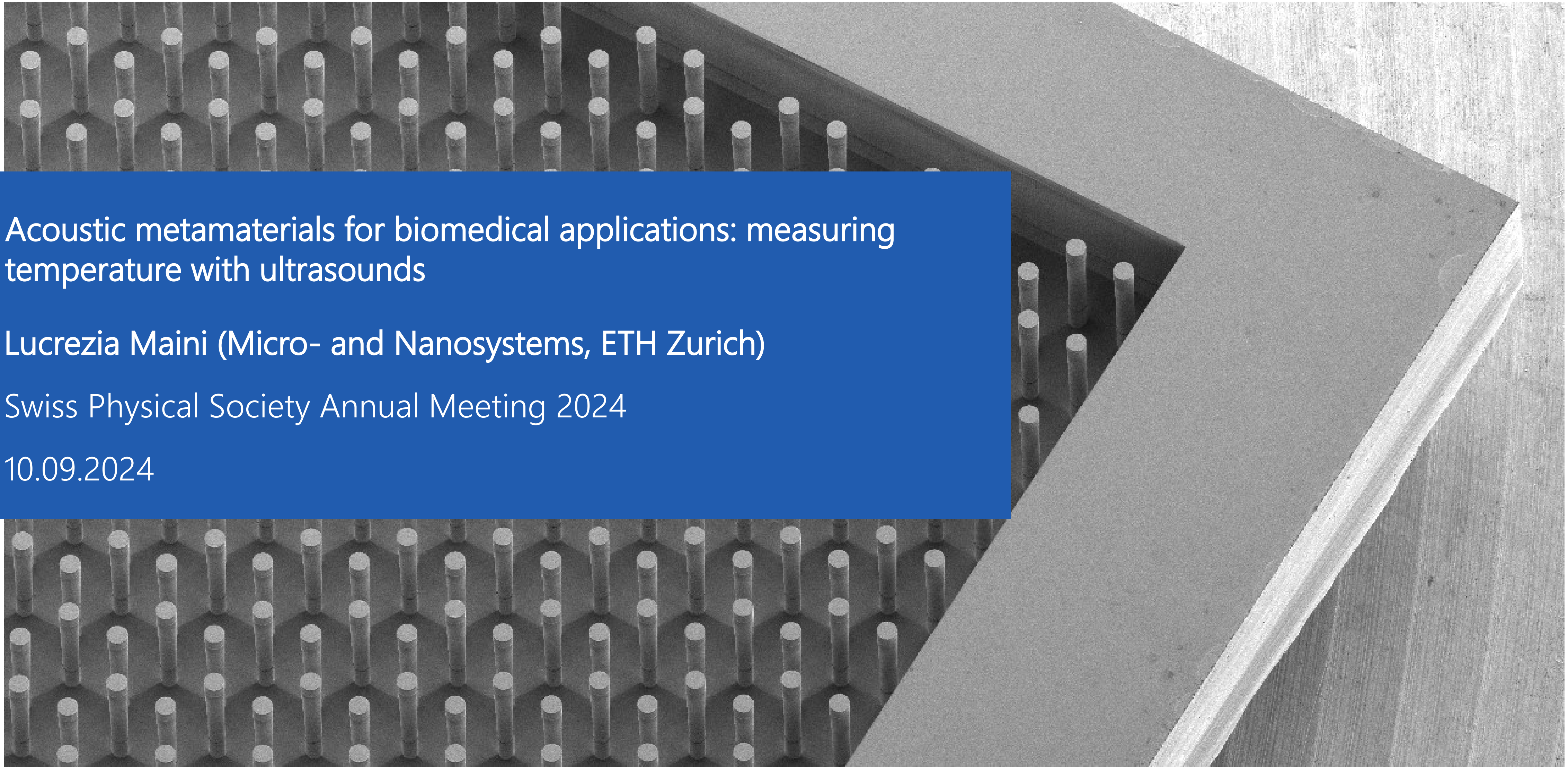
ETH zürich



Acoustic metamaterials for biomedical applications: measuring temperature with ultrasounds

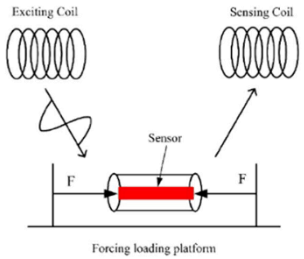
Lucrezia Maini (Micro- and Nanosystems, ETH Zurich)

Swiss Physical Society Annual Meeting 2024

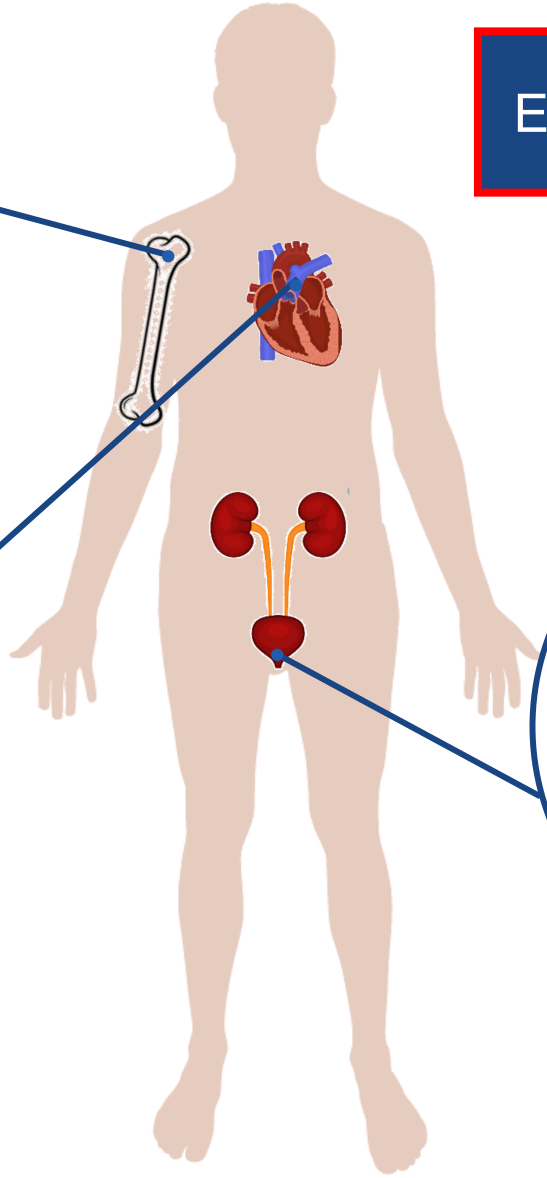
10.09.2024

Passive implantable sensors

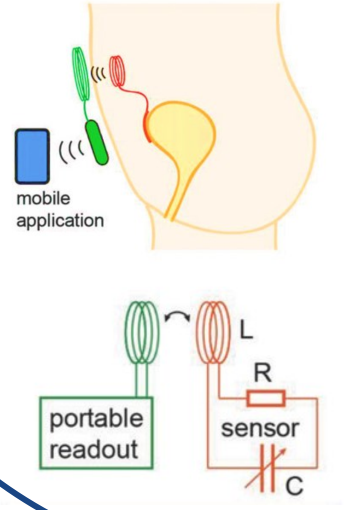
Electromagnetic coupling interrogation



Bone healing: inductive coupling [1]



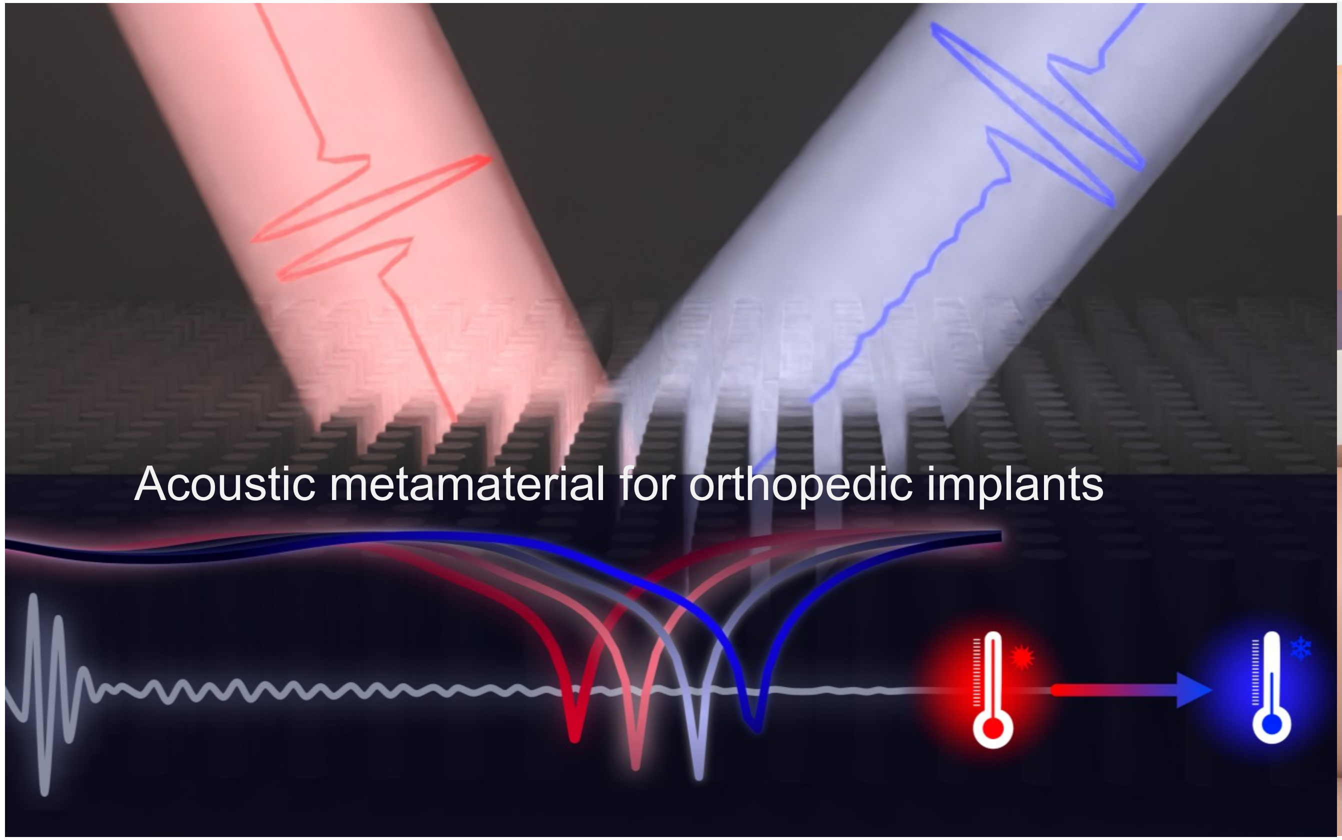
CardioMEMS [2]: pulmonary artery pressure monitoring



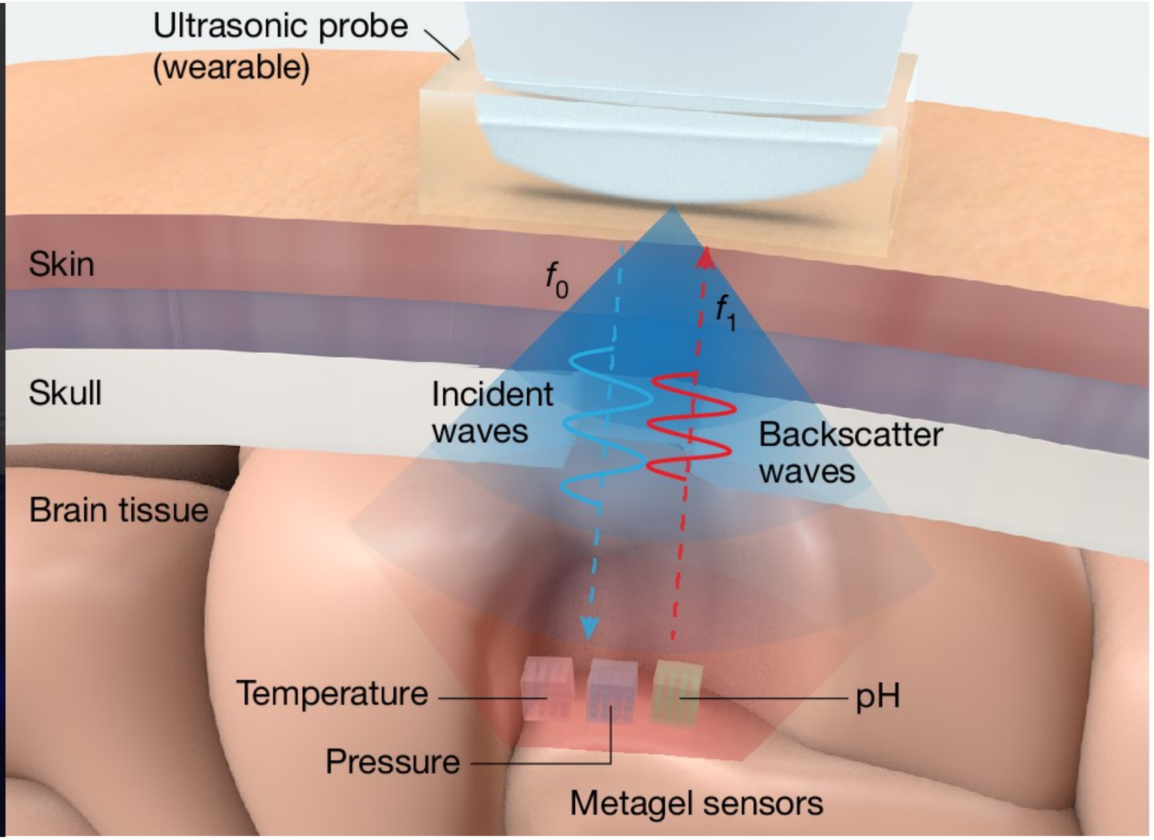
Bladder filling level passive measurement [3]

Ref.: [1] Y Tan et al., *Sensors* 17(2635), 2017
[2] Abraham and Perl, *J Am Coll Cardiol*, 70(3), 2017
[3] J Voros et al., *Adv Mater Technol*, 3, 2018

Towards a new approach



L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), January 2024



H. Tang et al., *Nature*, 630, 84-90, June 2024

Advantages of ultrasound waves:

- ✓ Safer in the body for long-term interrogation (lower power introduced in the body: up to 72x less) [1]
- ✓ No cables through the skin
- ✓ Compatible with ultrasound medical readouts

[1]: J. C. Lin, IEEE Antennas and propagation Magazine, 48(1), 2006

Outline

- Introduction
    - Acoustic metamaterials
    - Sensor operation
- Temperature characterization
    - Experimental design
    - Experimental results in-vitro
    - Understanding temperature sensitivity
    - Understanding temperature resolution
- Tissue mimicking materials
    - Towards a realistic setup
- Outlooks & conclusions

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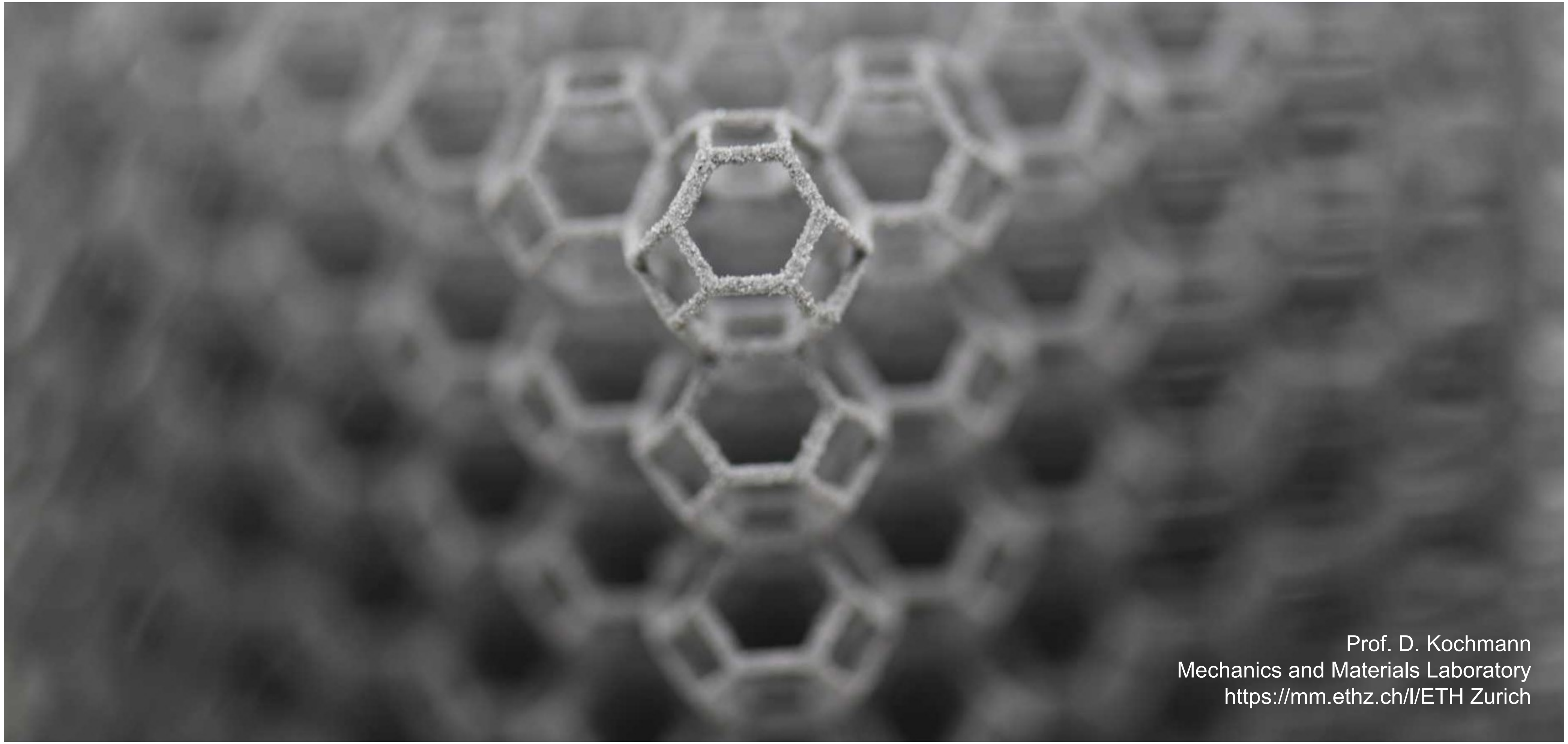
Why metamaterials?

Metamaterial: rationally designed composites made of tailored building blocks with effective medium properties beyond their constituting materials

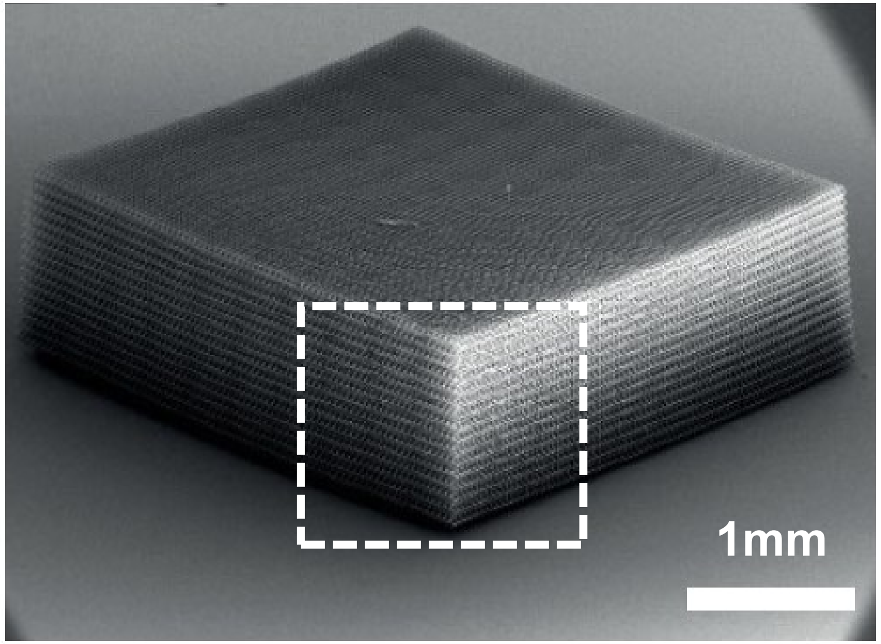


Prof. D. Kochmann
Mechanics and Materials Laboratory
https://mm.ethz.ch/l/ETH Zurich

Why metamaterials?

Metamaterial: rationally designed composites made of tailored building blocks with effective medium properties beyond their constituting materials

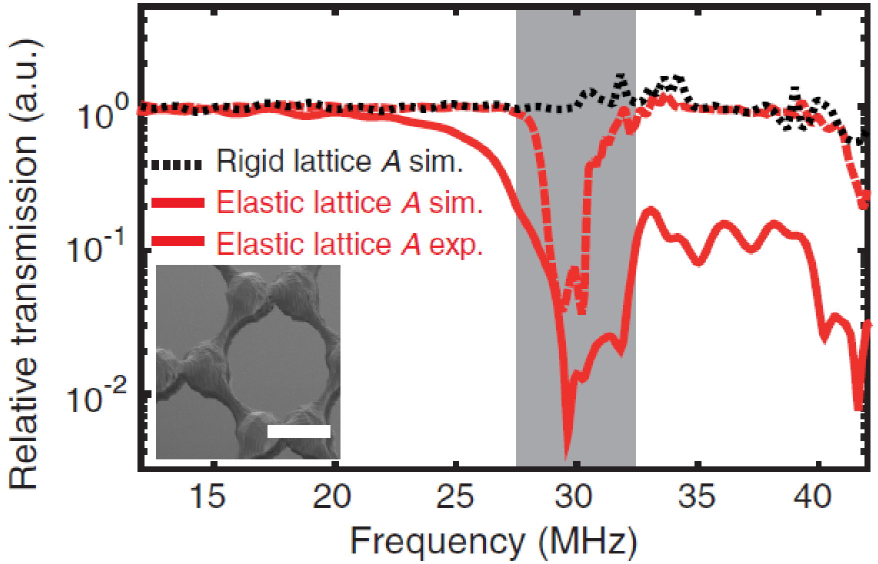
Mechanics



S Khoenel, St al. Kang, *Phys Rev Appl*, 2016

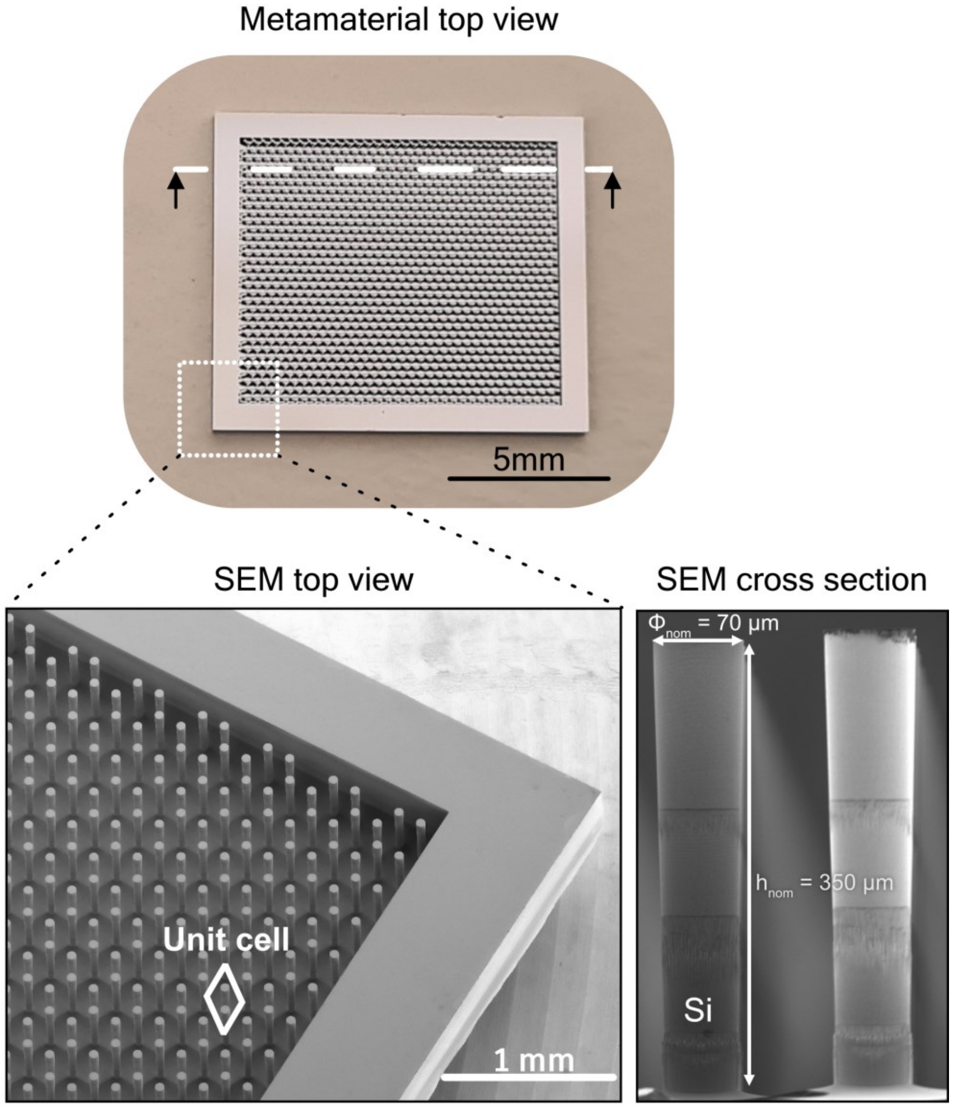
Acoustics

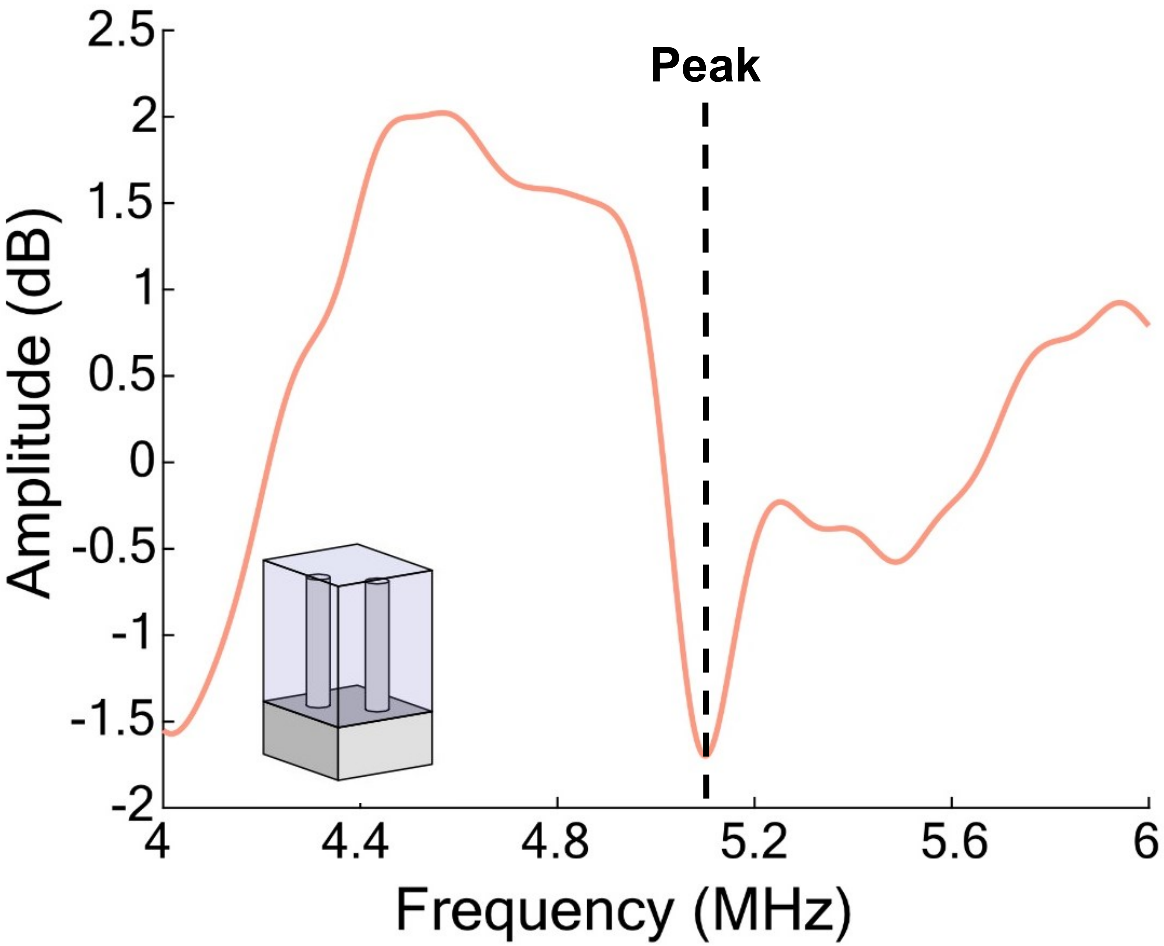
Tunable acoustic properties (**modes**, **band structure**):



M Kadic et al., 1, *Nature Reviews Physics*, 2019
J U Surjadi et al., 21, *Adv Eng Mater*, 2019

Acoustic sensor design





L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

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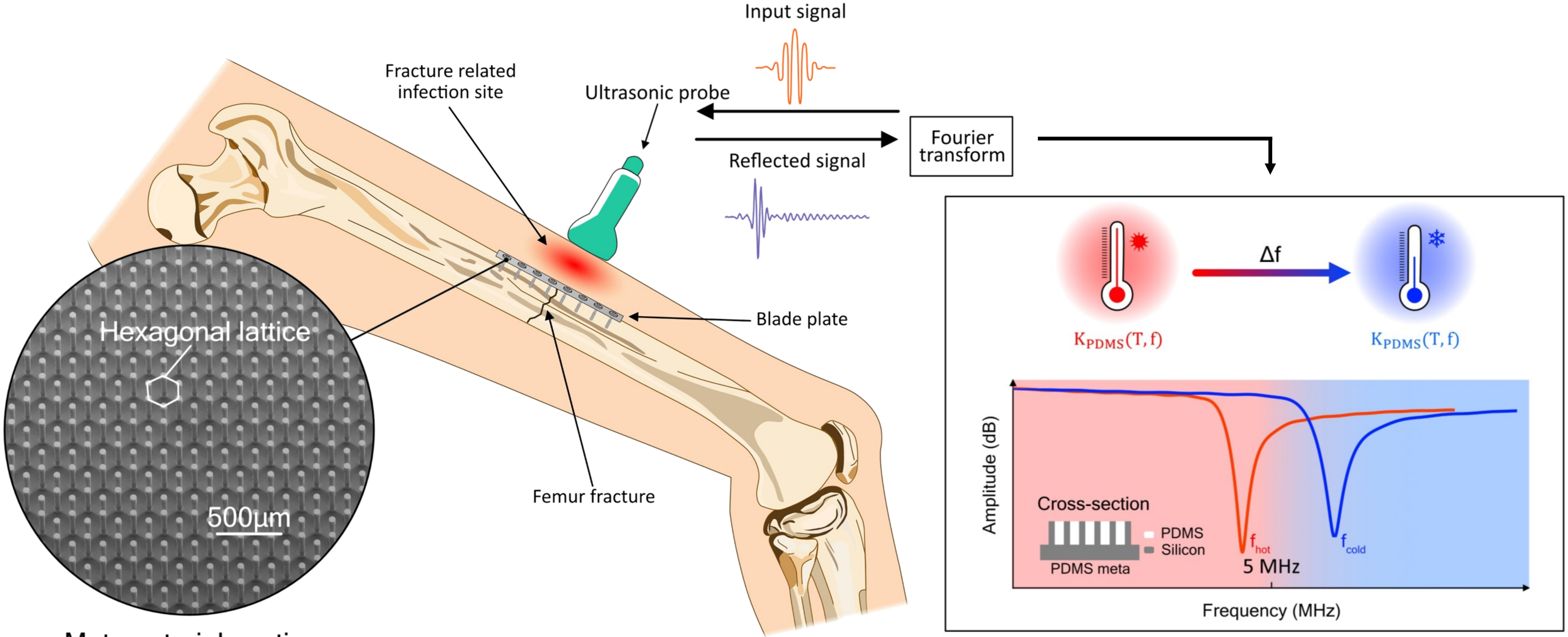
Post-operative complications monitoring



Metamaterial coating

L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

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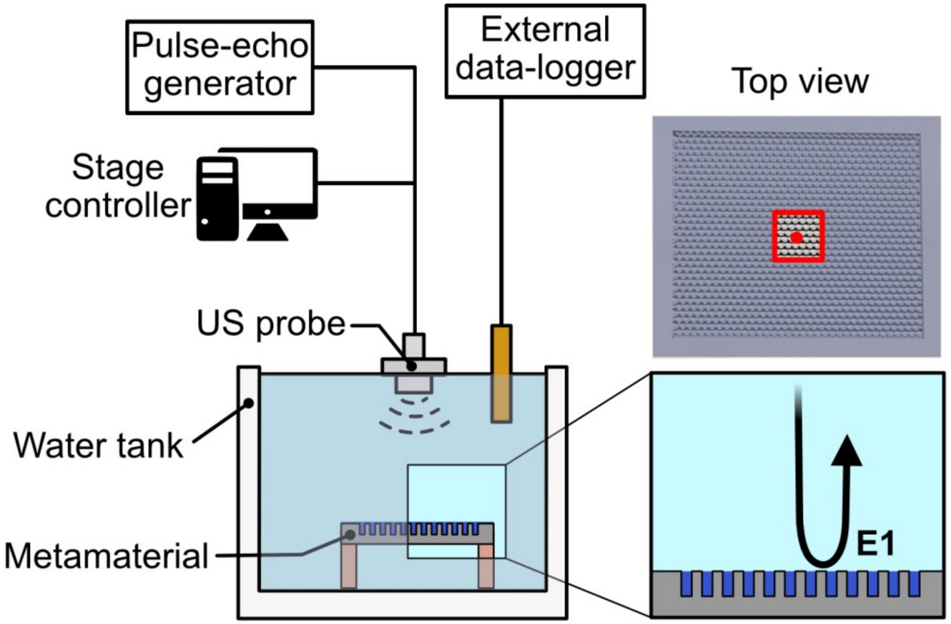
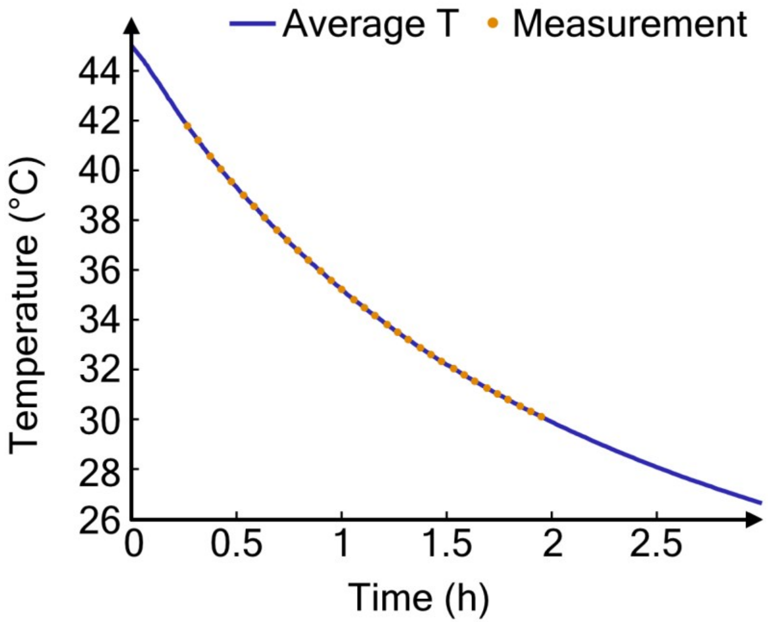
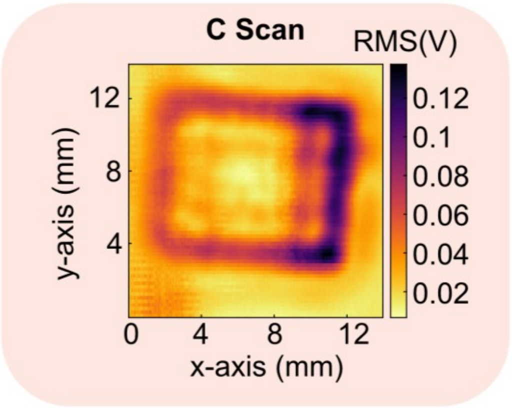
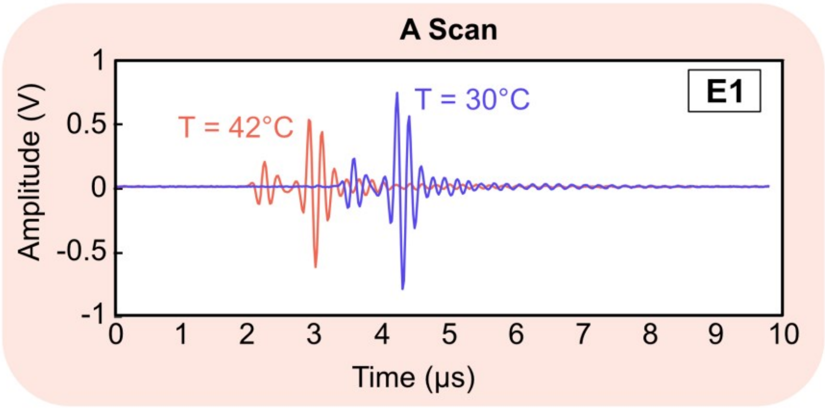
Experimental design









- Natural cooling of 5-liter water tank
- Time signals in pixels of selected area

L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

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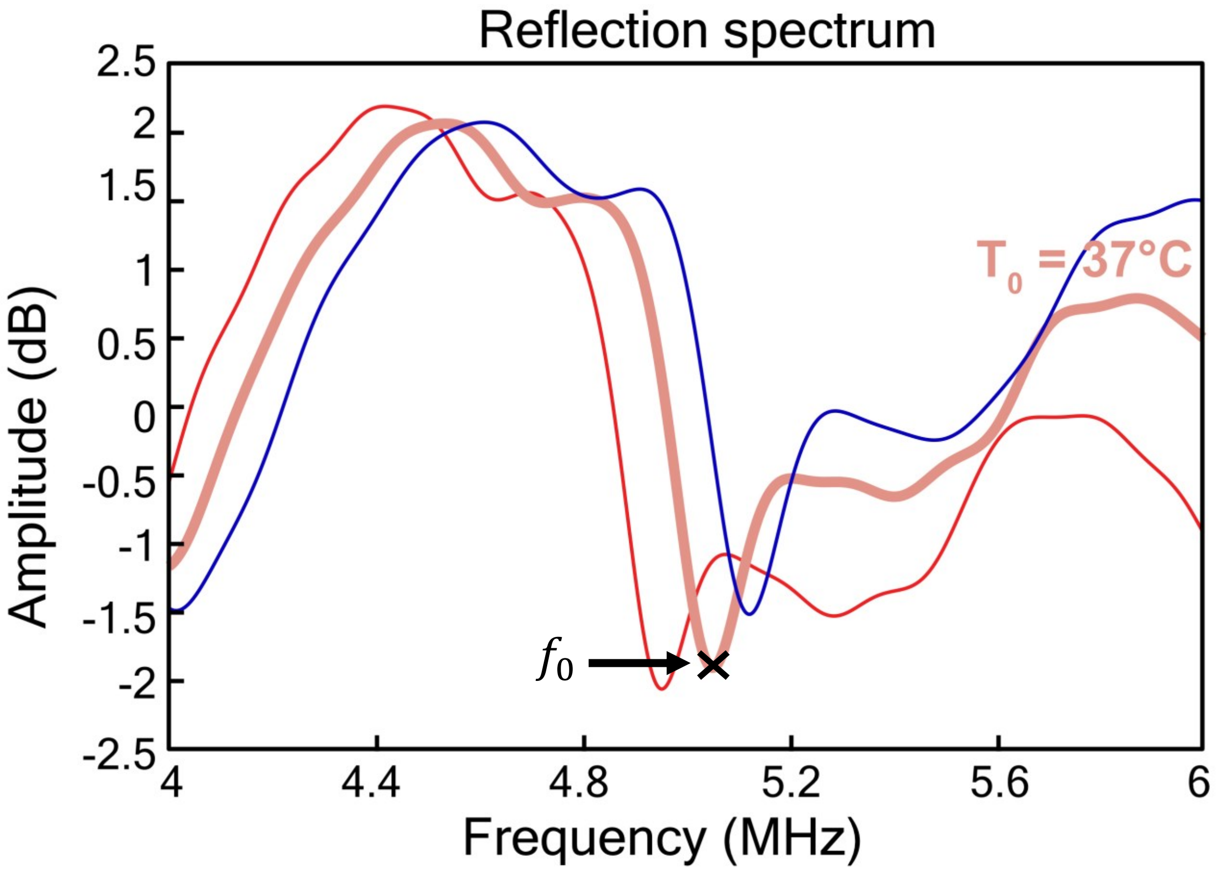
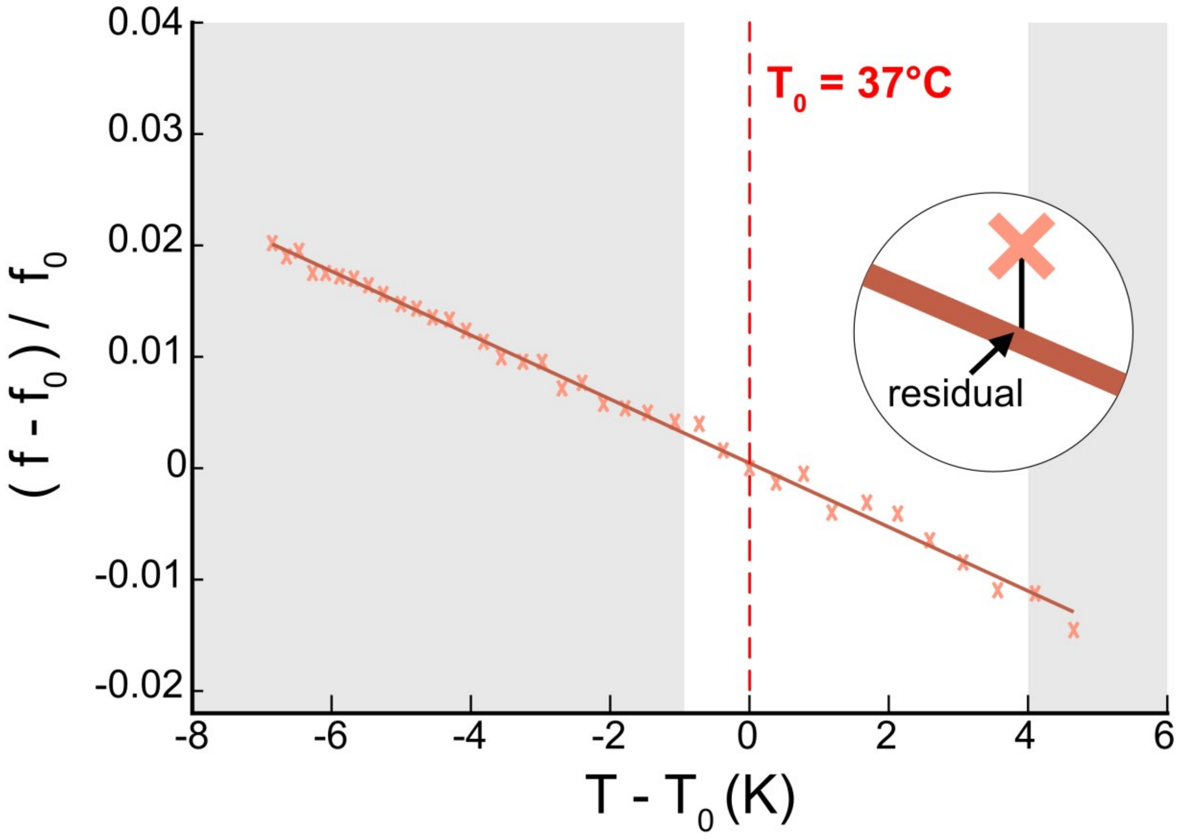
Experimental Temperature Behavior

$$S = \frac{df}{\Delta T}$$

$$R = \frac{\sigma_{res}}{S}$$

$$\Delta T = T - T_0,\ df = (f - f_0)/f_0$$

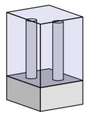




L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

Temperature sensitivity and resolution

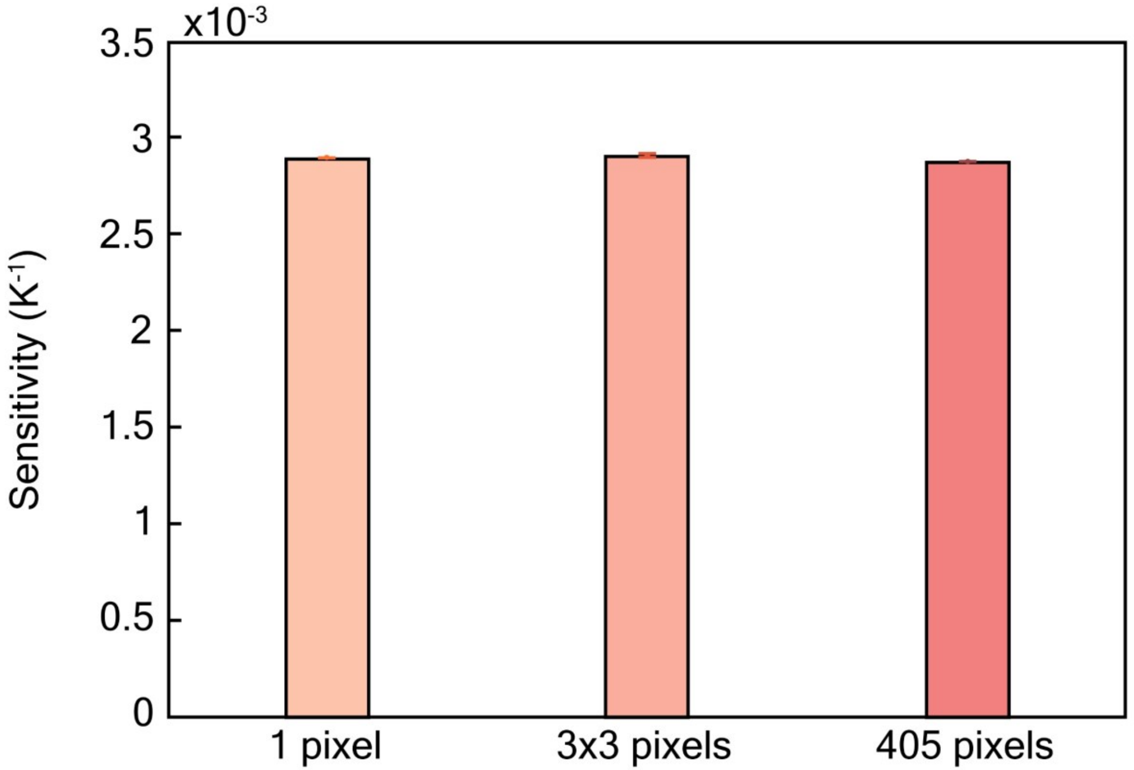
PDMS Meta

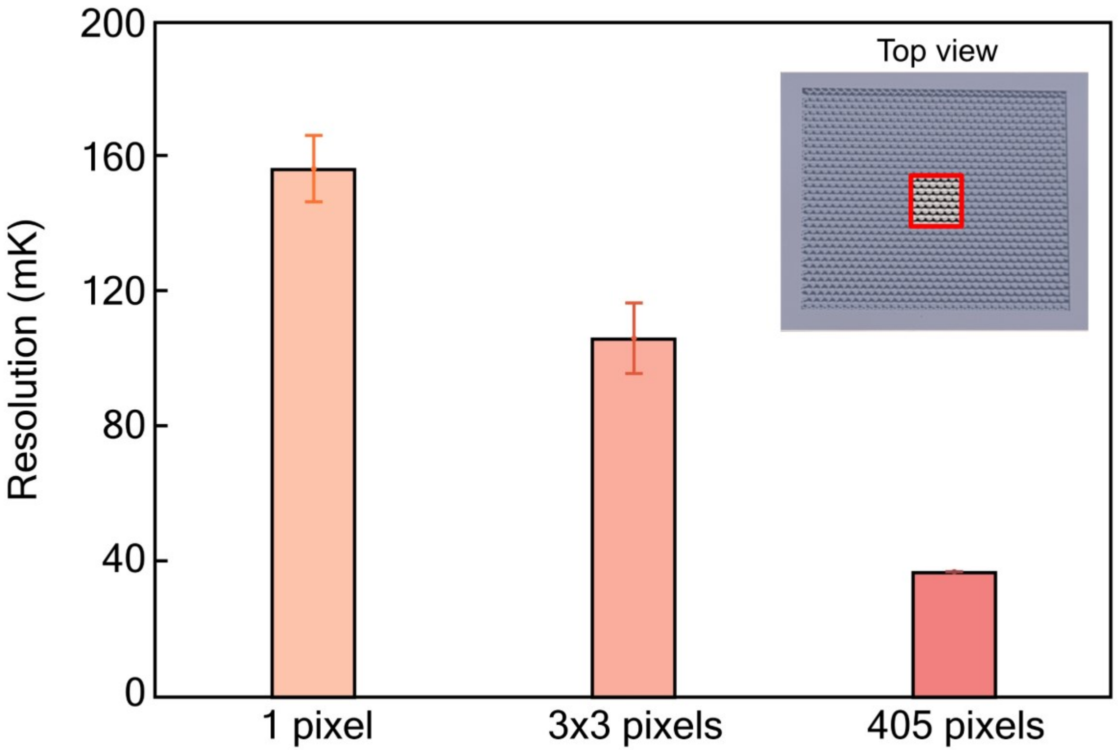


$$S = \frac{df}{\Delta T}$$

$$R = \frac{\sigma_{res}}{S}$$

$$\Delta T = T - T_0, \; df = (f - f_0)/f_0$$





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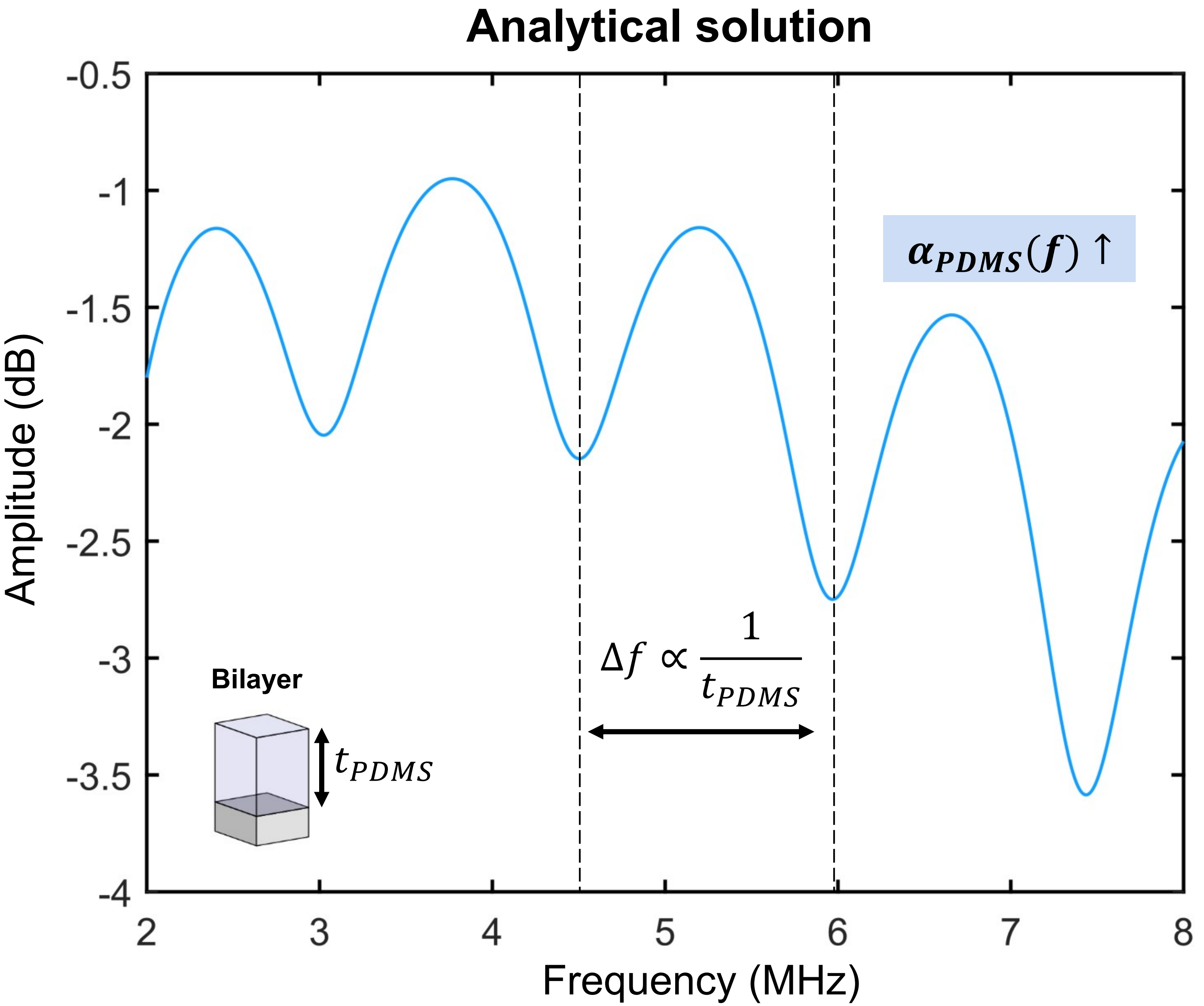
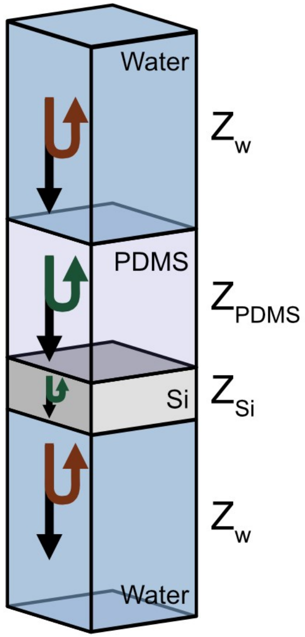
Why a metamaterial?



Multilayered structure:

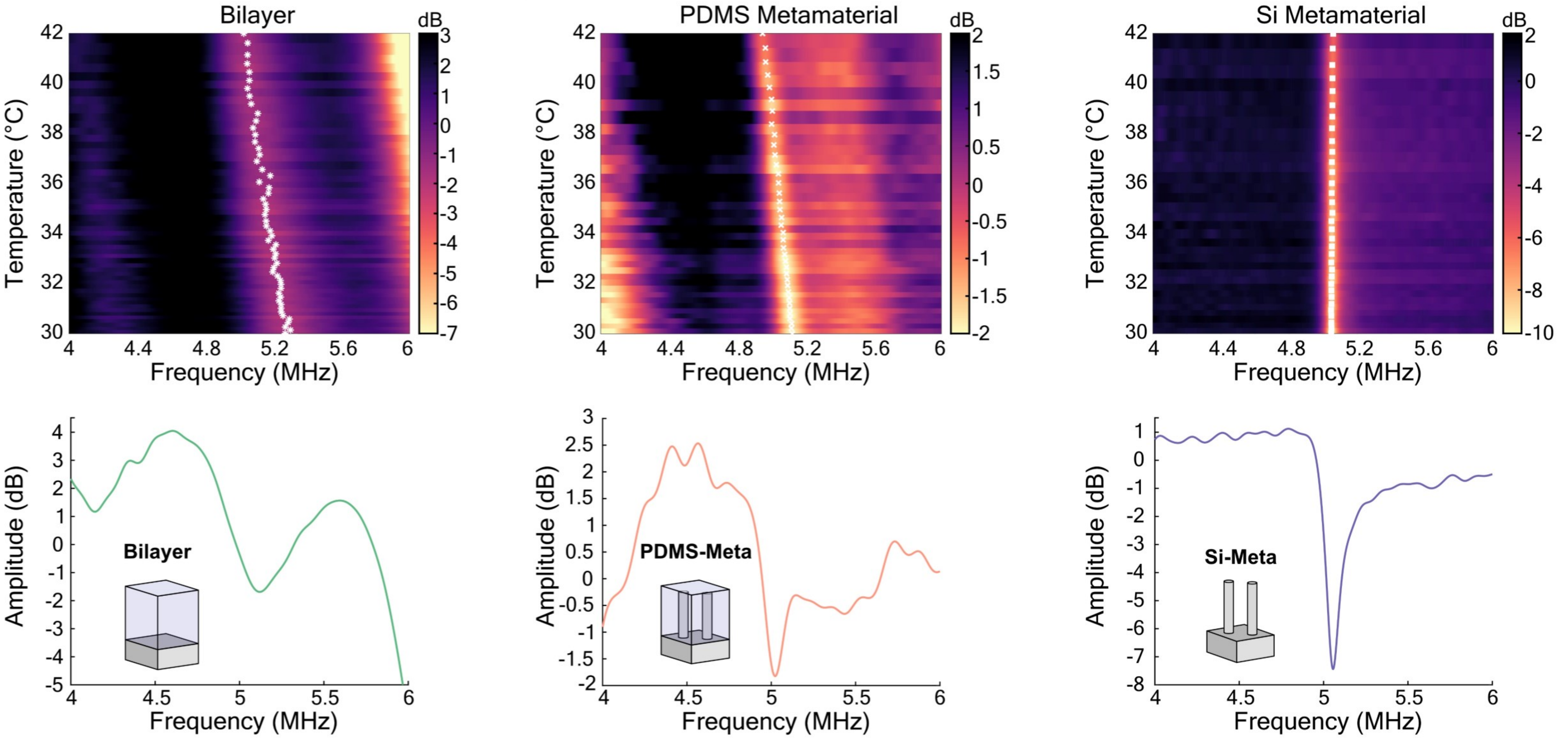
$$A_1/A_{n+1} = \prod_{j=1}^{n} (Z_{in}^{j} + Z_j)/(Z_{in}^{j} + Z_{j+1}) e^{i\varphi_j}$$



Impedance matching condition: $f = \frac{(n+1)}{2} \cdot \frac{c}{d}$

LM Brekovski, *Waves in Layered Media*, 1980, Academic Press

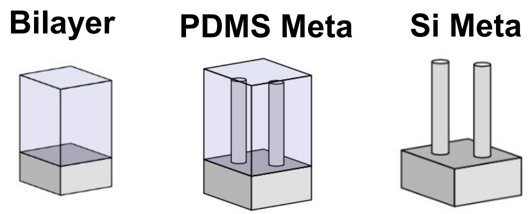
Temperature sensitivity and resolution

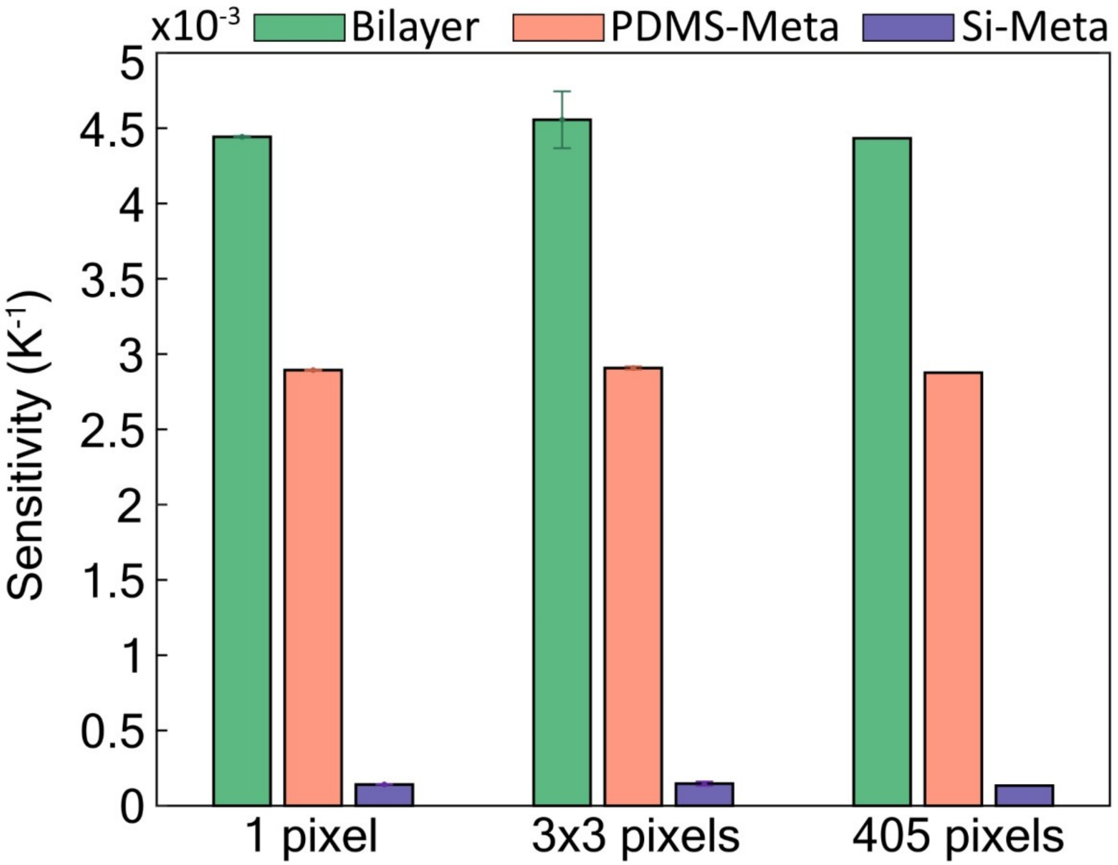


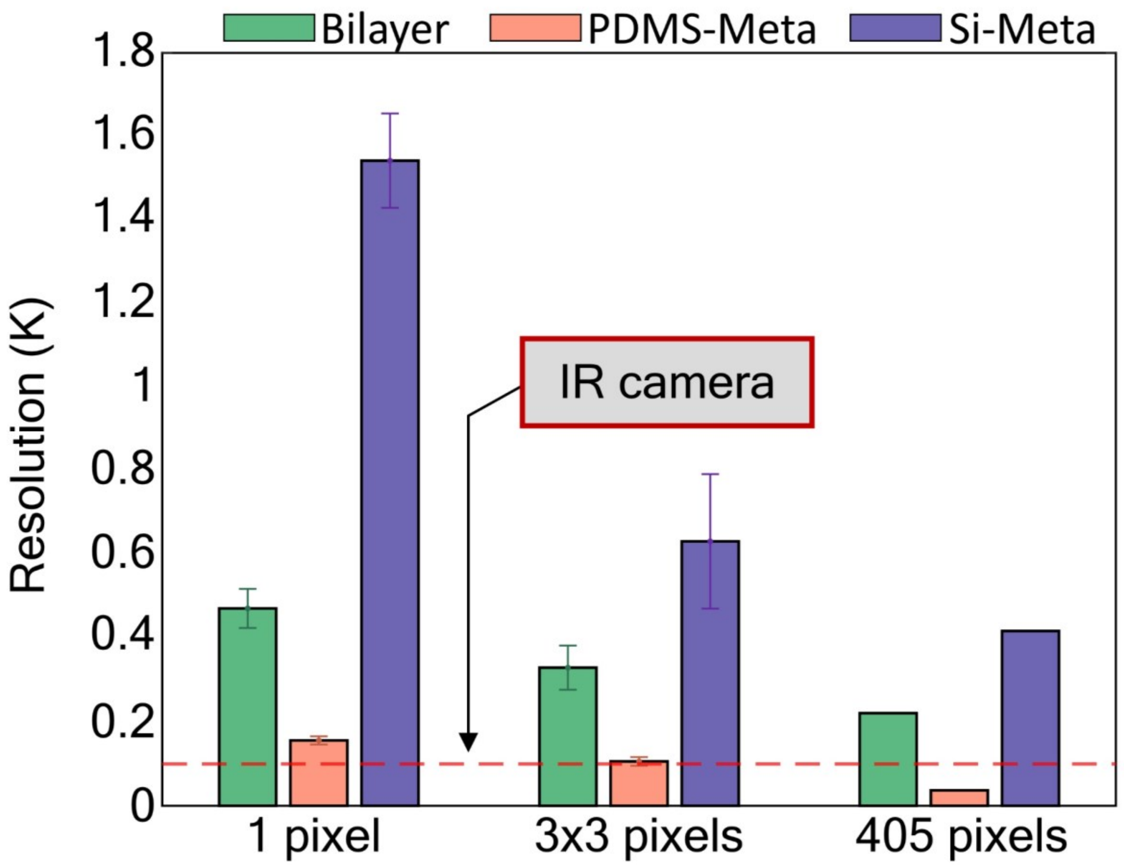
(*) FFTs measured at 37˚C

L. Maini et al., *Nature Microsystems & Nanoengineering,* 10(8), 2024

Temperature sensitivity and resolution

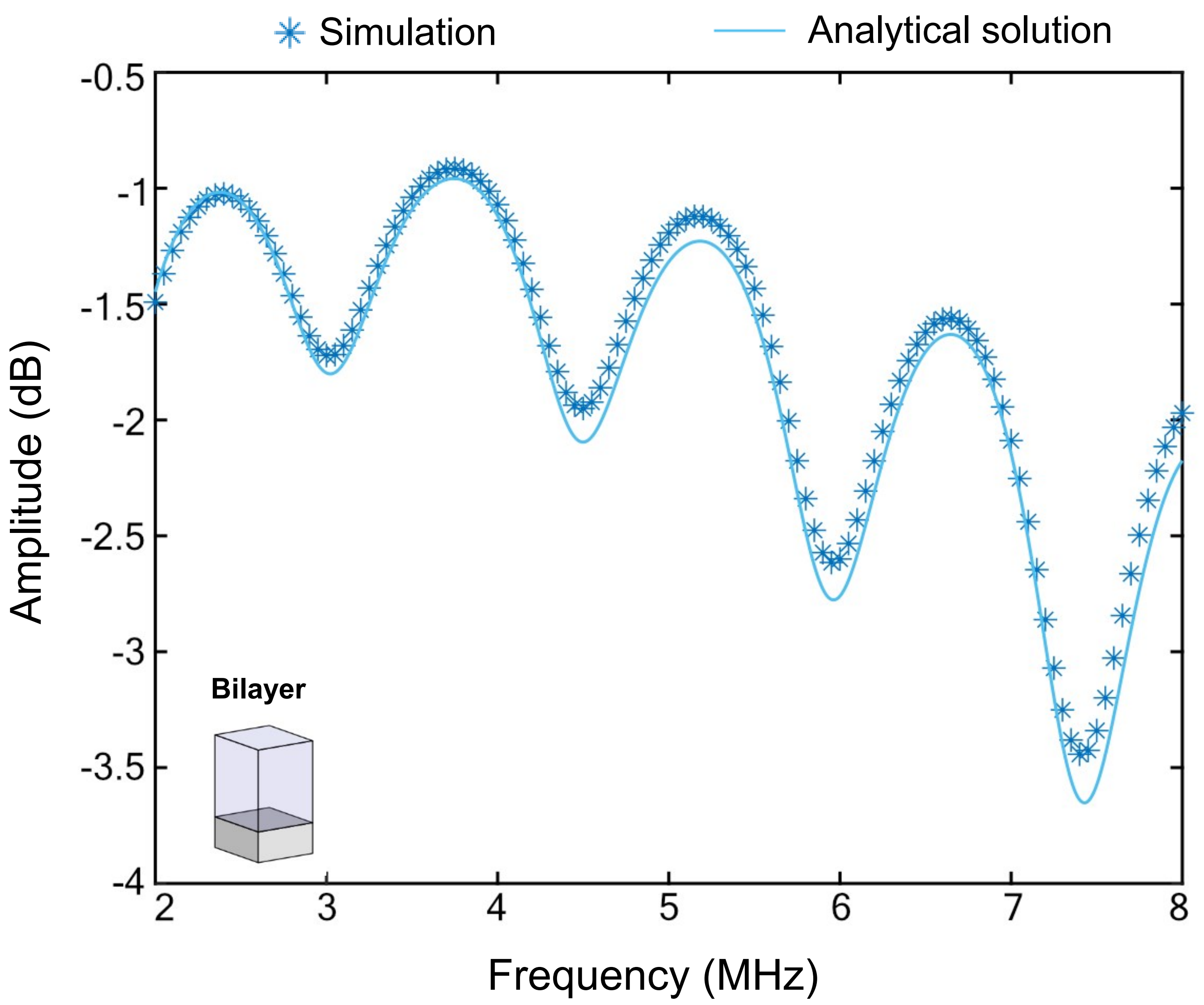






L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

Understanding temperature sensitivity



$\hat{c}_i$ experimentally measured from [3]:

$$\hat{c}_i = \frac{2\pi f}{2\pi f / c_i + j\alpha_i} \quad \text{with} \quad i = L \text{ or } S$$

L: longitudinal S: shear

C_{ii} interpolated:

$$C_{11}(f) = \rho_P \, \hat{\boldsymbol{c}}_L{}^2, \quad C_{44}(f) = \rho_P \, \hat{\boldsymbol{c}}_s{}^2$$

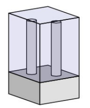
Customized material properties for PDMS:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{pmatrix} = \begin{pmatrix} \boldsymbol{C_{11}} & \boldsymbol{C_{12}} & \boldsymbol{C_{12}} & 0 & 0 & 0 \\ \boldsymbol{C_{12}} & \boldsymbol{C_{11}} & \boldsymbol{C_{12}} & 0 & 0 & 0 \\ \boldsymbol{C_{12}} & \boldsymbol{C_{12}} & \boldsymbol{C_{11}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \boldsymbol{C_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \boldsymbol{C_{44}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{C_{44}} \end{pmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{pmatrix}$$

[1] V. Genoves et al., *Polymer Testing*, 124, 108067, 2023
[2] NR Skov et al., *Physical Review Applied* 12, 2019
[3] G Xu et al., *Physical Review Applied* 13, 2020

Understanding temperature sensitivity

PDMS Meta



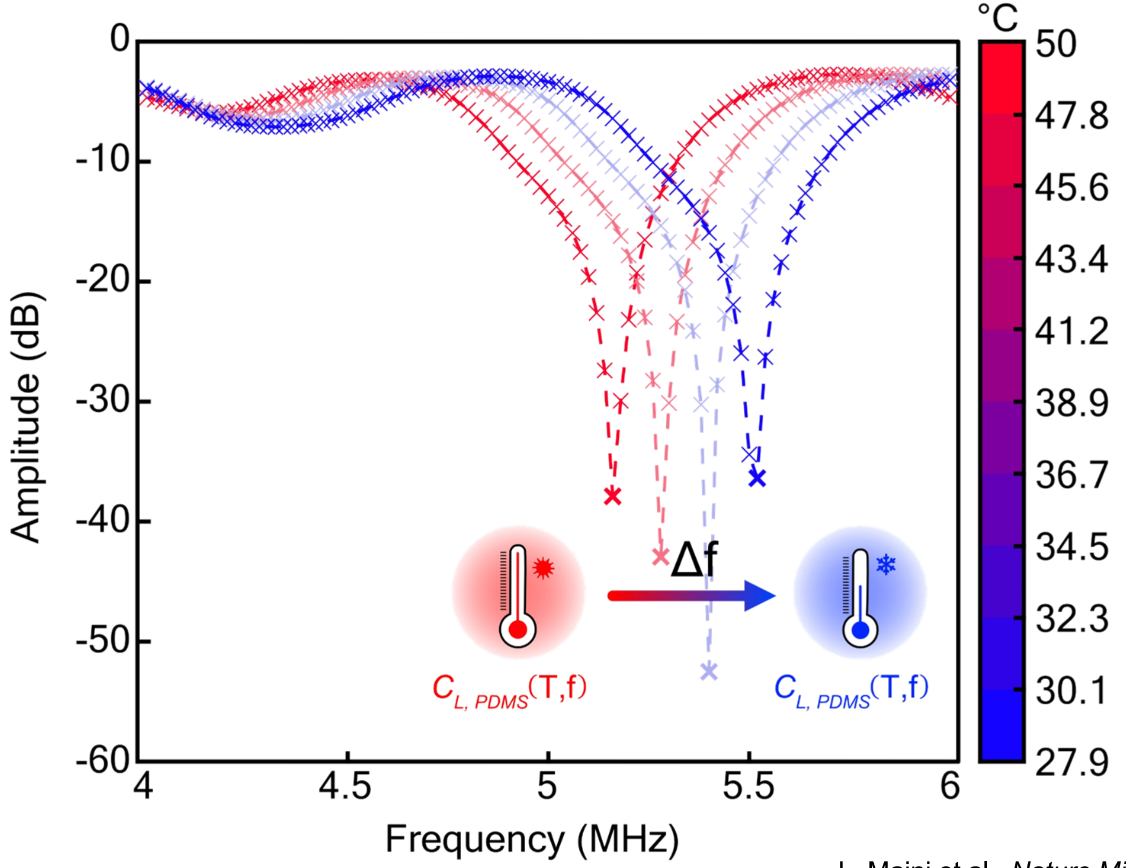
Experimentally measured: $\frac{\Delta c_{L,PDMS}(T)}{c_{L,PDMS}(50°C)}[\%] = 7\%$ [1]

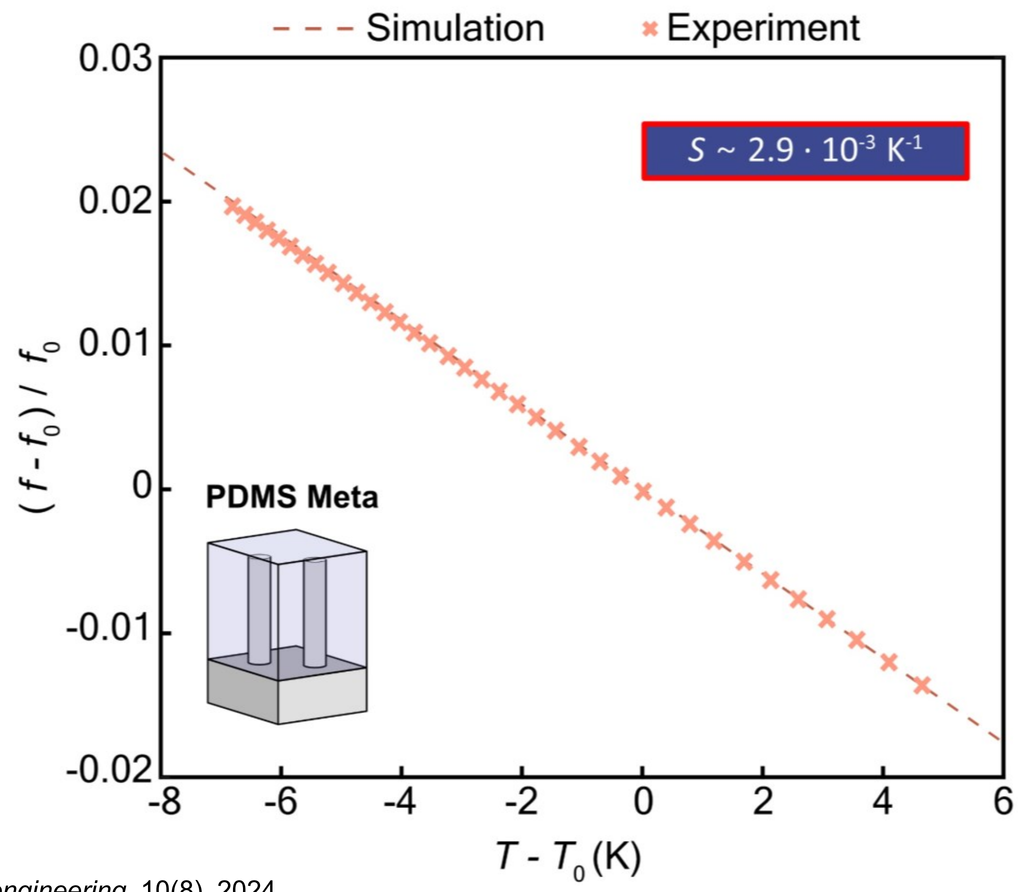
bulk modulus **[GPa]**

$$c_L(T) = \sqrt{\frac{K(T) + \frac{4}{3}G}{\rho}}$$

shear modulus **[MPa]**

FEM Simulation





L. Maini et al., *Nature Microsystems & Nanoengineering*, 10(8), 2024

[1] V. Genoves et al., *Polymer Testing*, 124, 108067, 2023
lucrezia.maini@micro.mavt.ethz.ch

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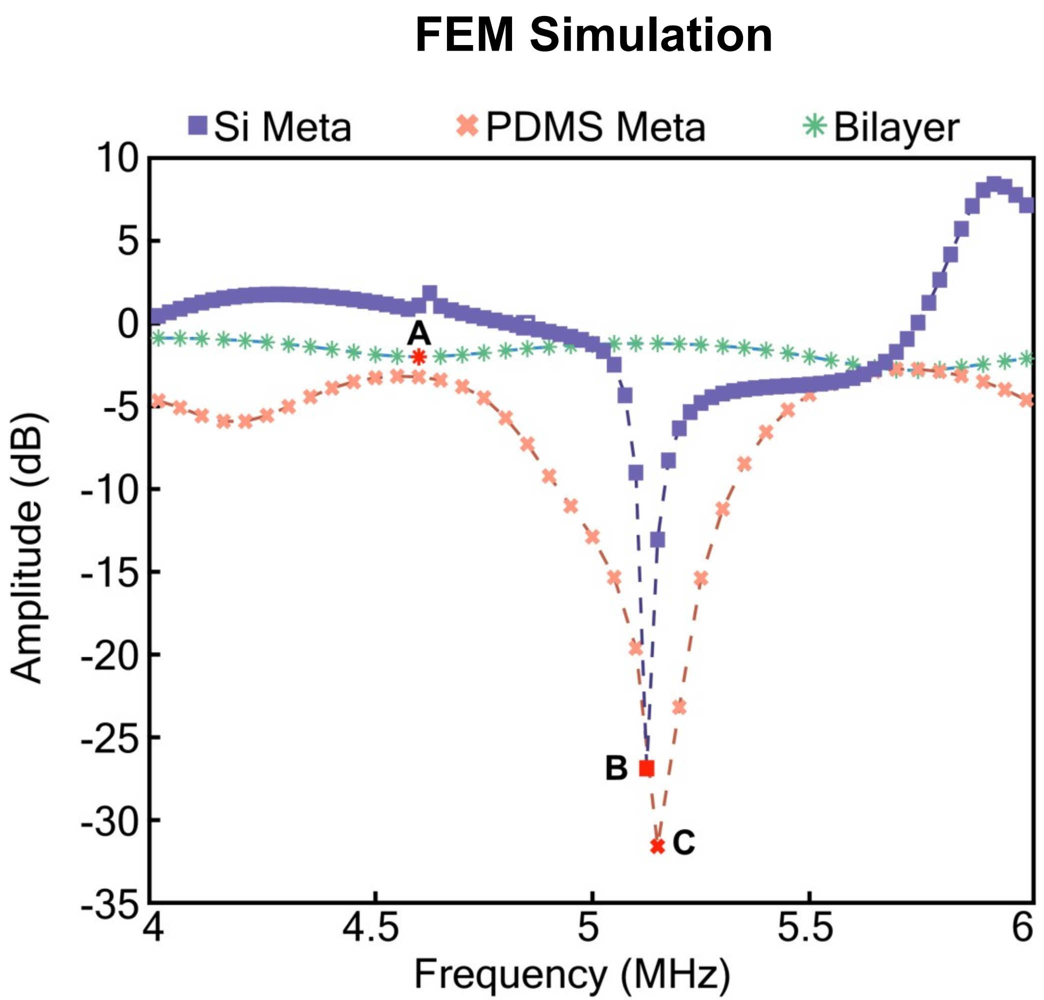
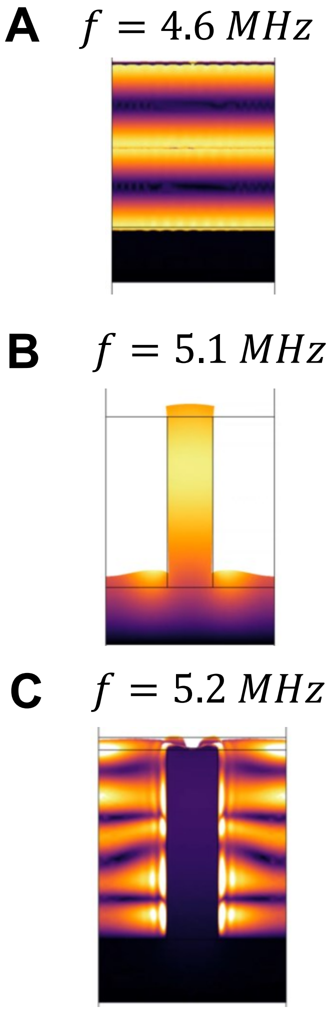
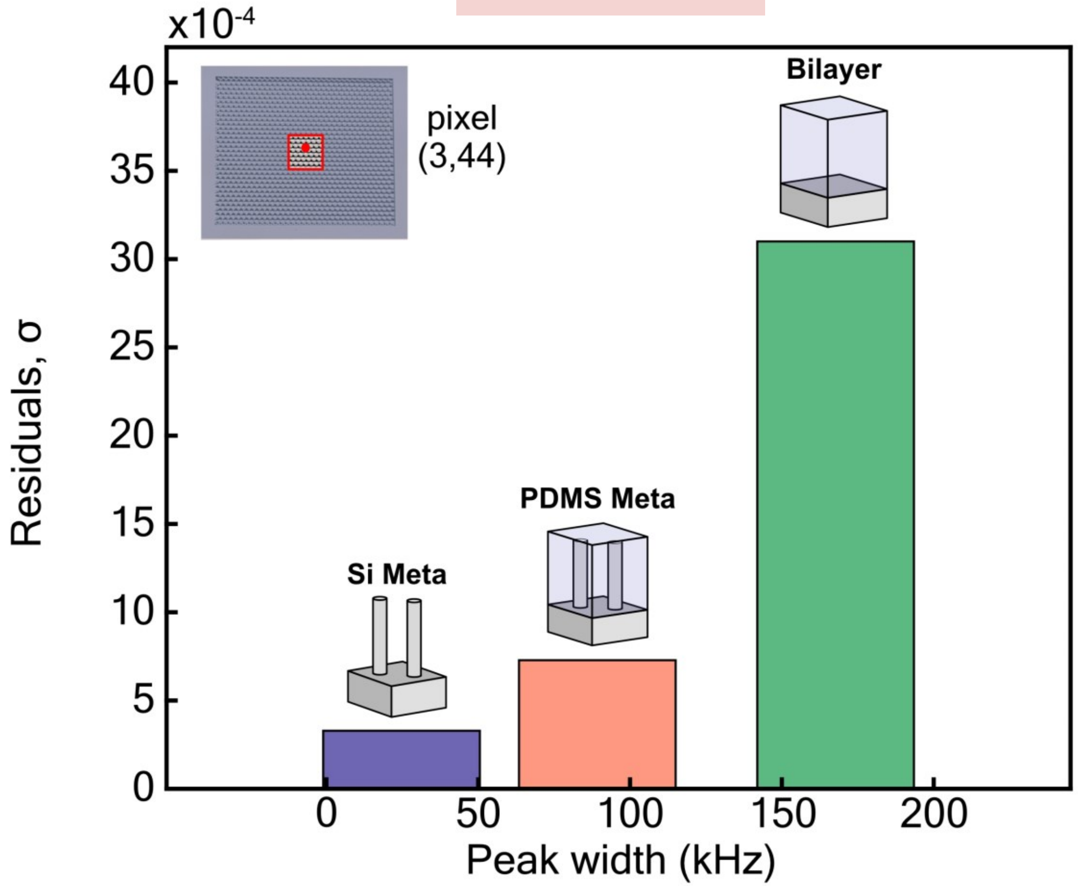
Understanding temperature resolution

$$R = \frac{\sigma_{res}}{S}$$







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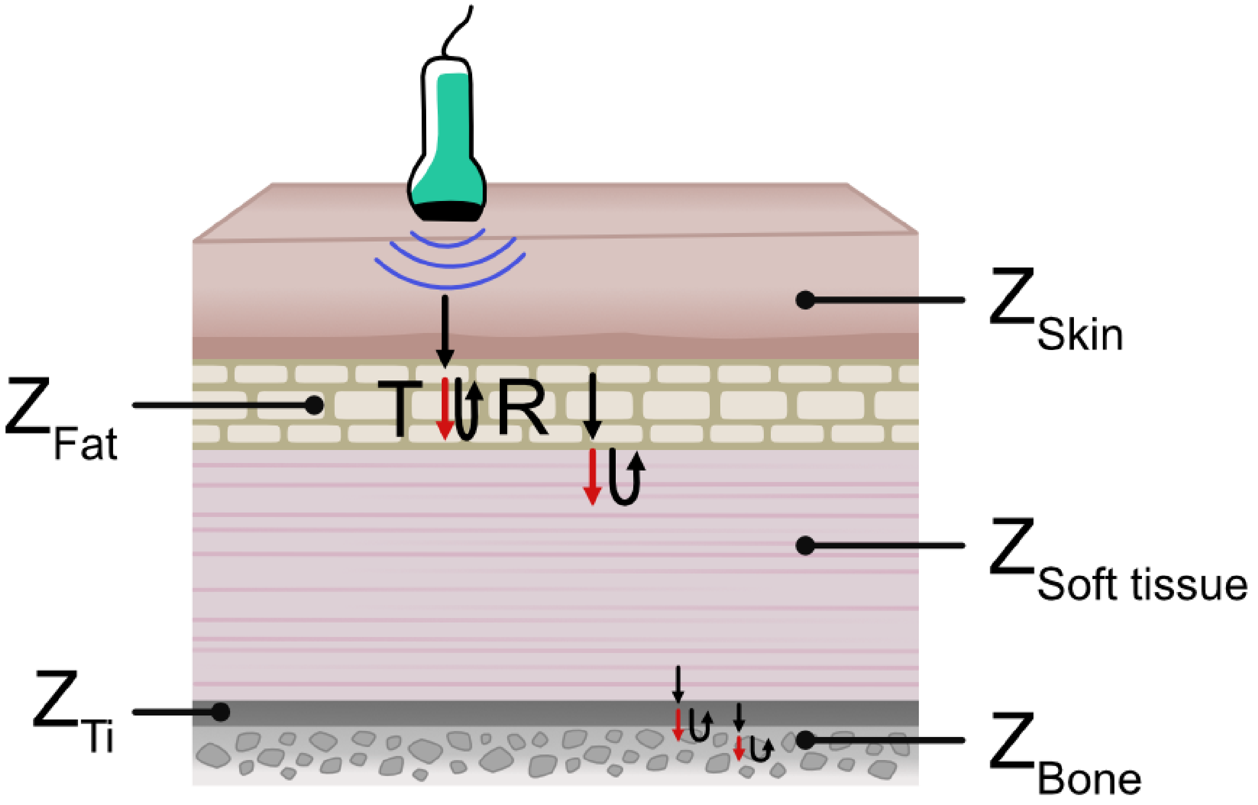
Towards a realistic setup



TMM: 8.2 % graphite in water

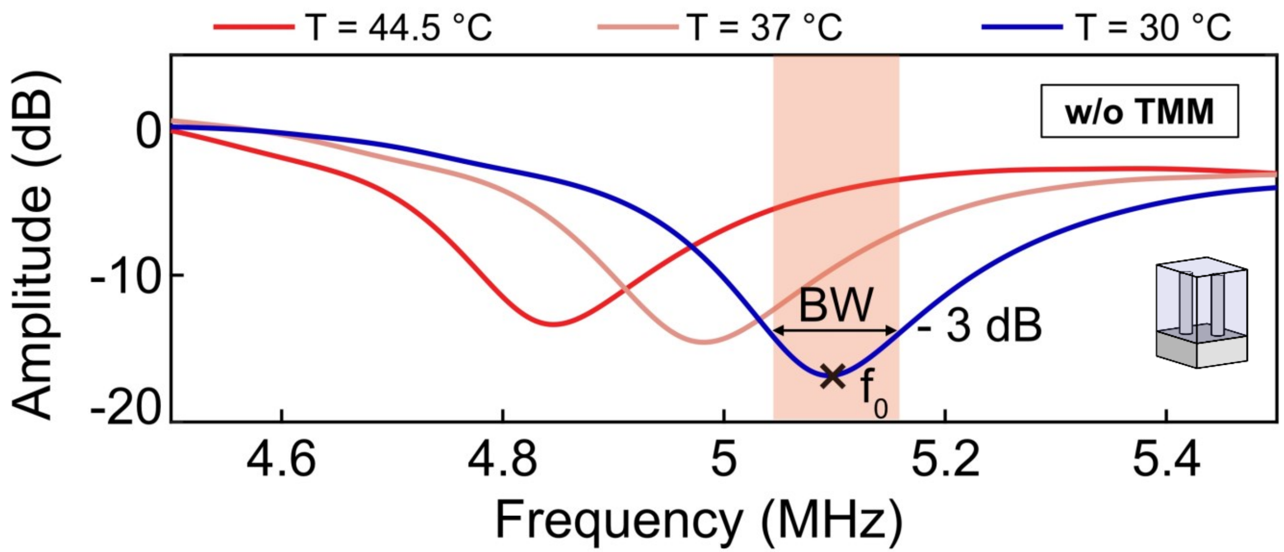
From Yannick Merz's Bachelor Thesis

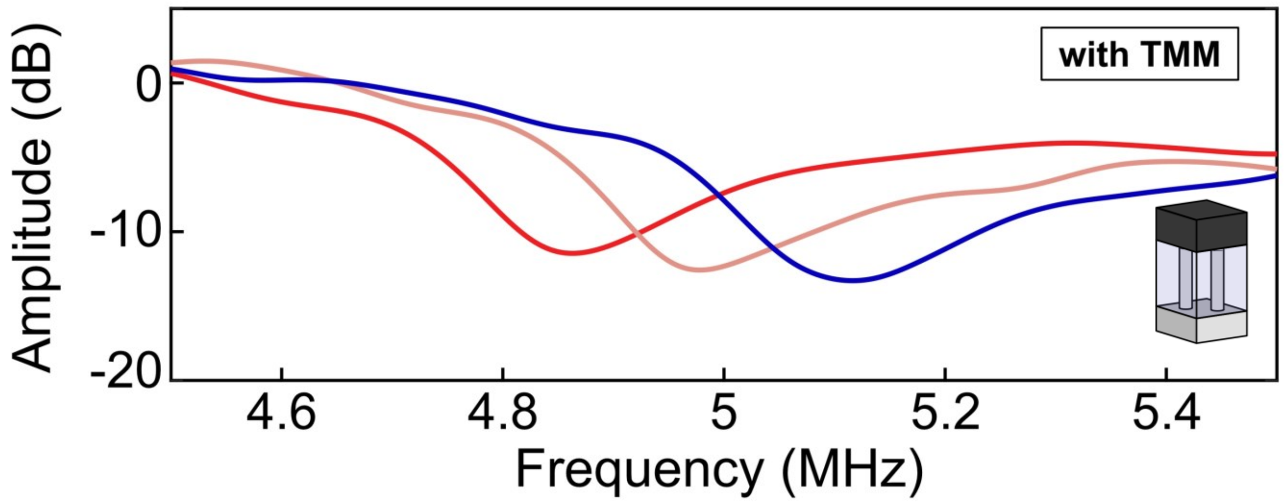
(*) Constant Agar [%] : 2%

[1] TD Mast, *Acoustic Research Letters Online, 1,* 37–42, 2000
[2] SA Gross et al., *The Journal of the Acoustical Society of America,* 64(2), 423–457, 1978
[3] J. Ophir et al., ULTRASONIC ATTENUATION MEASUREMENTS OF IN VIVO HUMAN MUSCLE (Chap. 3), 1982
[4] KD Nassiri et al., *Ultrasonics* 17(5), 230-232, 1979
[5] H. Shankar et al., *Anesthesiology*, 115(5),1109–1124, 2011

(*) TMM: Tissue Mimicking Material

TMM effect on the metamaterial





	Temperature			S [1/K]	R [K]
	44.5˚ C	37˚C	30˚C		
f_0 (MHz)	4.84	4.98	5.1	$-3.6 \cdot 10^{-3}$	0.03
BW (kHz)	135	139	118		

f_0 (MHz)	4.86	4.98	5.12	$-3.6 \cdot 10^{-3}$	0.12
BW (kHz)	173	189	190		

- Sensitivity value is preserved with and w/o TMM

(*) TMM: Tissue Mimicking Material

L. Maini et al., Eurosensors XXXVI, Debrecen, Hungary, 2024 [*AMA Proceedings*, OT3.269, pp. 60-61]

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Outlooks and conclusions

- Acoustic metamaterials new approach in implantable sensors for wireless interrogation
- Introduction of TMMs does not perturb the temperature **sensitivity**
- Temperature **resolution** ~0.1 K in presence of TMMs

Next steps:

- Phased array transducers could improve temperature performances (spatial averaging)
- Investigation with other parameters of interest (e.g. strain)

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- Dr. Nikola Cesarovic
- Prof. Dr. Volkmar Falk

IBM-BRNC

CMi-EPFL

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