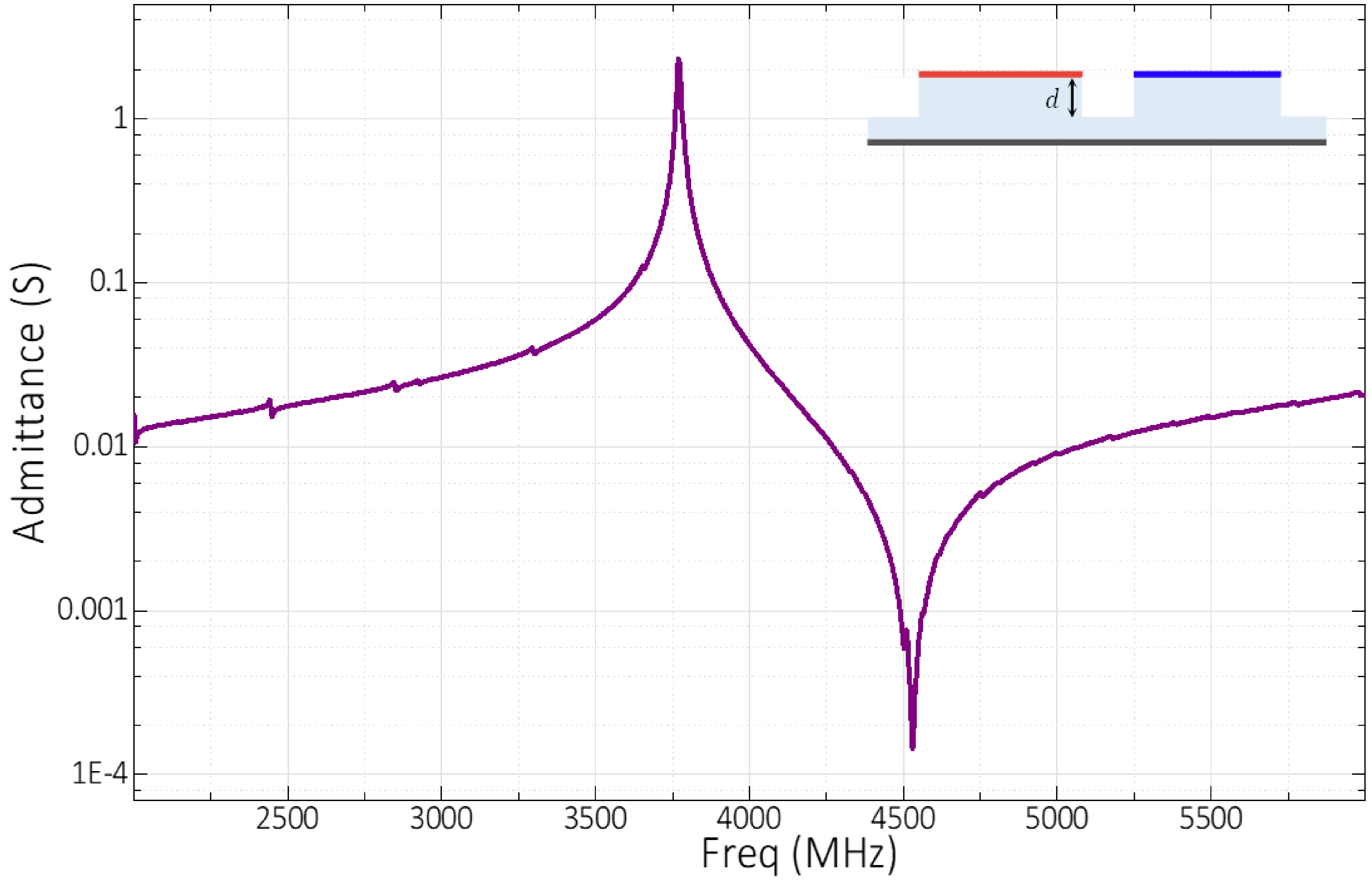
* Yandrapalli et al, JMEMS, *submitted*

#4 – $LiNbO_3$ YBAR

- Simulations reveal many spurious modes in-band
  - Travelling wave perpendicular to the electrodes
- With trenches the spurious are heavily suppressed



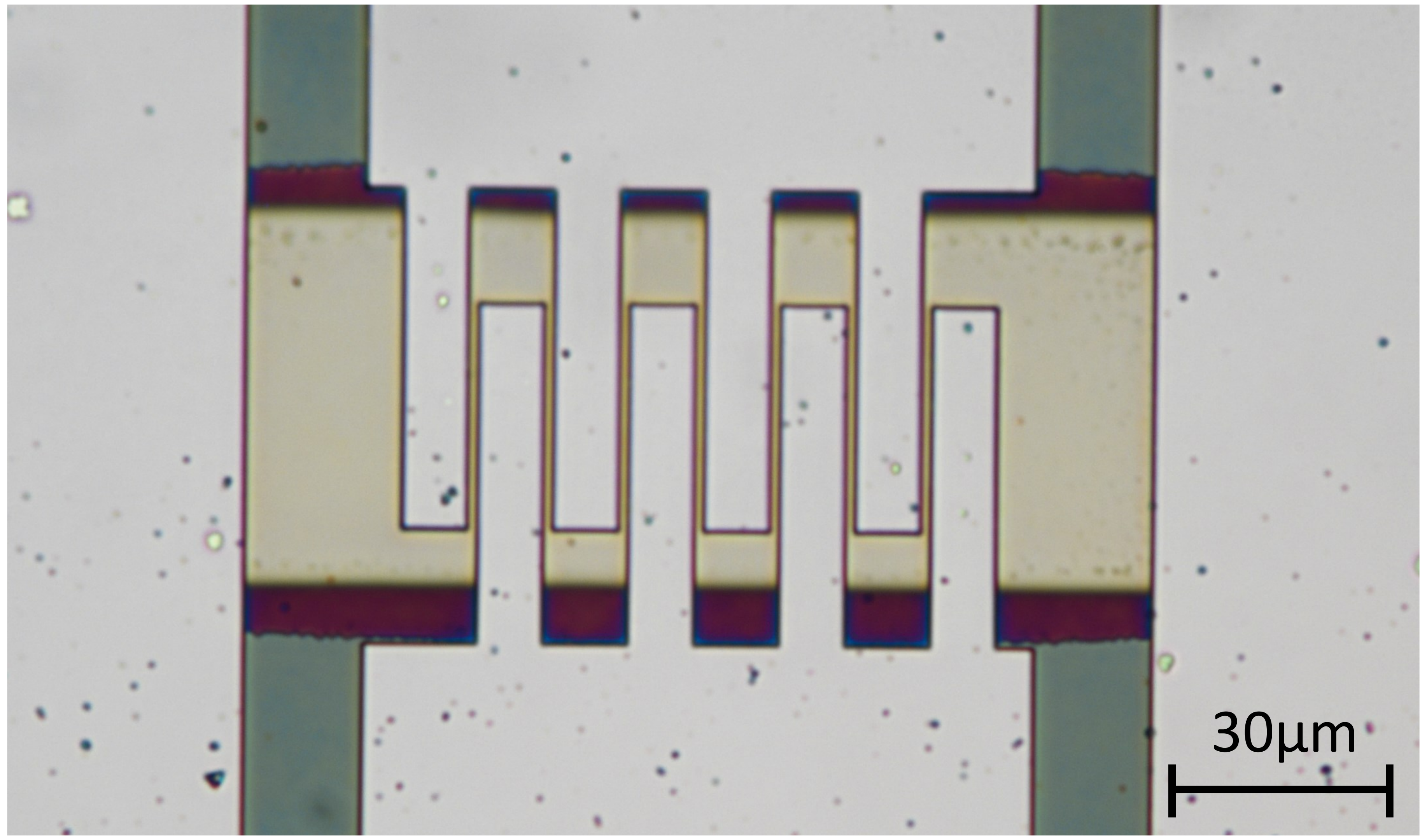


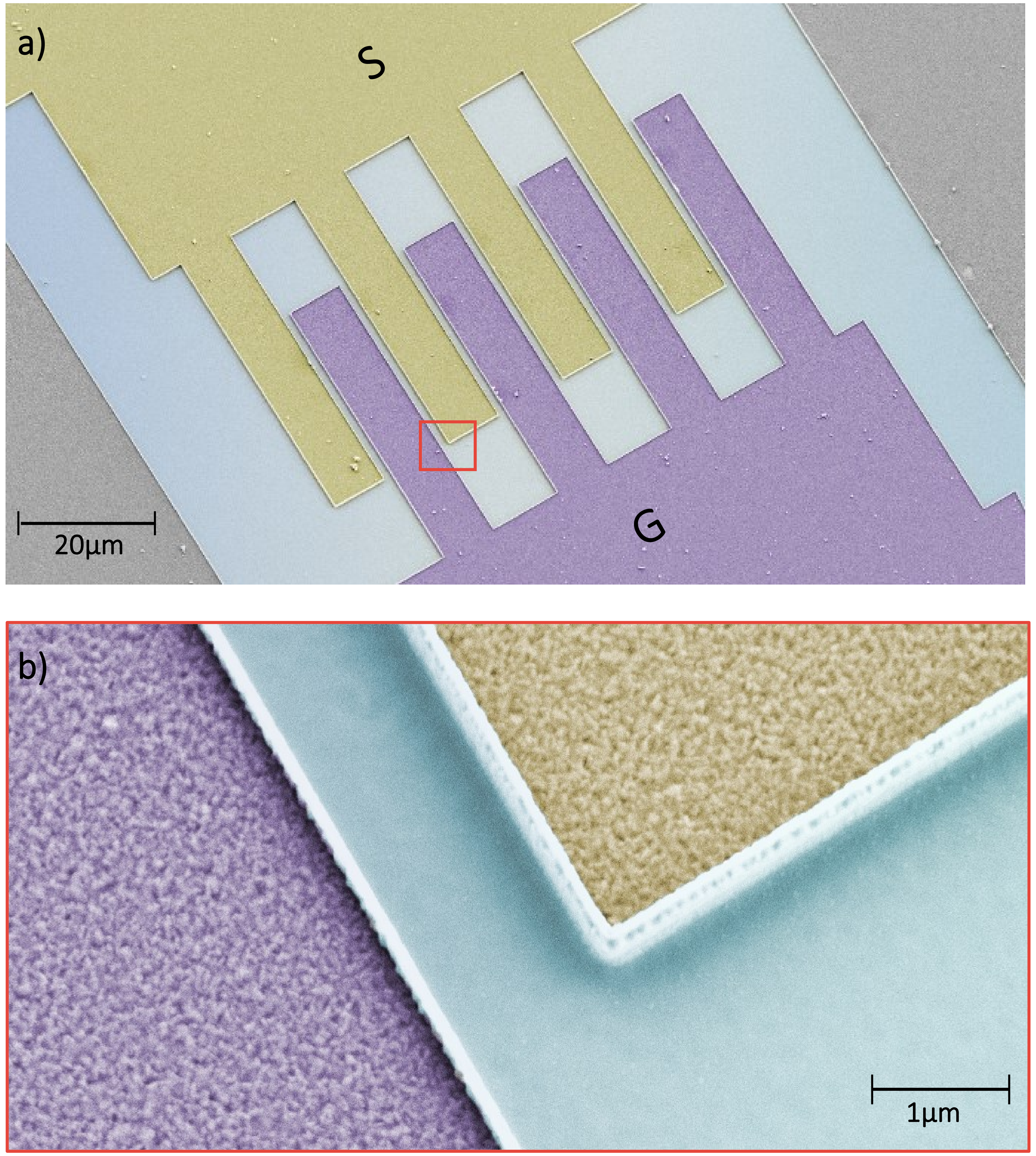


* Yandrapalli et al, JMEMS, *submitted*

#4 – $LiNbO_3$ YBAR

- Fabrication with floating metal

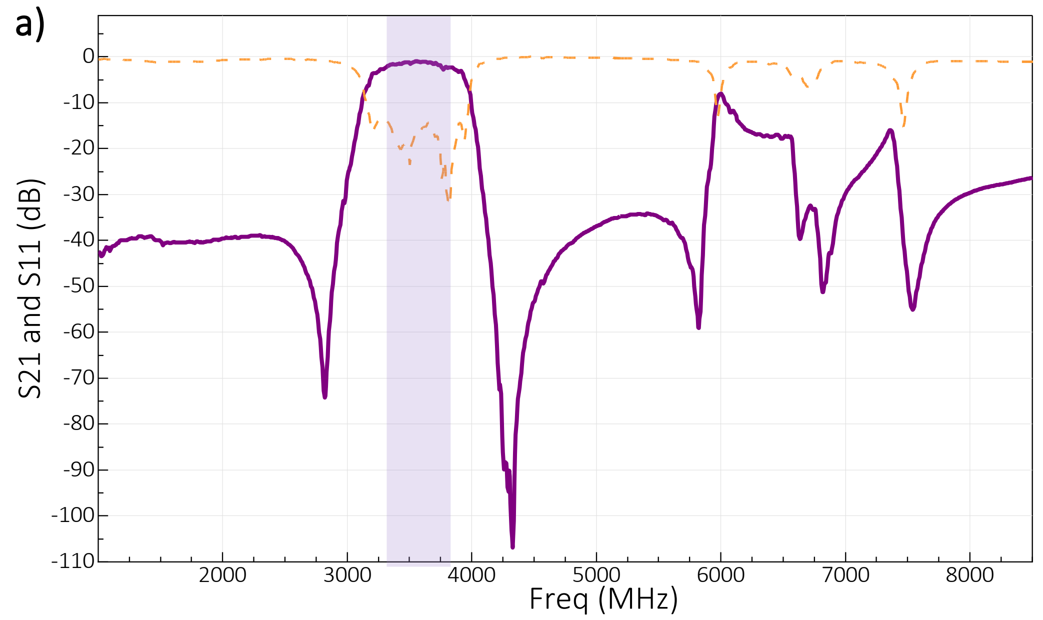




* Yandrapalli et al, JMEMS, *submitted*

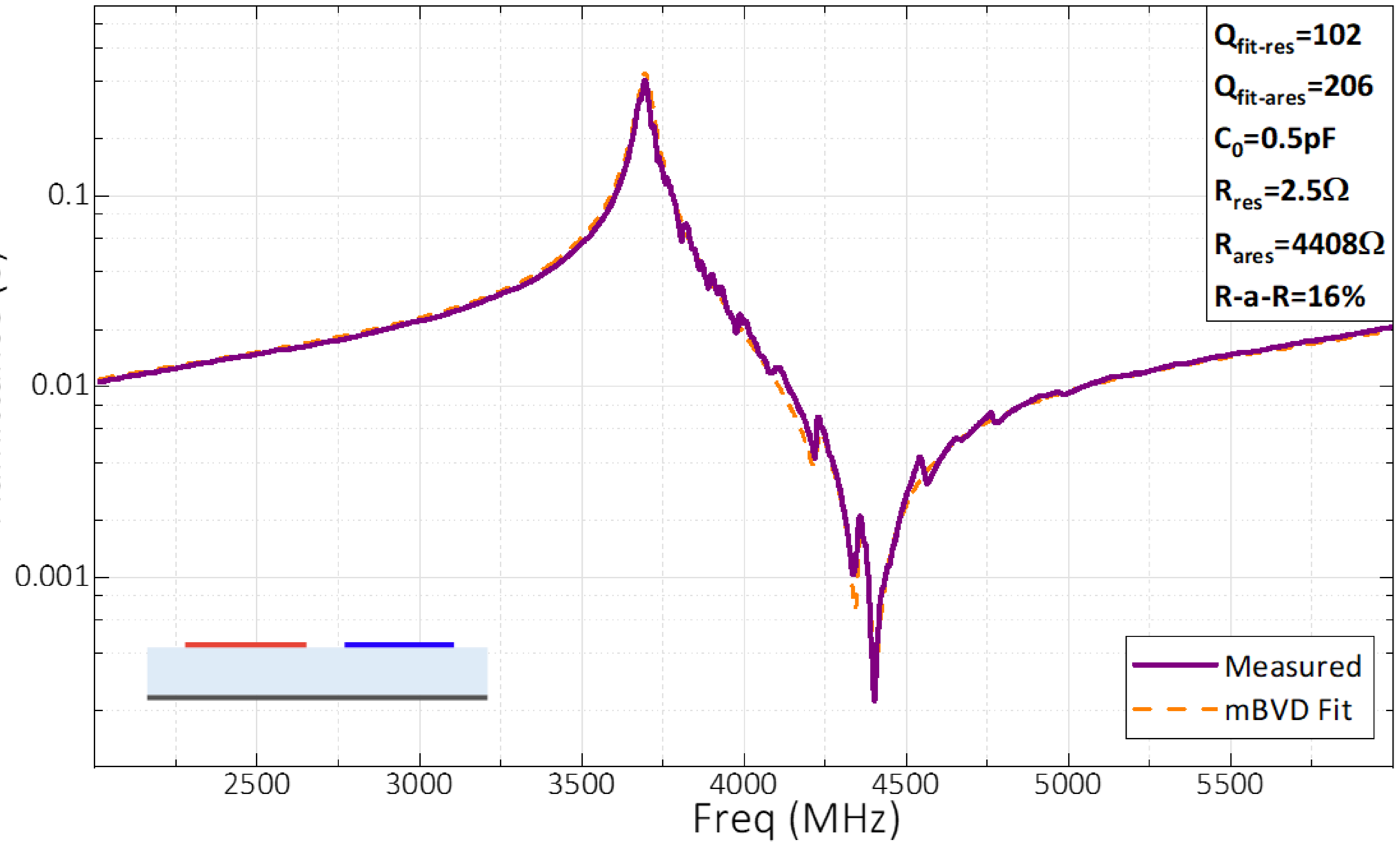
EPFL #4 – $LiNbO_3$ YBAR

Filter Simulation (being produced)

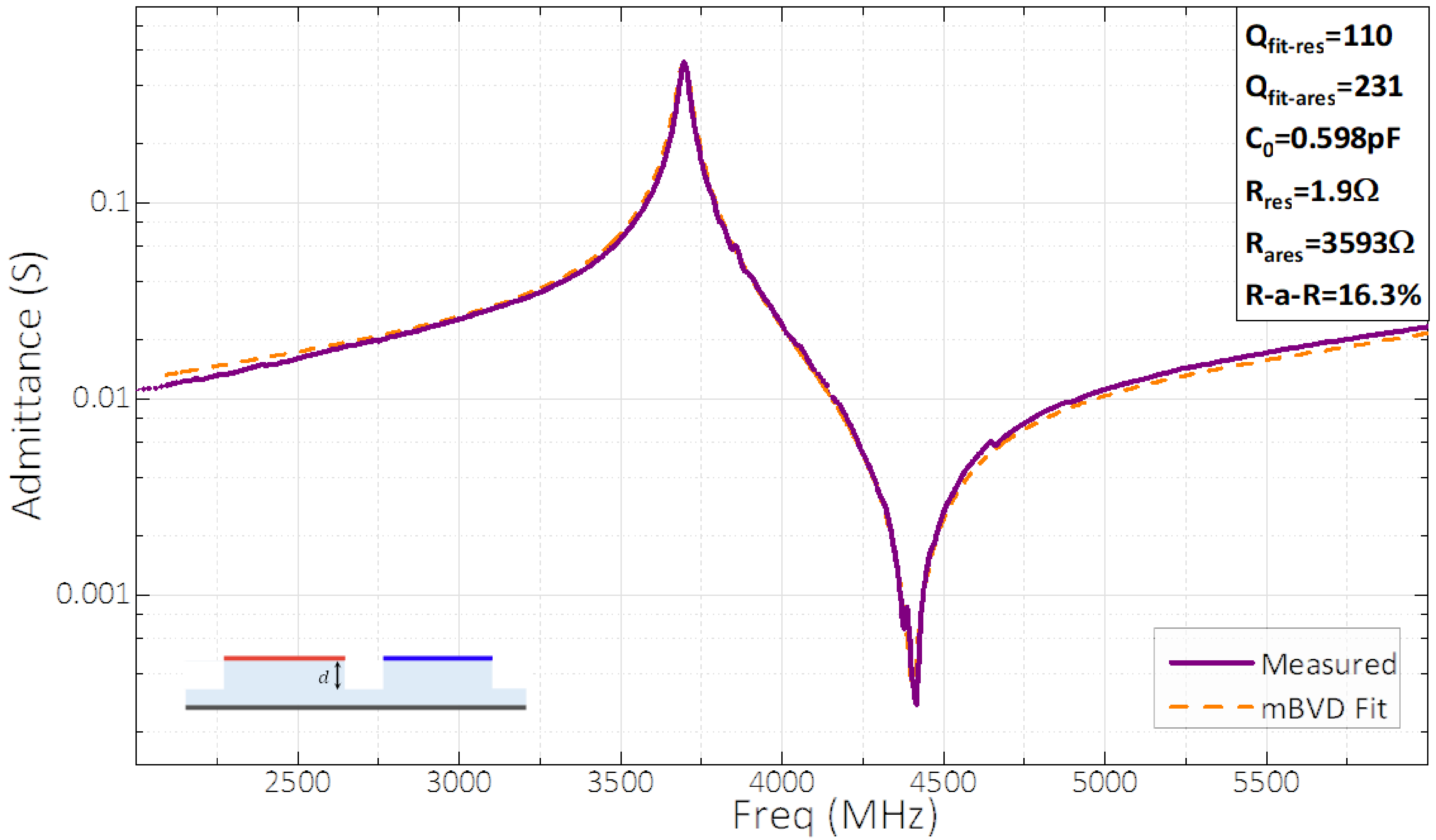


- Experimental confirmation of simulation results
- Coupling RaR up to 17.5%
- Compromised Q

Good candidate for n78



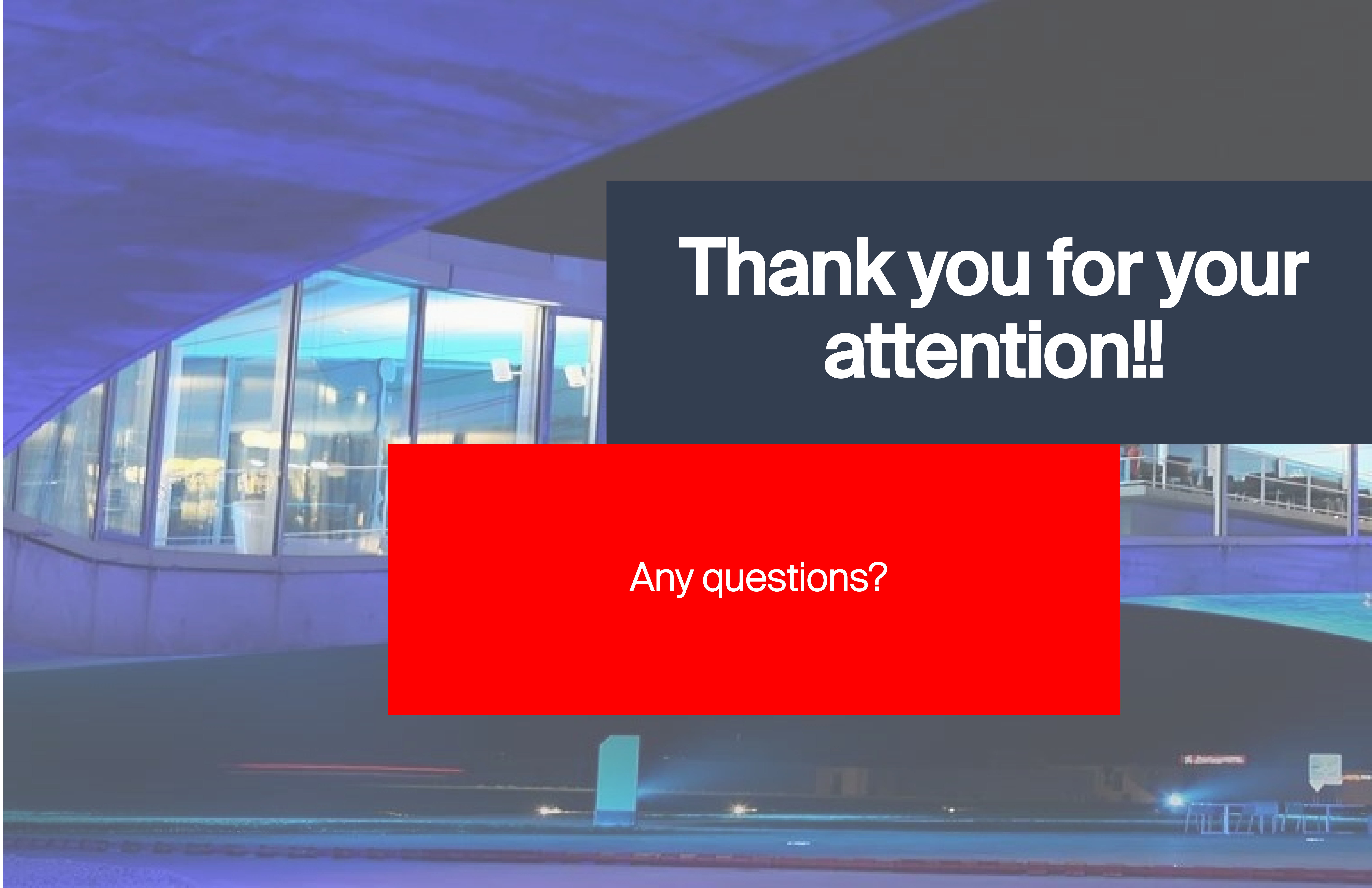
No trenches



With Etched Trenches

* Yandrapalli et al, JMEMS, *submitted*

EPFL



Thank you for your attention!!

Any questions?

École polytechnique fédérale de Lausanne