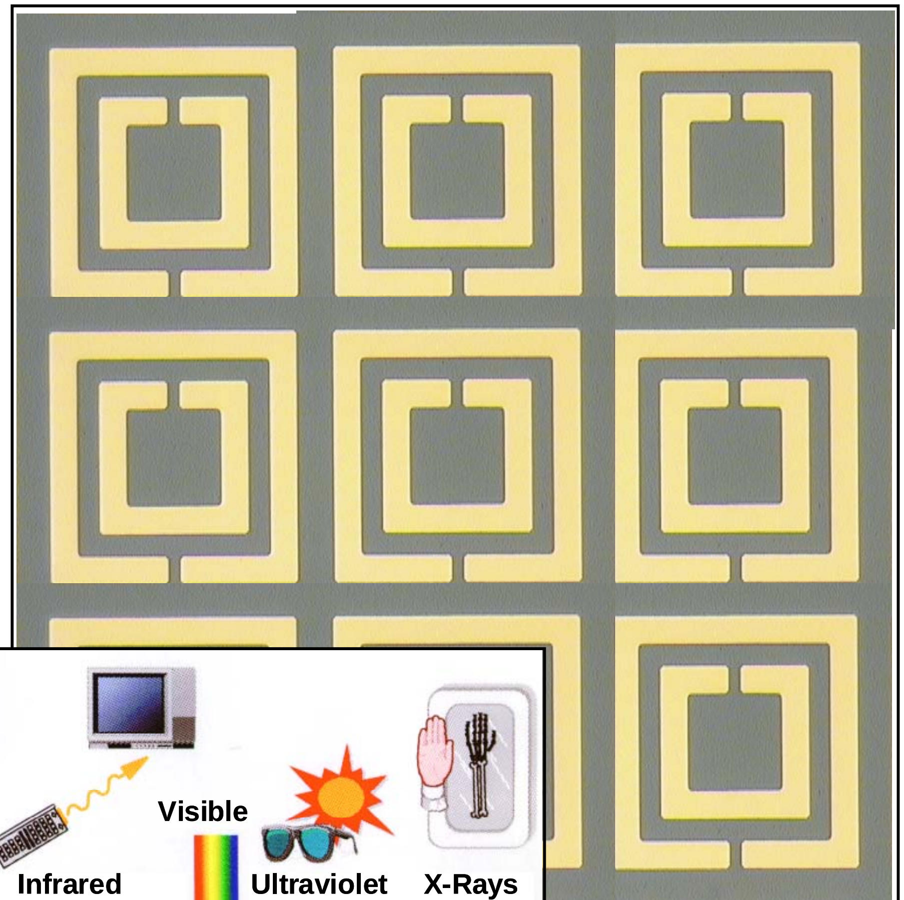
Terahertz Metamaterials: Reducing Losses and Enabling a New Chem-Bio Detection Platform

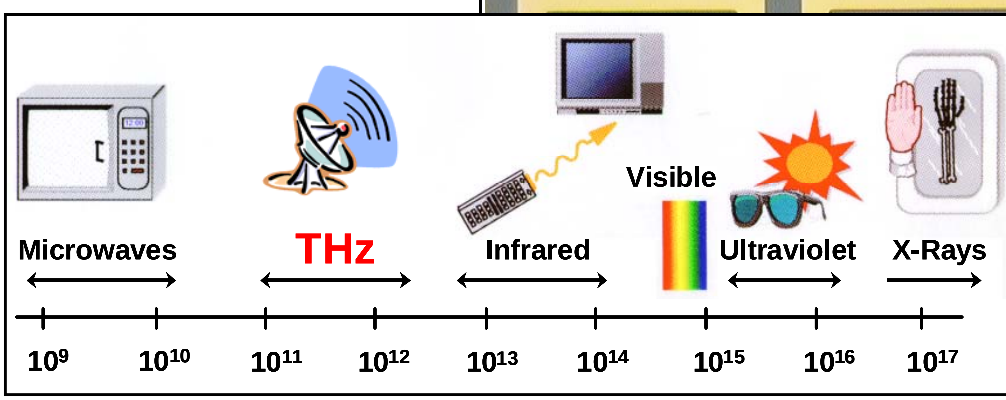
SAND2008-2330C



Xomalin G. Peralta, Ph. D.

Applied Photonic Microsystems
Sandia National Laboratories

May 1, 2008.



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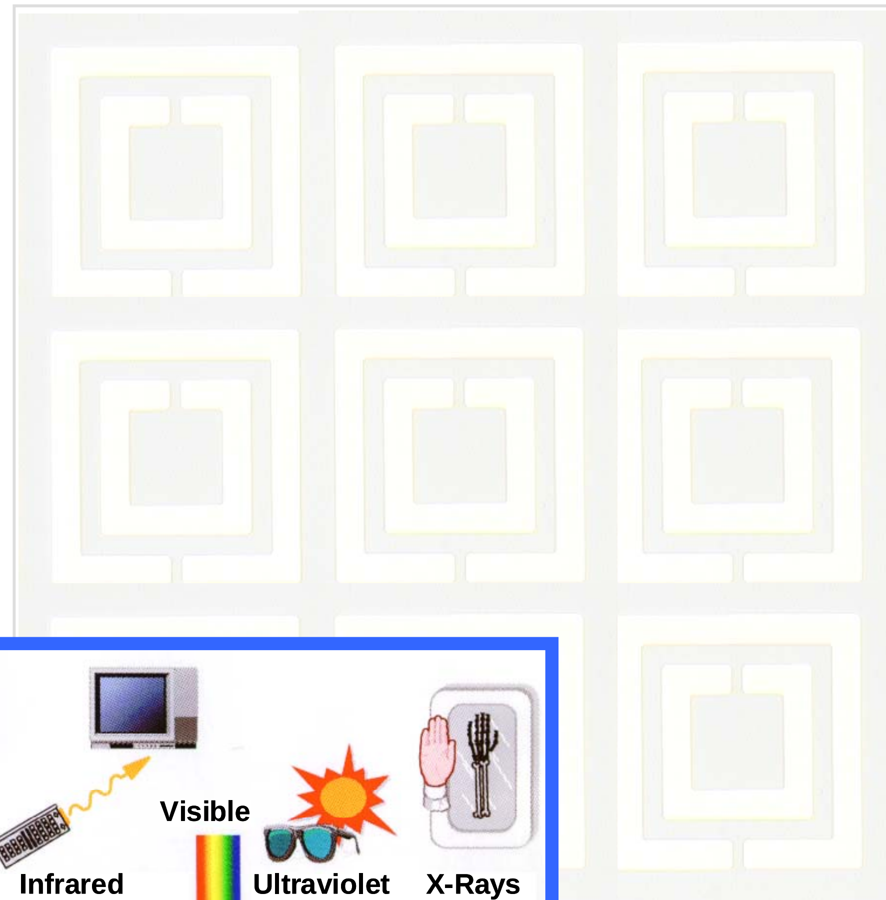

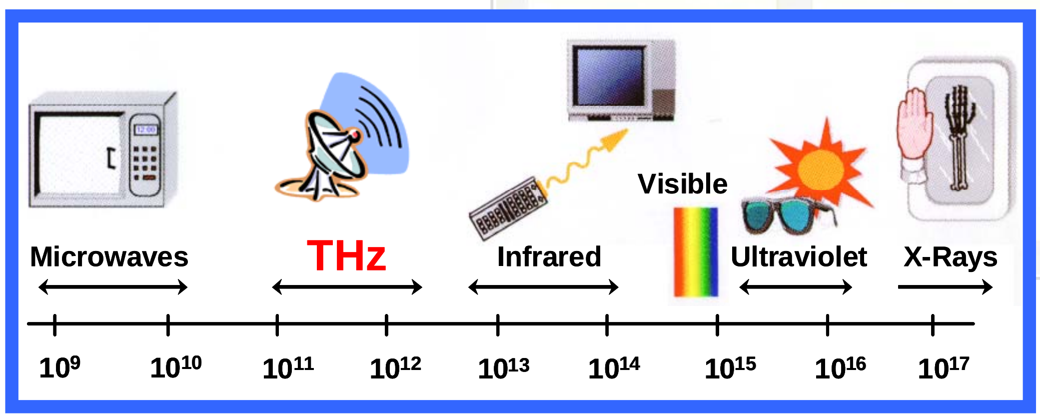

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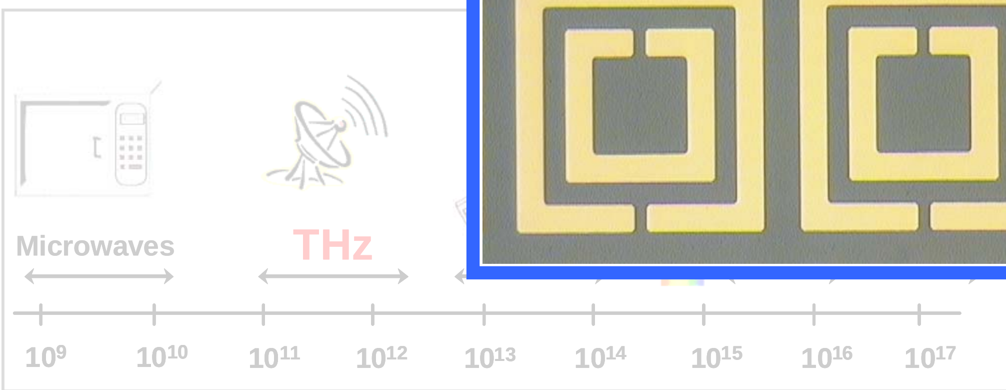

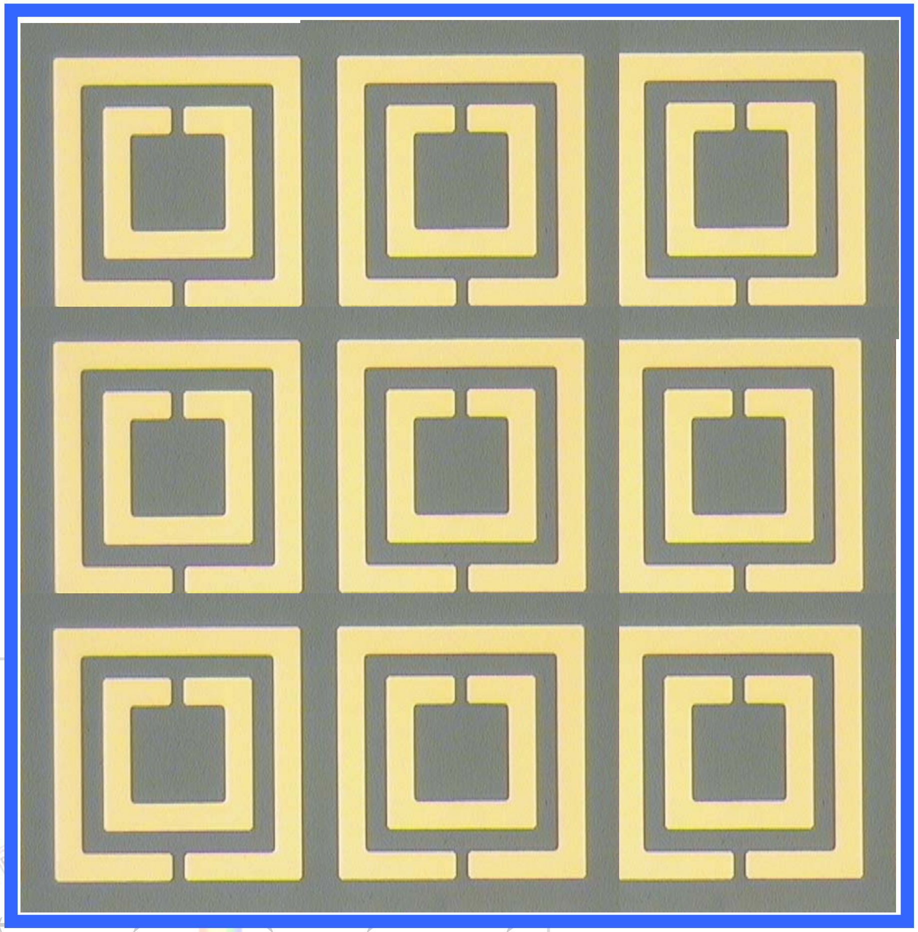

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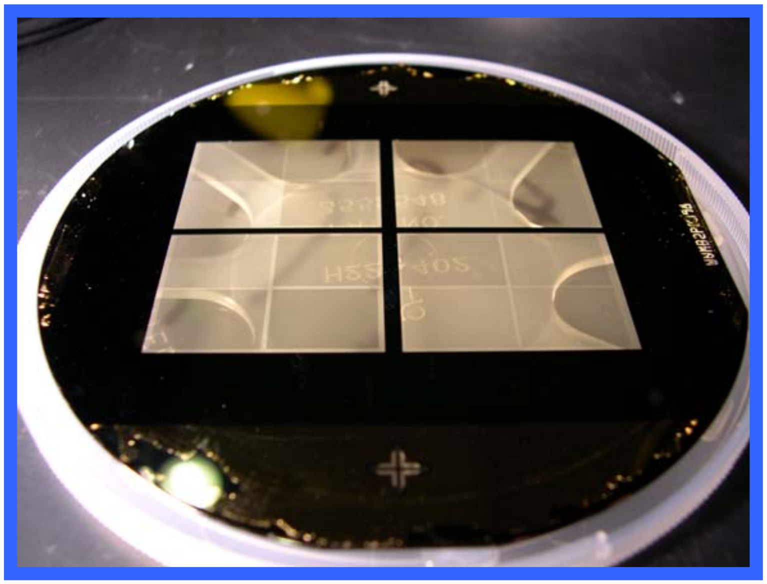

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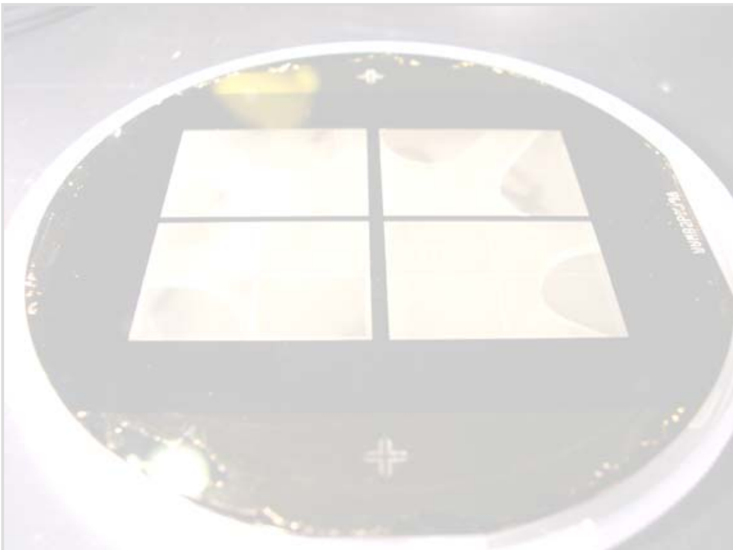
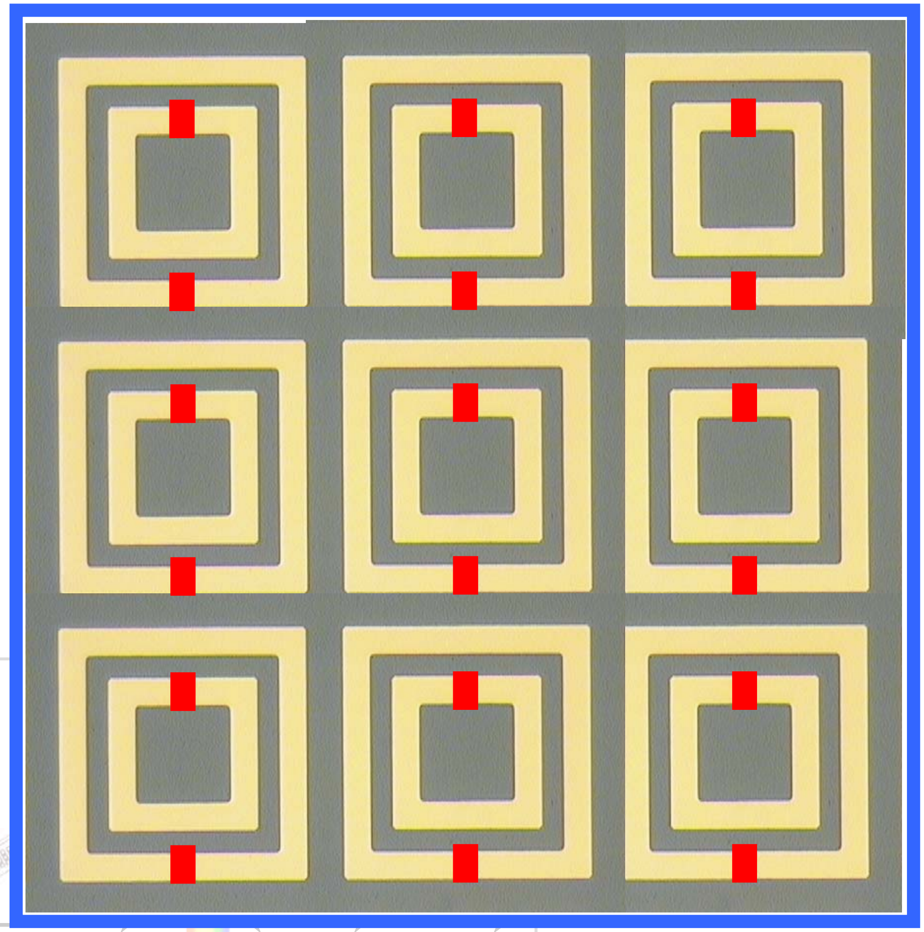
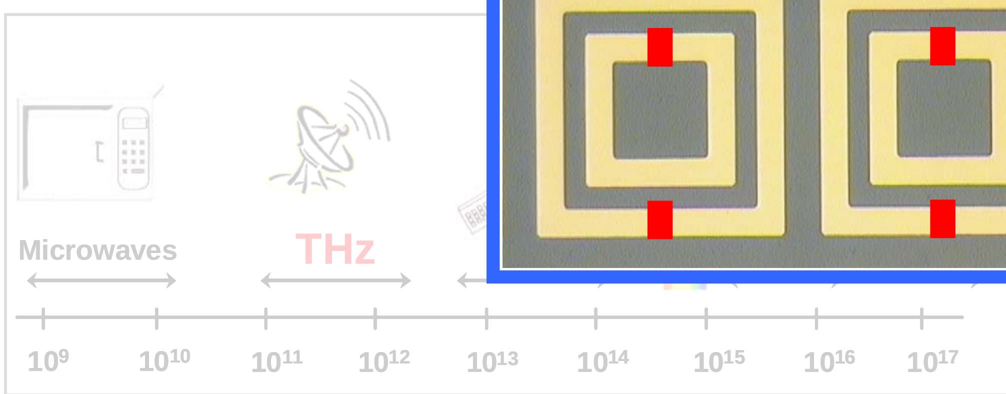
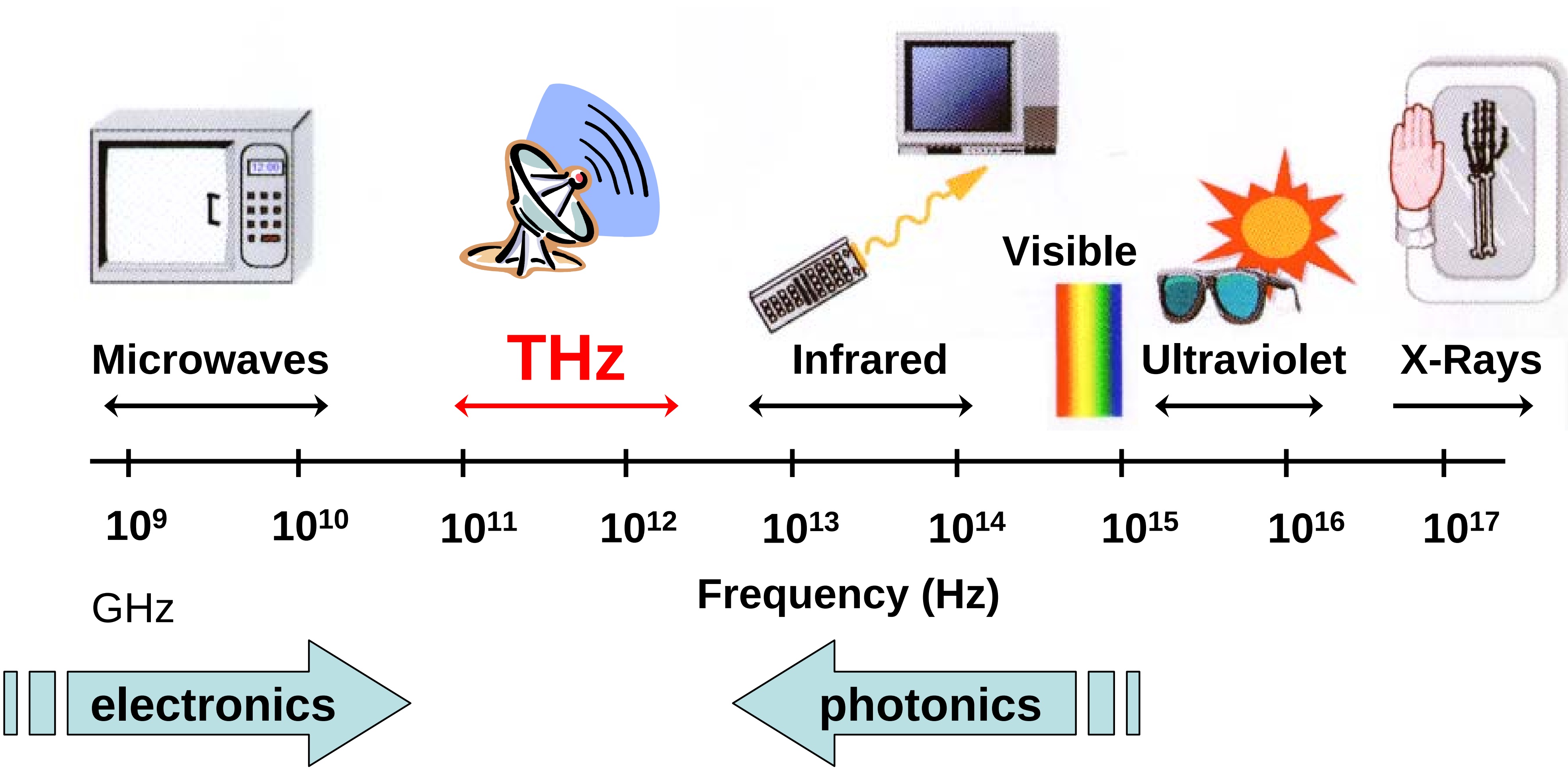
Terahertz Metamaterials: Reducing Losses and Enabling a New Chem-Bio Detection Platform







Where is the far-infrared or Terahertz (THz) region?



ν = 1 THz; λ = 300μm; wave number = 33cm^{-1}; energy = 4meV

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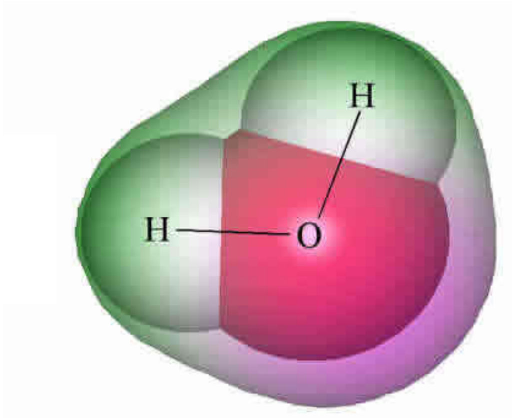
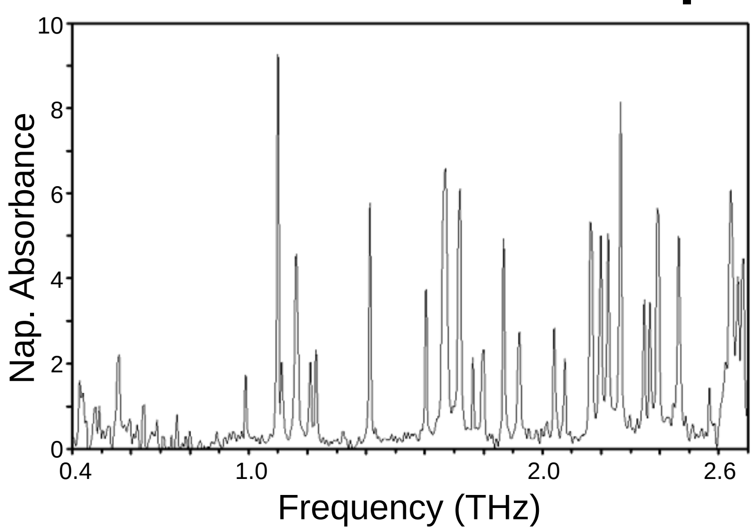
Why is it of interest? Rotational modes of small free molecules lie in the THz region



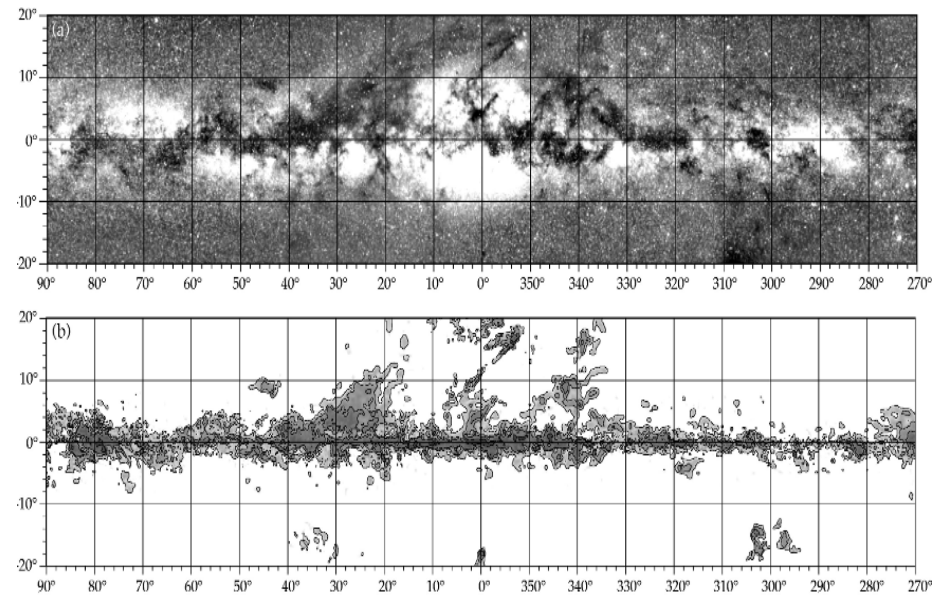
Absorbance of water vapor



R. J. Foltynowicz, Sandia report 2005-5709.

Application: Astrophysics

Galactic optical emission and CO emission @ 115GHz



T. M. Dame et al., Astrophys. J. 547, 792 (2001).

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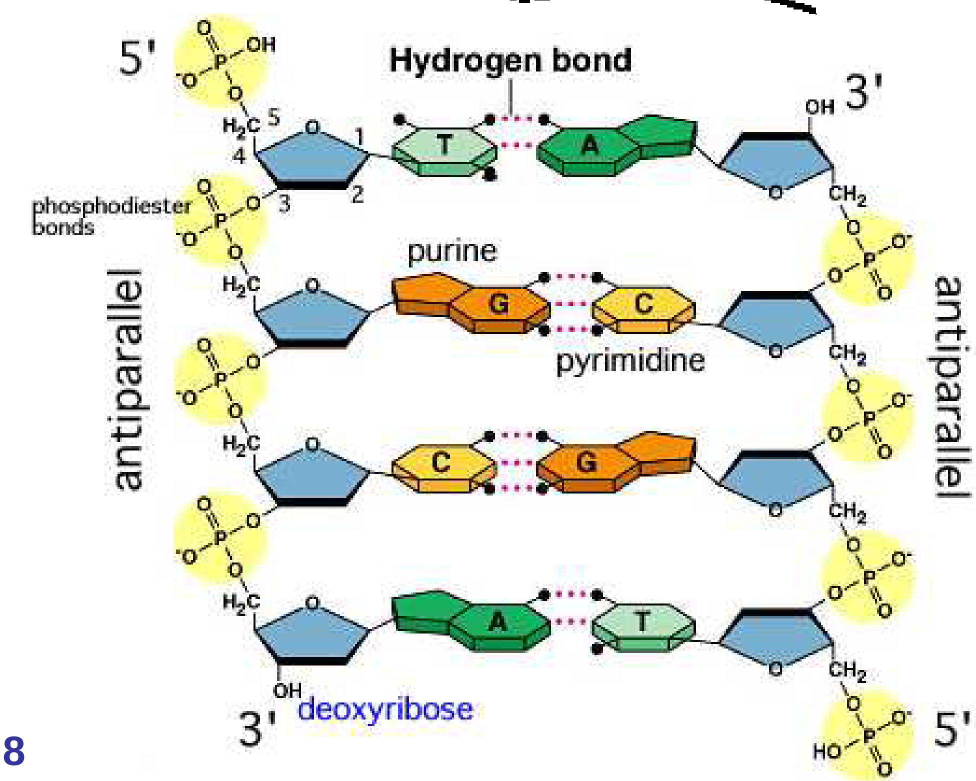
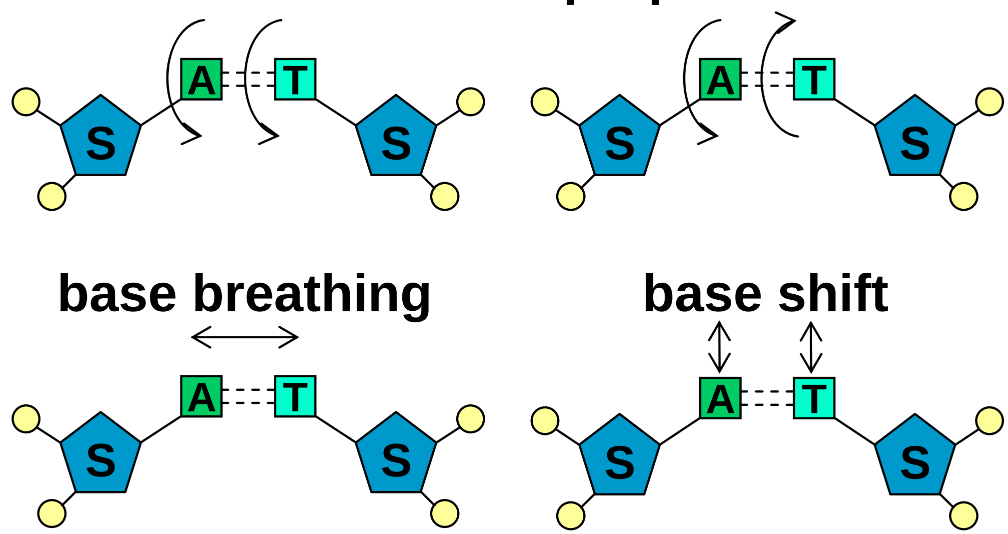
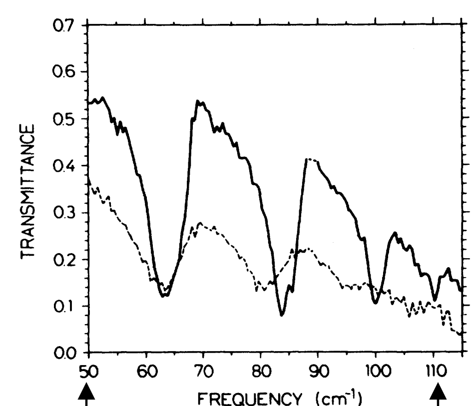
Vibrational rotational modes of large groups of molecules are in the THz region



DNA vibrational modes





1.5THz 3.3THz

J. W. Powell et al., PRA 35, 3929 (1987).

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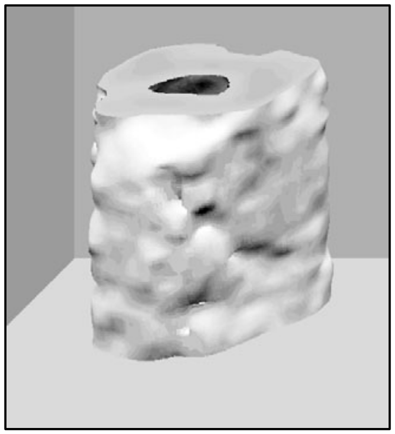
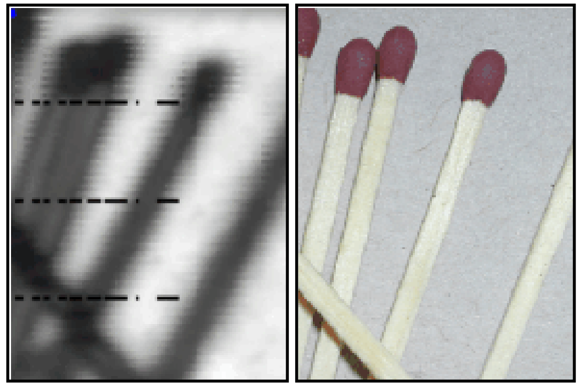
There are several emerging technological applications of THz radiation

Tomography and Imaging

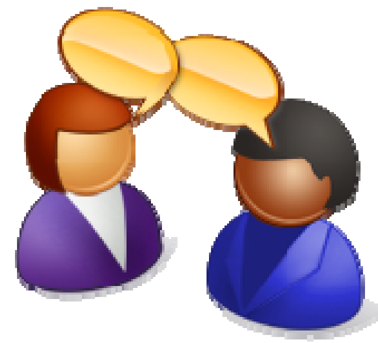


B. Ferguson et. al, Phys. Med. Bio. (2002).



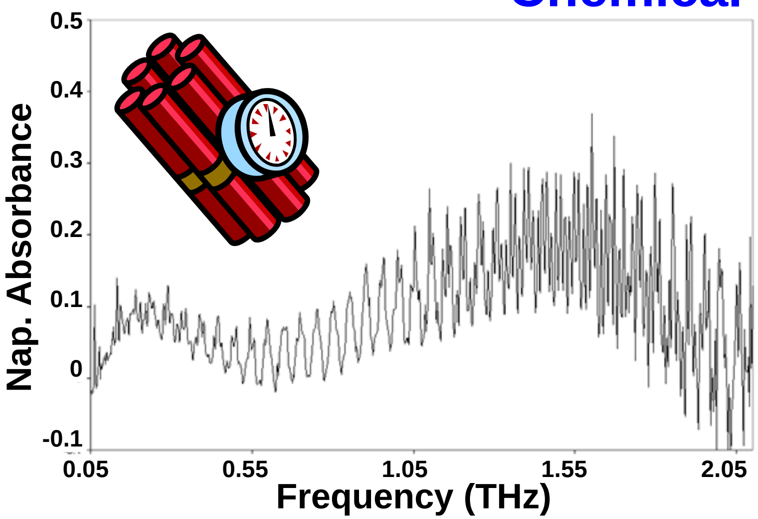
P. Planken, DELFT.

Communications



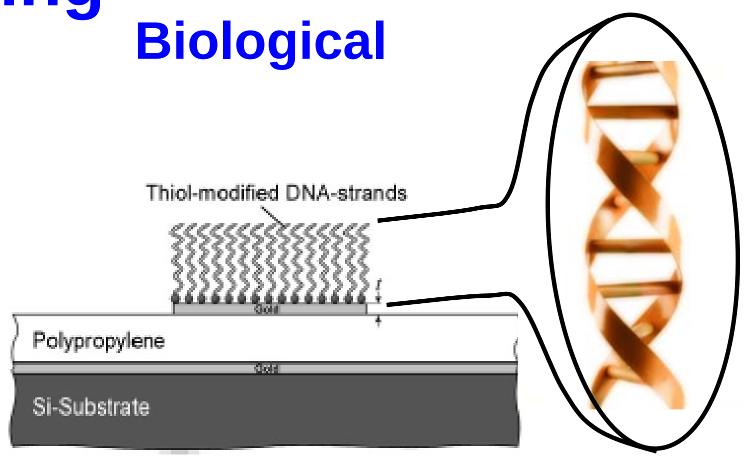
Sensing

Chemical



Courtesy of M. C. Wanke, SNL.

Biological



M. Nagel et al., Phys. Med. Biol. **48** (2003) 3652.

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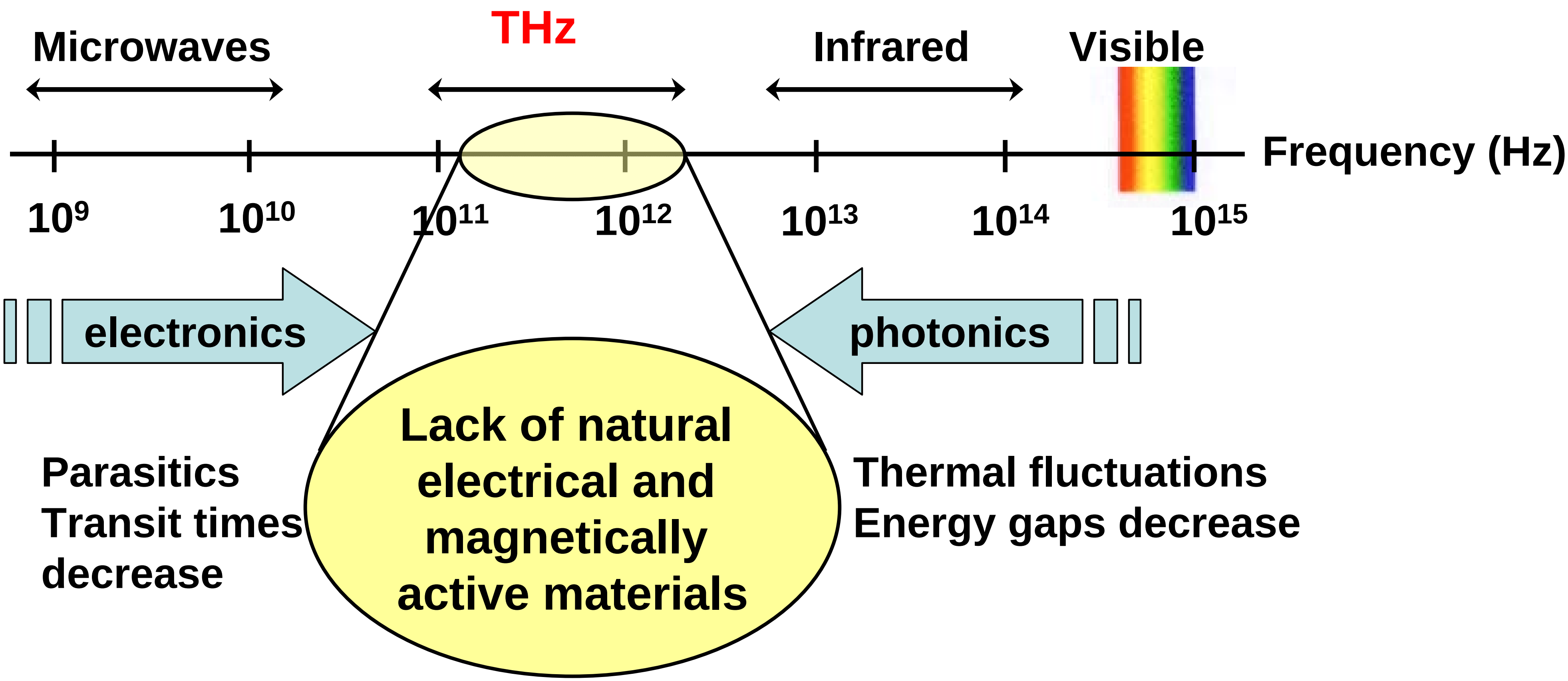
Why is there a void in science and technology at THz frequencies?



Metamaterials can provide tools to solve this problem!

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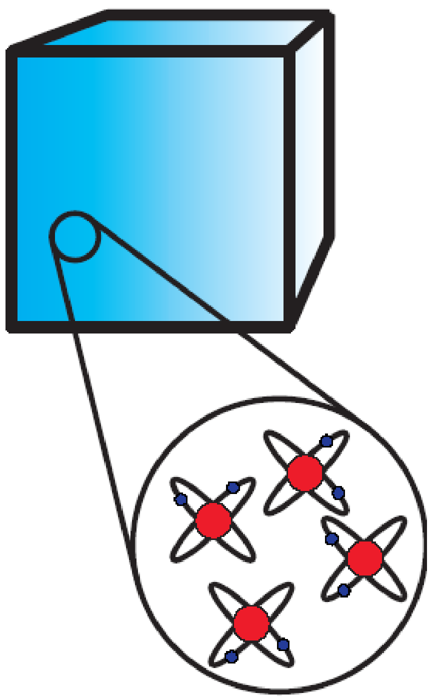
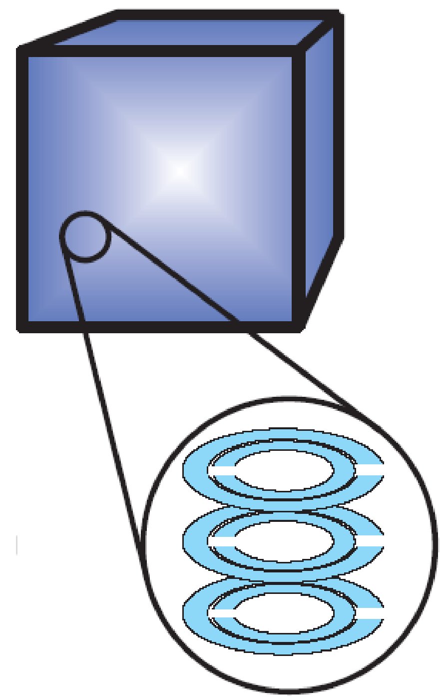
What are metamaterials?

μετα = beyond



A natural material composed of atoms.



A metamaterial is composed of artificially structured “atoms”.

Metamaterials are artificial materials with properties that go beyond those of the constituent materials or naturally occurring materials.

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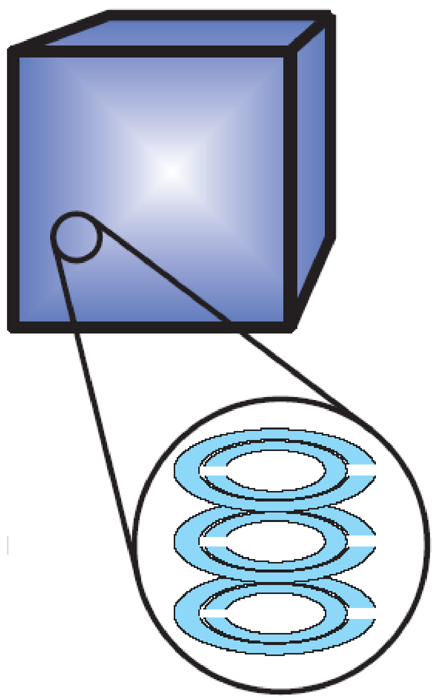
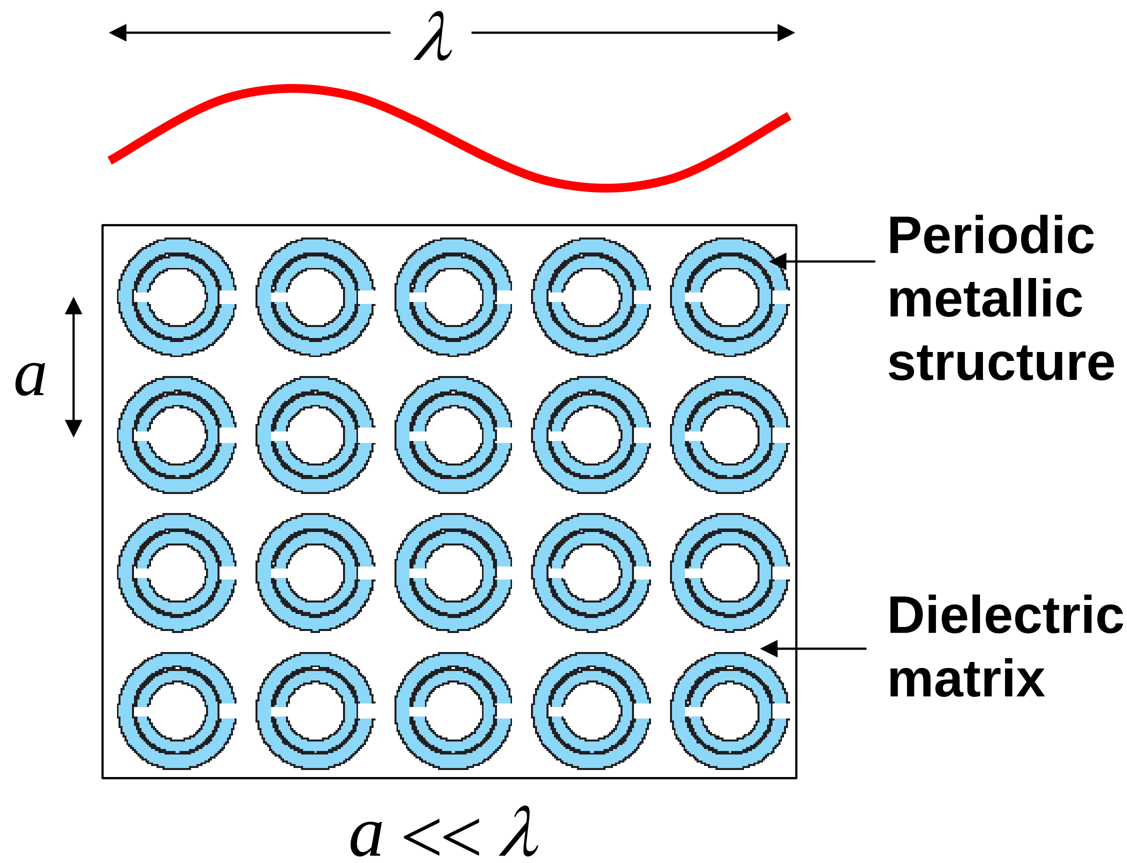
The properties of the “atoms” and their distribution determine the properties of the metamaterial





The individual units are designed to have specific electromagnetic properties.

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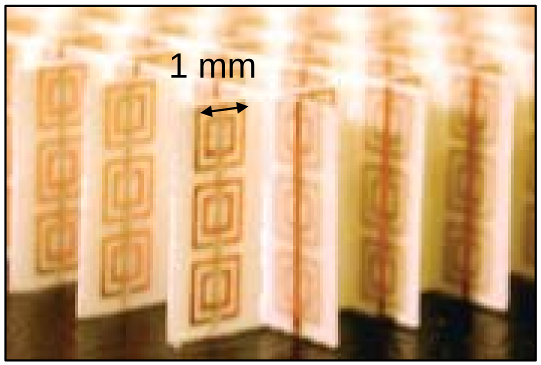
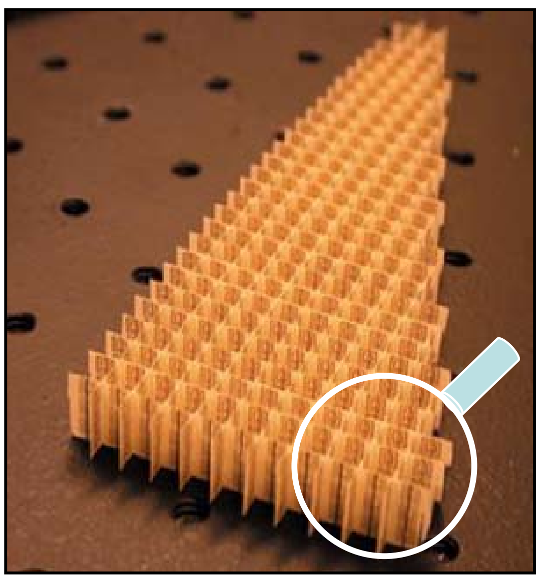
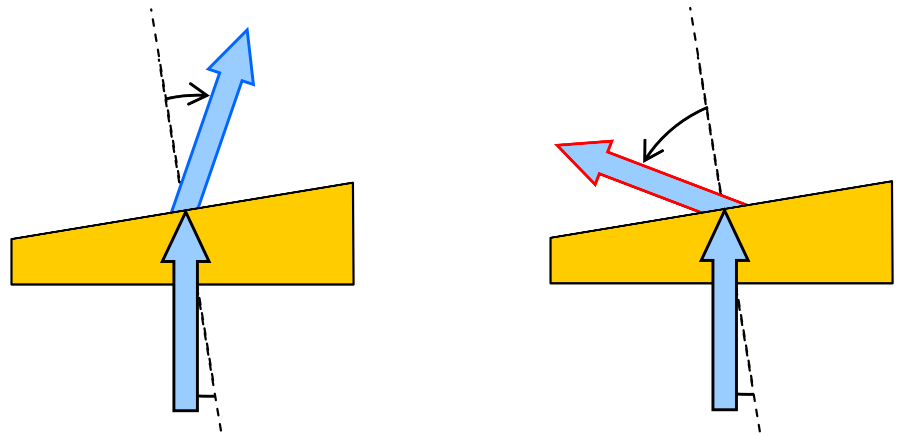
Example: negative index of refraction at microwave frequencies

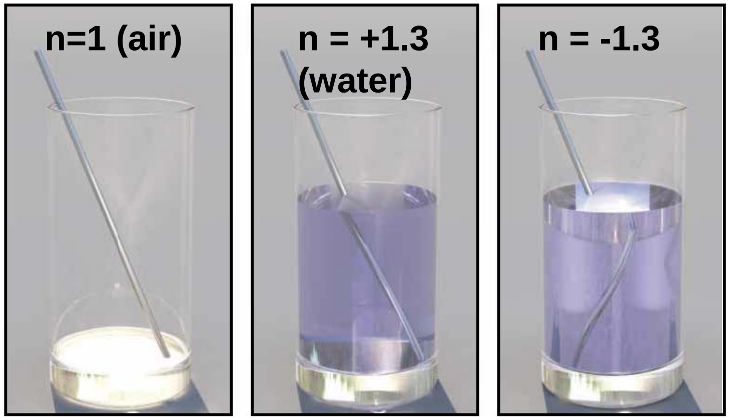




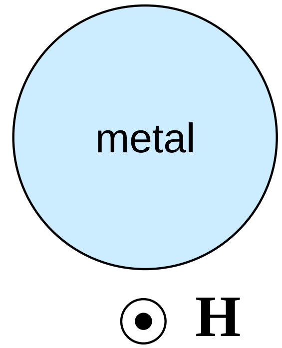


Normal material

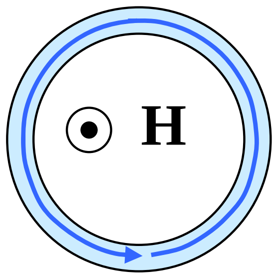
Negative index material



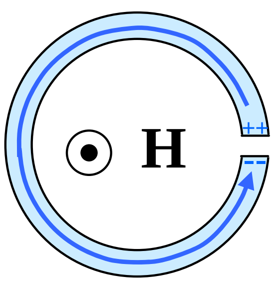
Understanding the electromagnetic response of double circular split-ring resonators

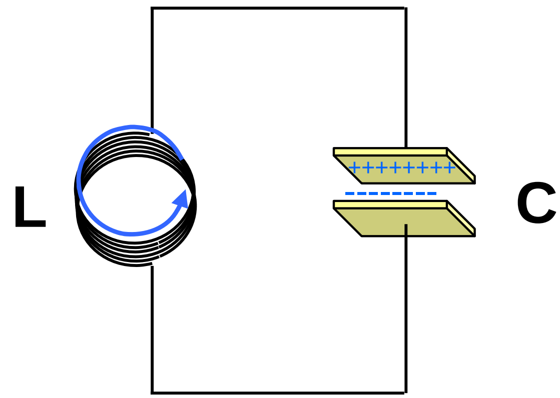


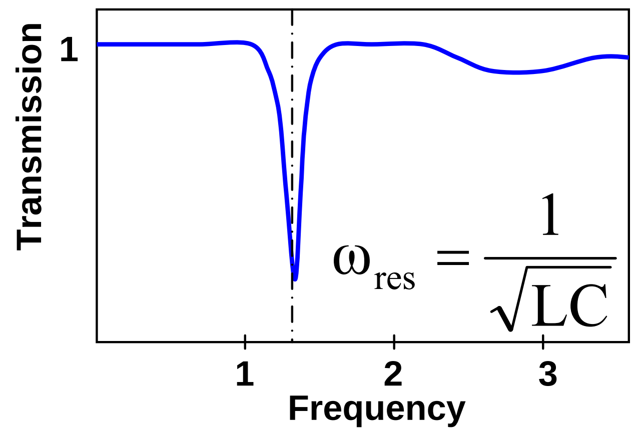
Make it a ring so H induces a current



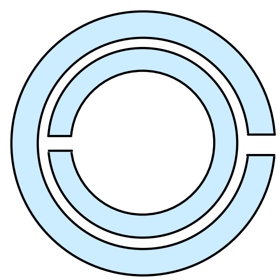
Cut the ring to introduce a capacitance





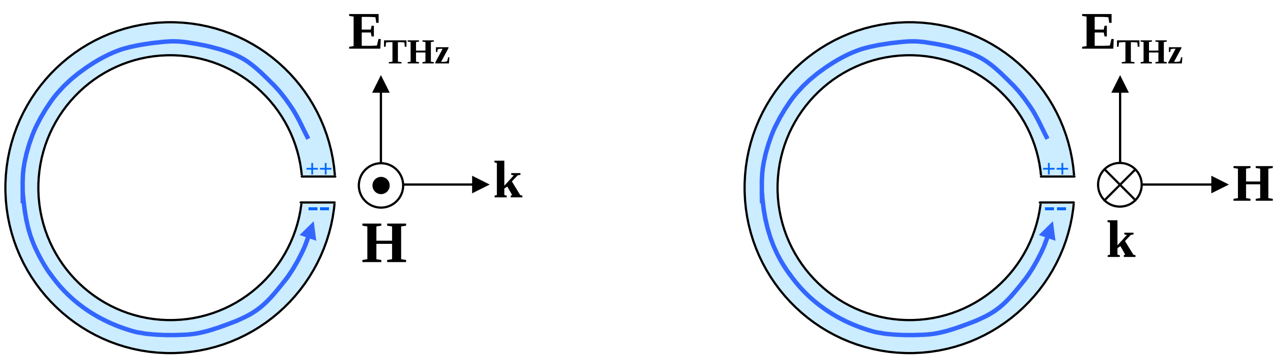


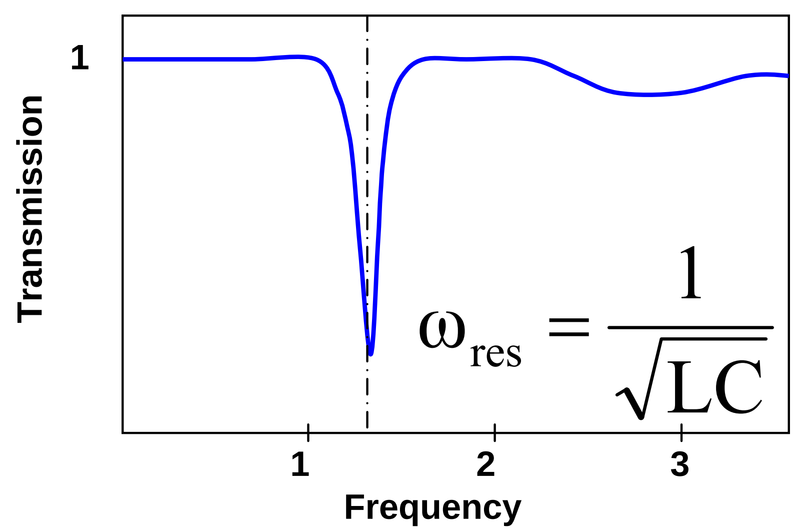
Double the ring to strengthen resonance



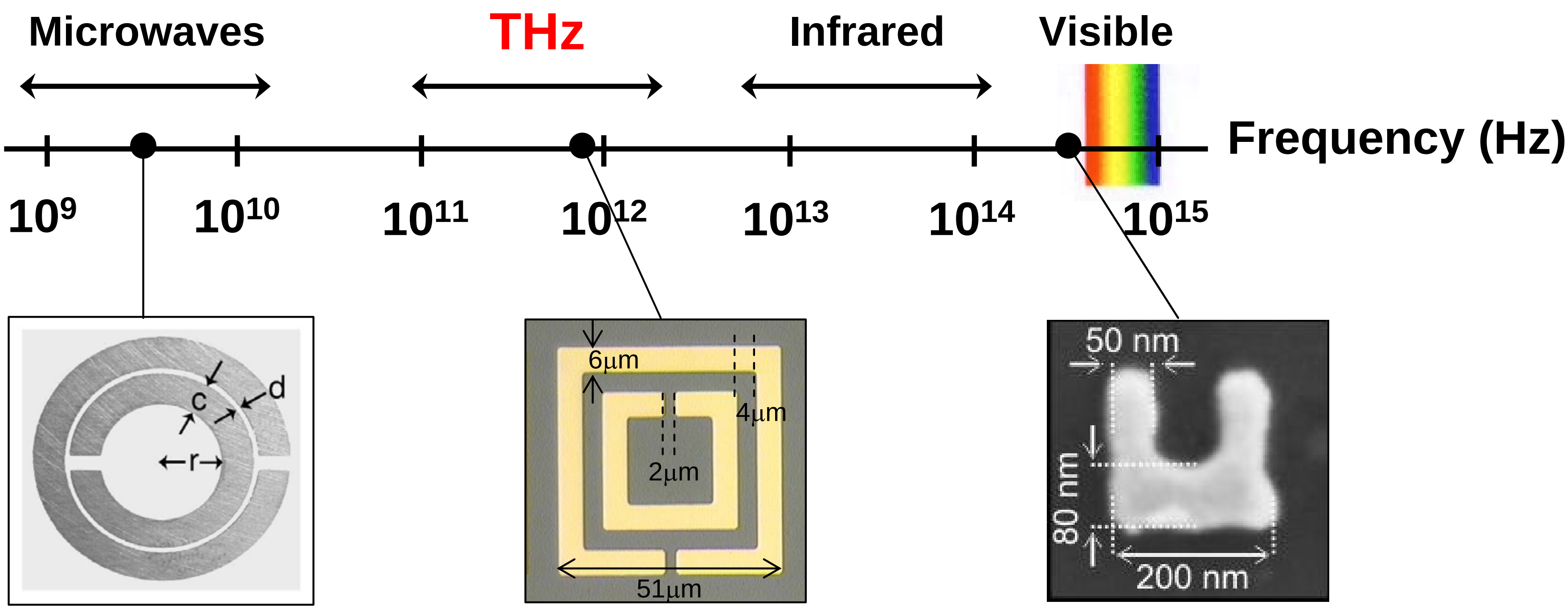
J.B. Pendry et al., IEEE Trans. Microwave Tech. **47**, 2075 (1999).

A current can also be induced by an electric field





Scaling the size of the metamaterials changes the resonant frequency



PCB boards

c = 0.8 mm
d = 0.2 mm
r = 1.5 mm

Standard photolithography

Electron Beam or Focused Ion Beam lithography

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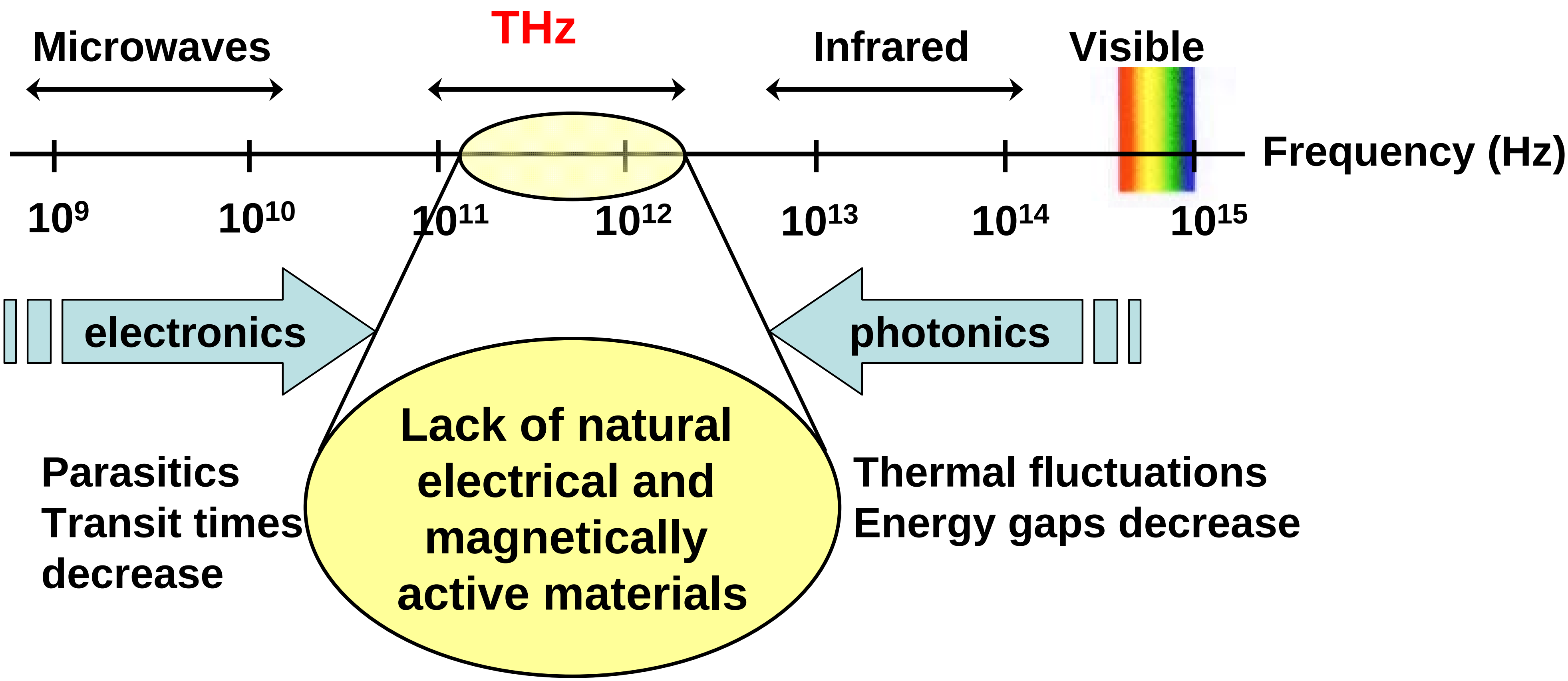
Metamaterials can help bridge the THz gap



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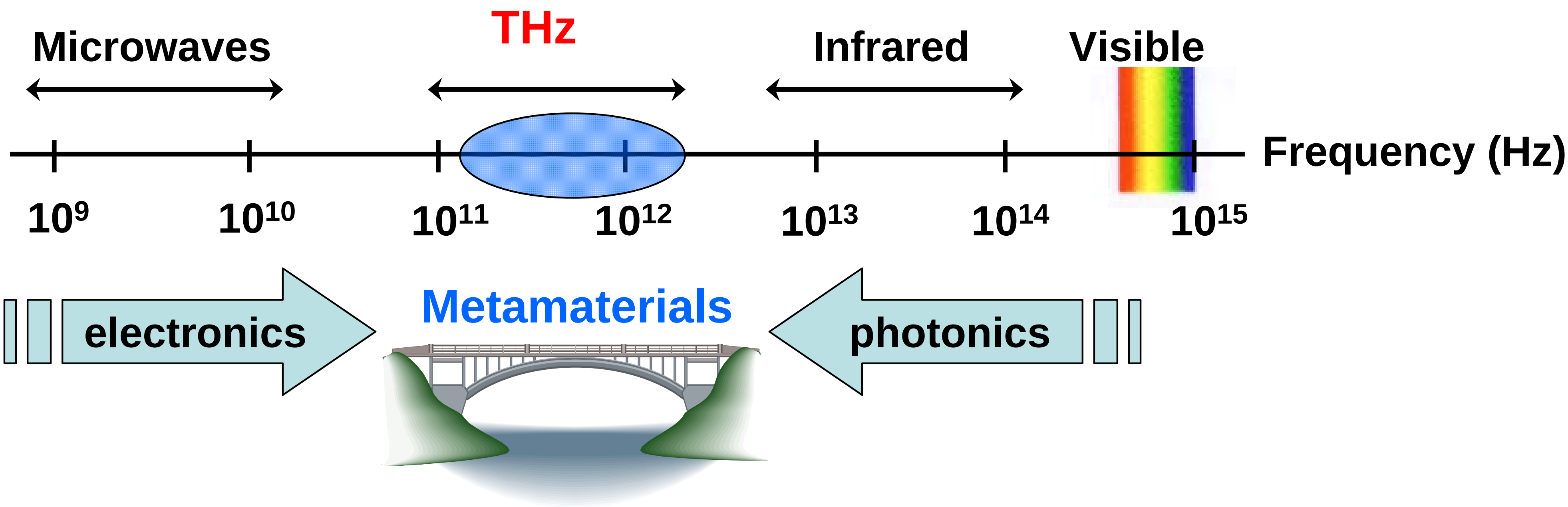
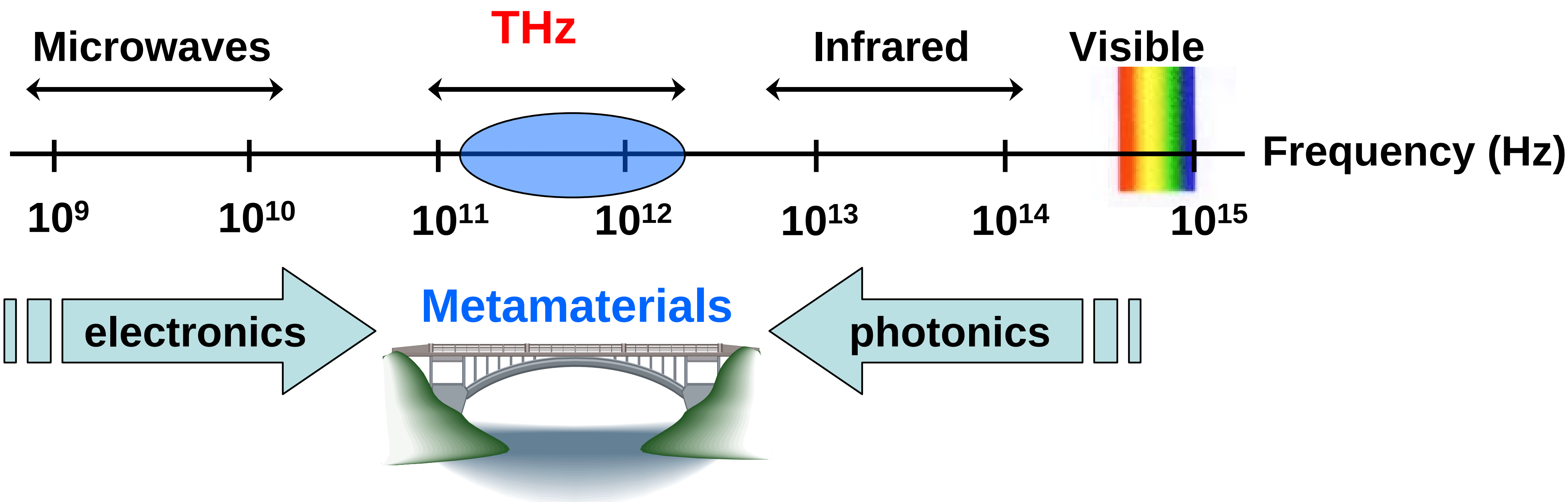
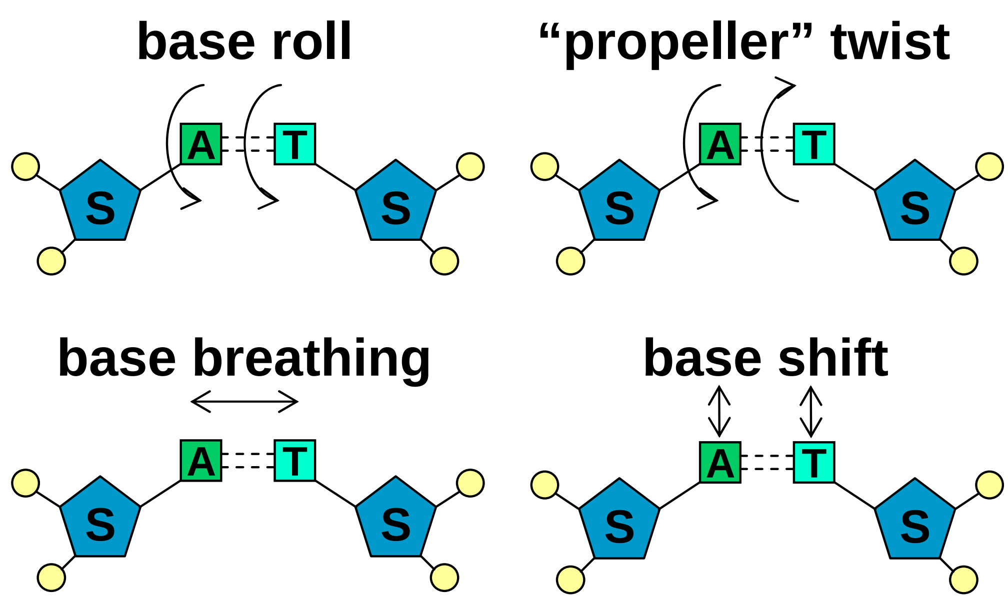
Metamaterials can help bridge the THz gap



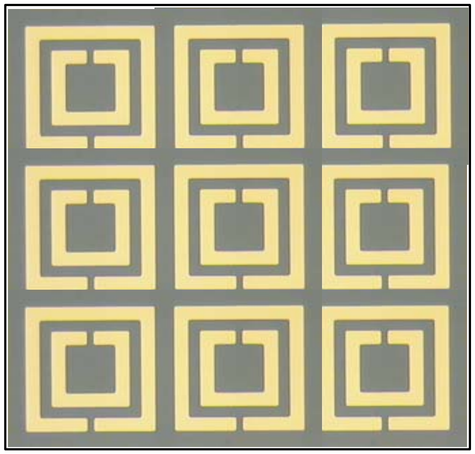
Metamaterials can help bridge the THz gap and interrogate biomolecules is new ways



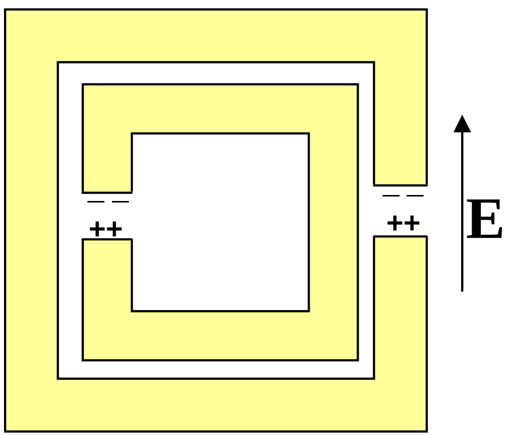


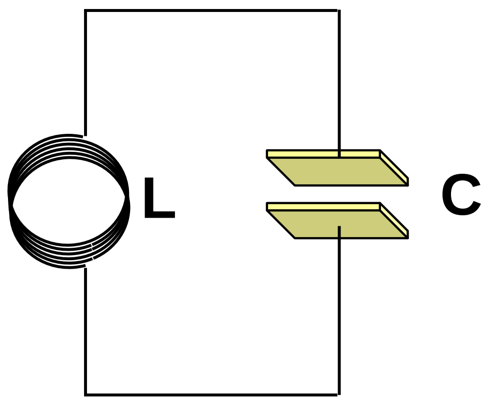
Can we use THz metamaterials as chem-bio sensors?

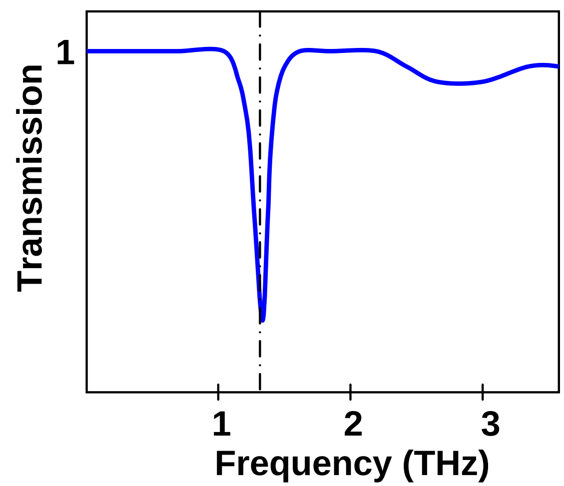
YES! We can use the sensitivity of metamaterials to the dielectric environment as a sensing mechanism



$$\omega_{res} = \frac{1}{\sqrt{LC}}$$







There is a shift in the resonance due to a change in capacitance.

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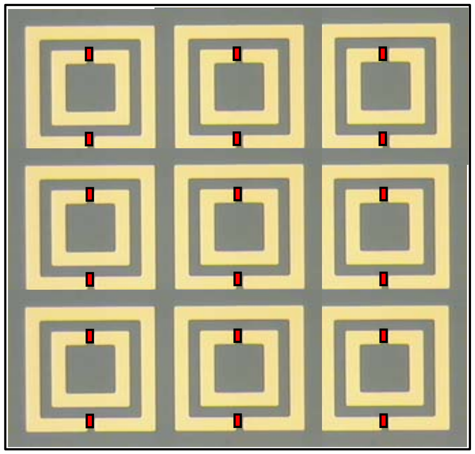
YES! We can use the sensitivity of metamaterials to the dielectric environment as a sensing mechanism



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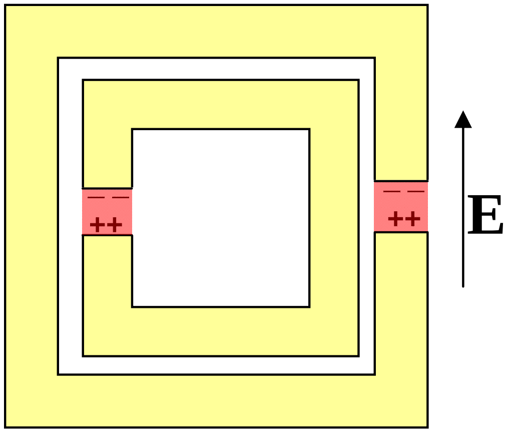
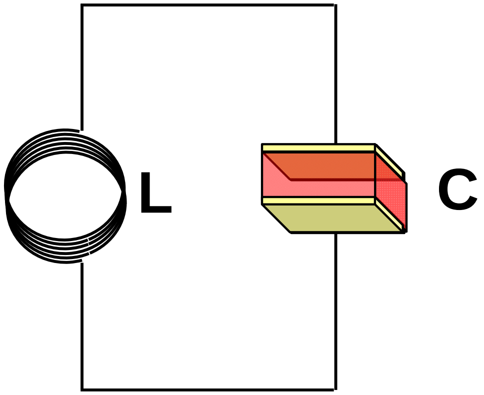
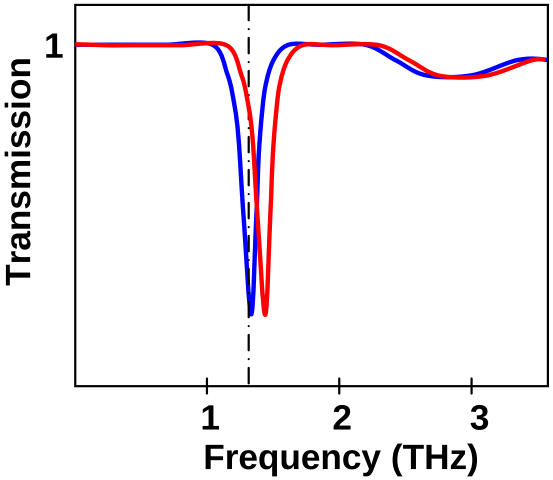
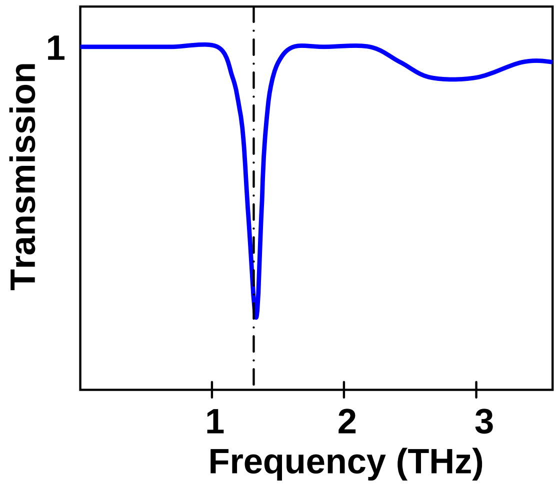






There is a shift in the resonance due to a change in capacitance.

Change in capacitance combined with resonant absorption enhances detection



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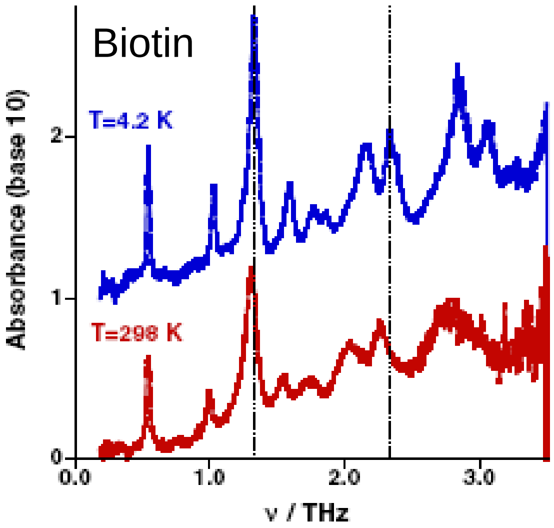

T. M. Korter et al., Chem. Phys. Lett., 385 (2004) 45.

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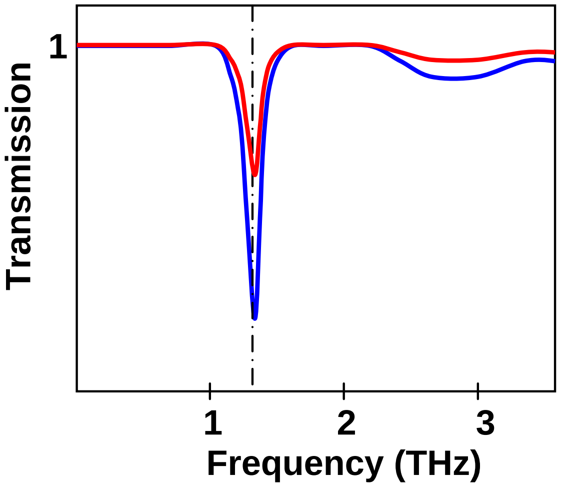
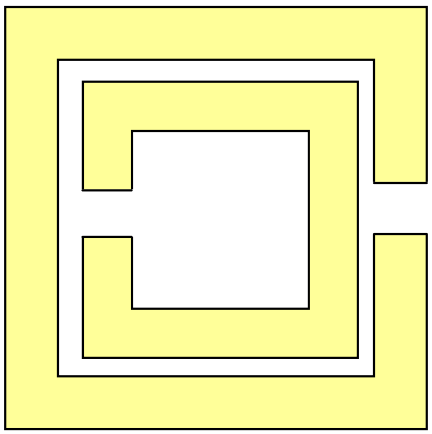
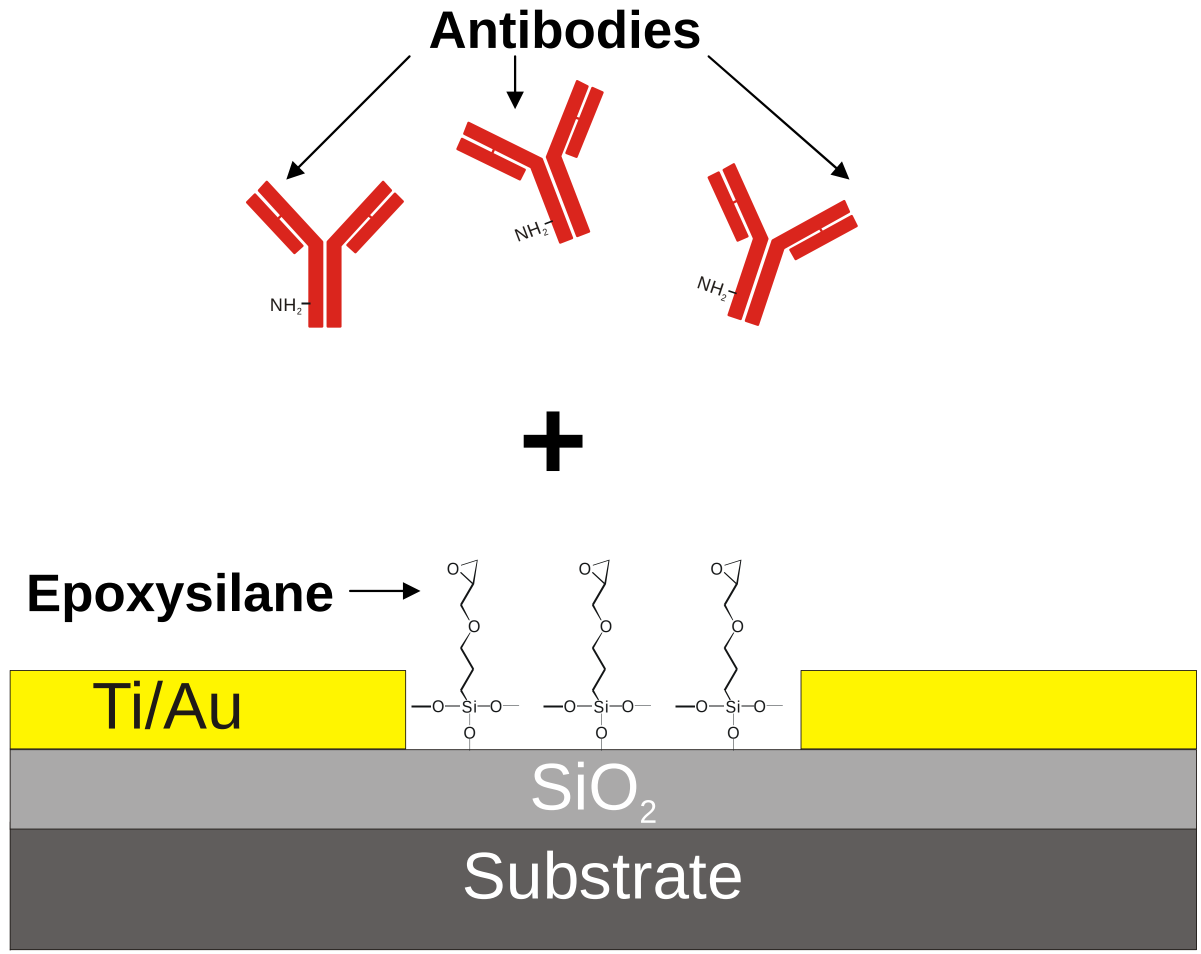


Surface functionalization uses linker molecules to attach biomolecules to inorganic surfaces

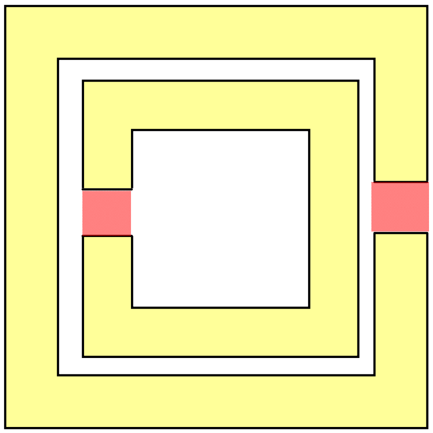


Top view

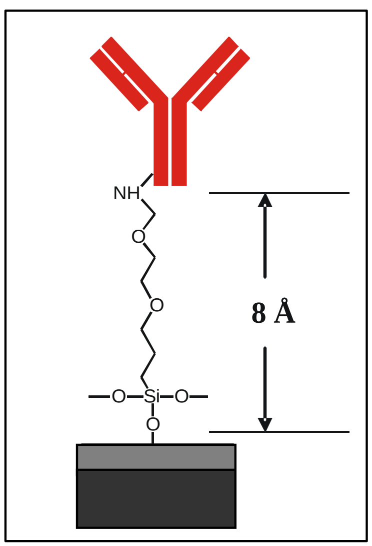


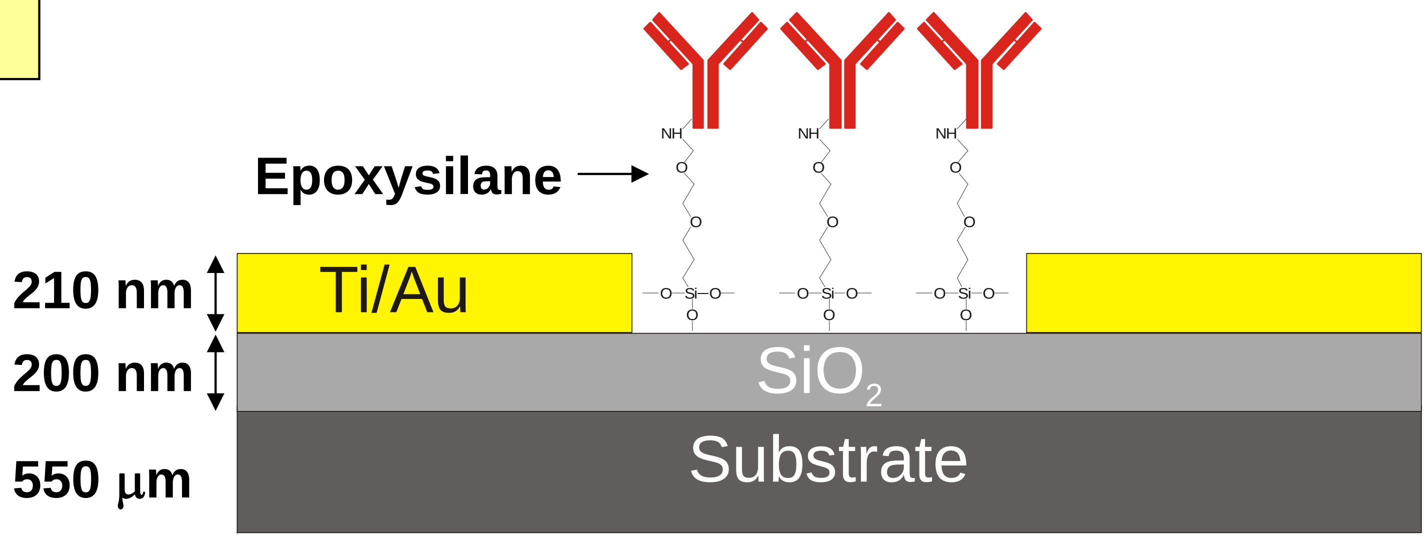
Side view

Surface functionalization uses linker molecules to attach biomolecules to inorganic surfaces



Top view





Side view

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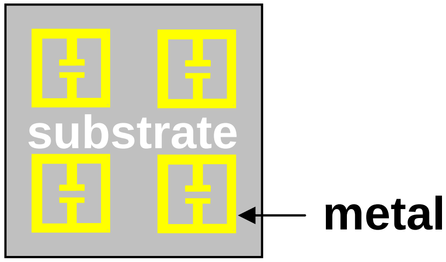
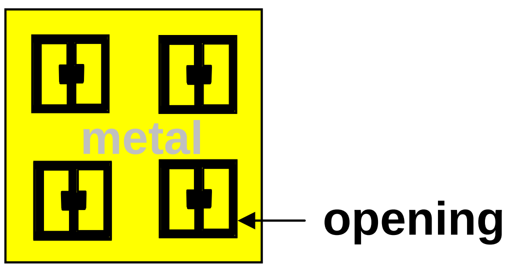
Demonstration of surface functionalization

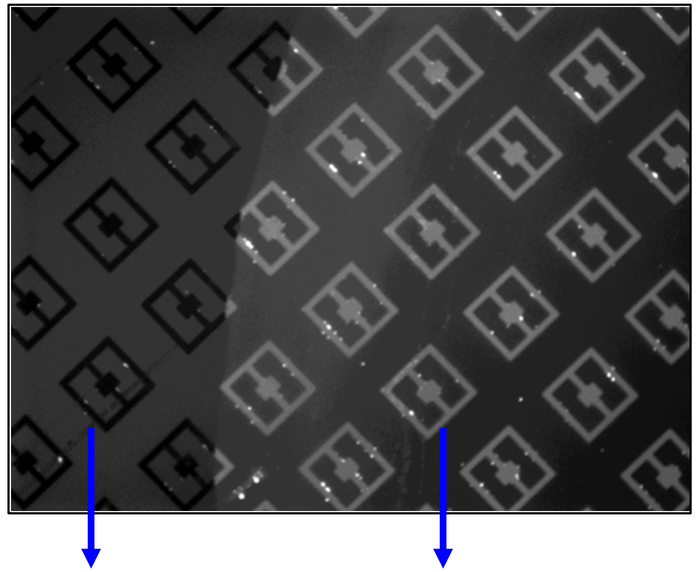


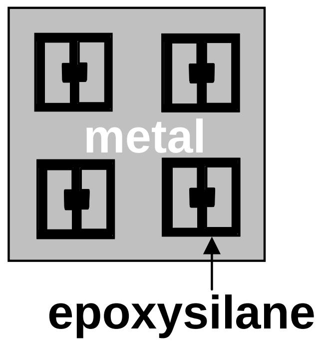
Regular metamaterial

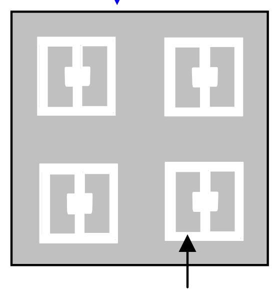


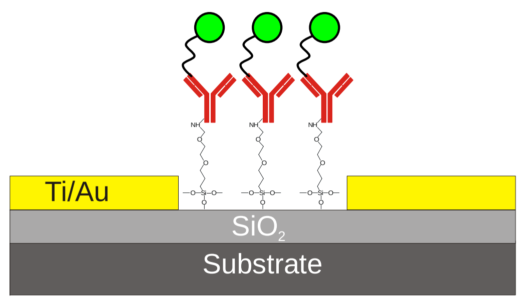
Complementary pattern for functionalization

Functionalized metamaterial









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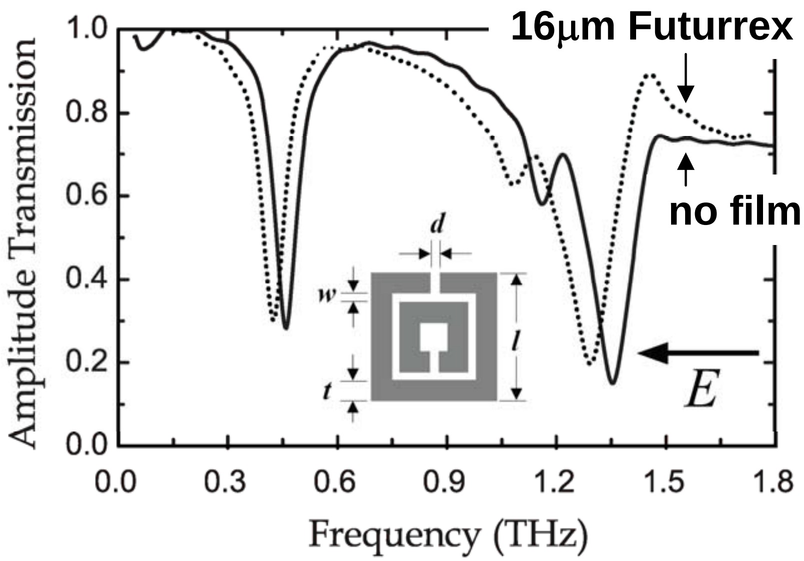
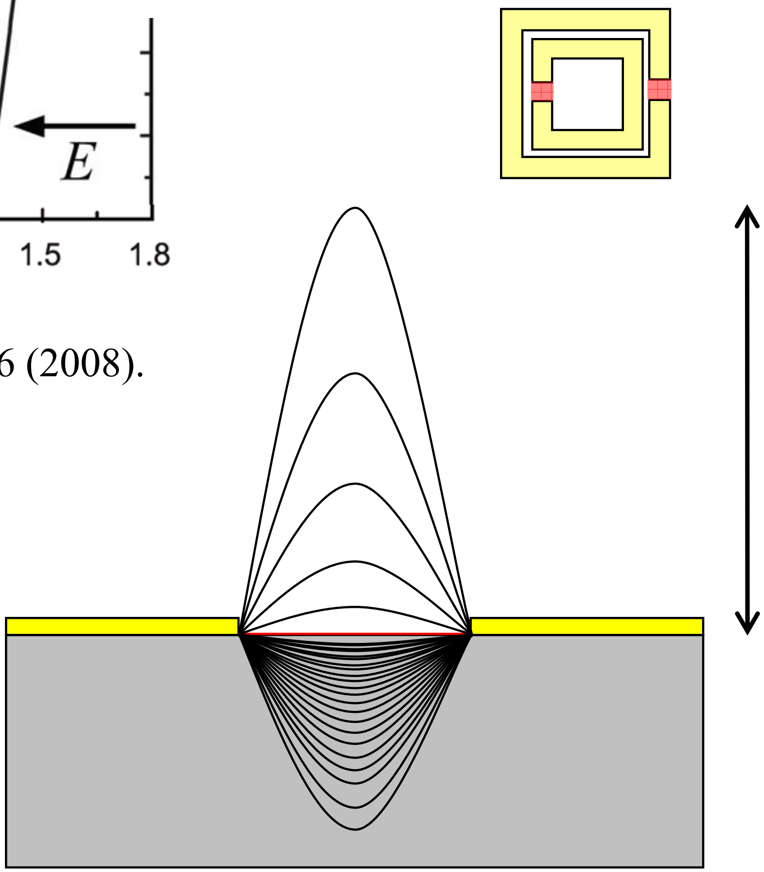
There exist several challenges in detecting a monolayer of biomolecules



R. Singh et al., Opt. Exp. 16, 1786 (2008).

Linewidth limits sensitivity



Fringing fields extend ~20μm

Concentration of electric flux in the substrate

Can we eliminate or reduce the substrate?

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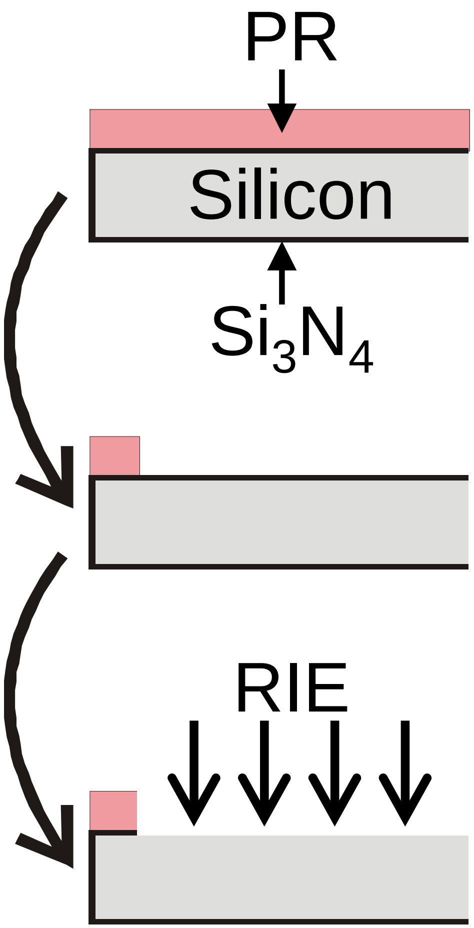
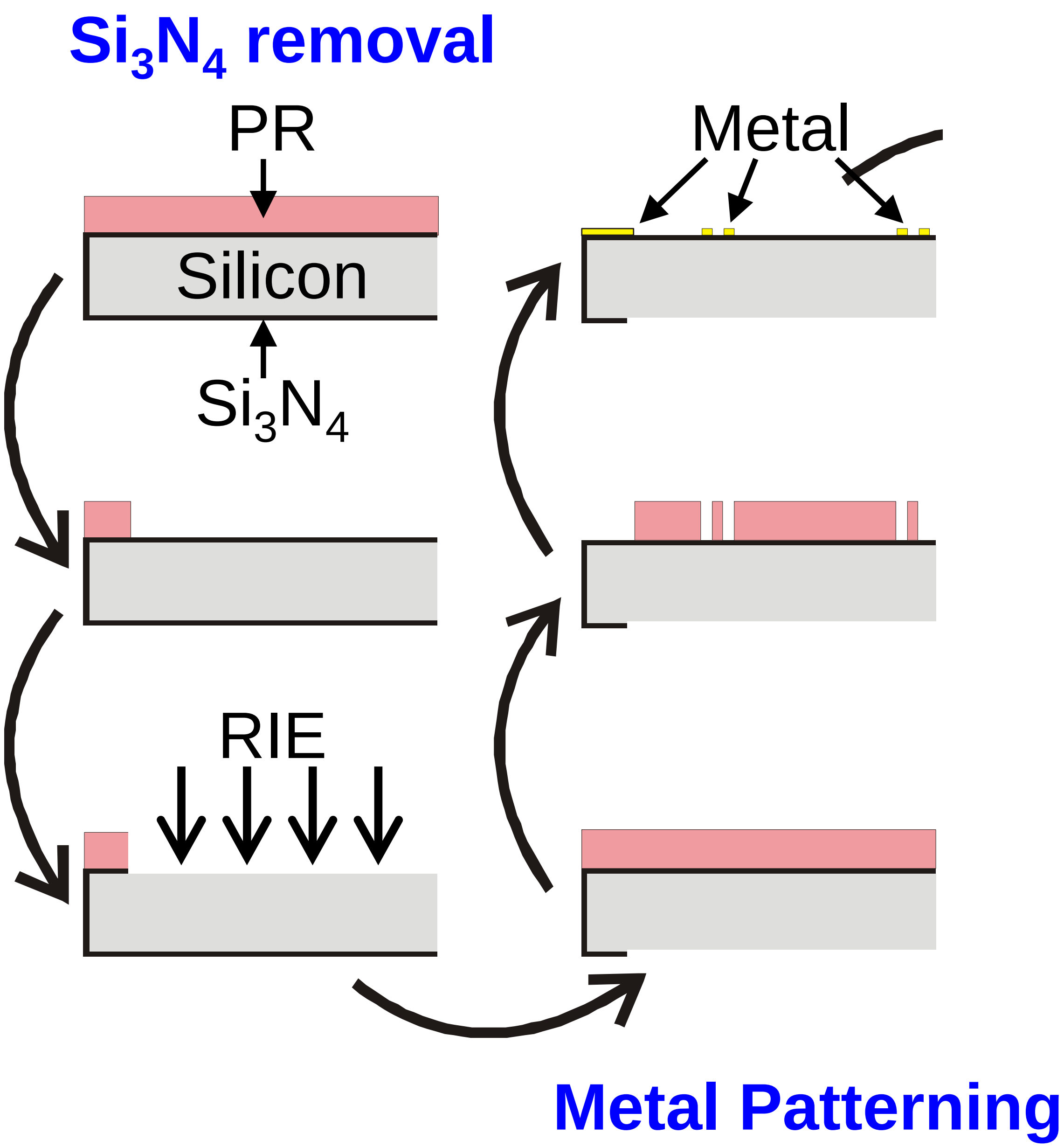
YES! We can fabricate THz metamaterials on silicon nitride membranes

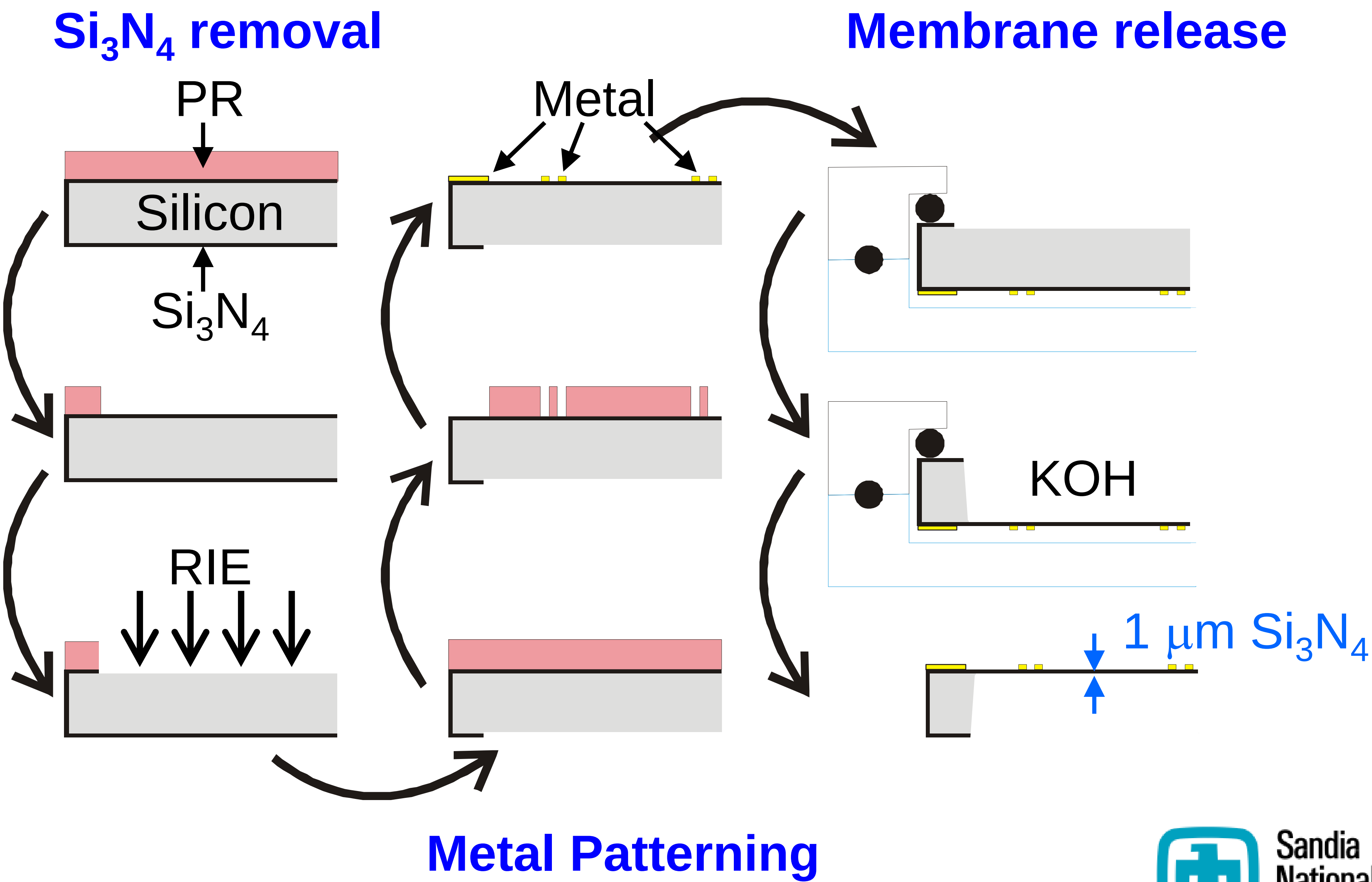
Si_3N_4 removal



YES! We can fabricate THz metamaterials on silicon nitride membranes



YES! We can fabricate THz metamaterials on silicon nitride membranes



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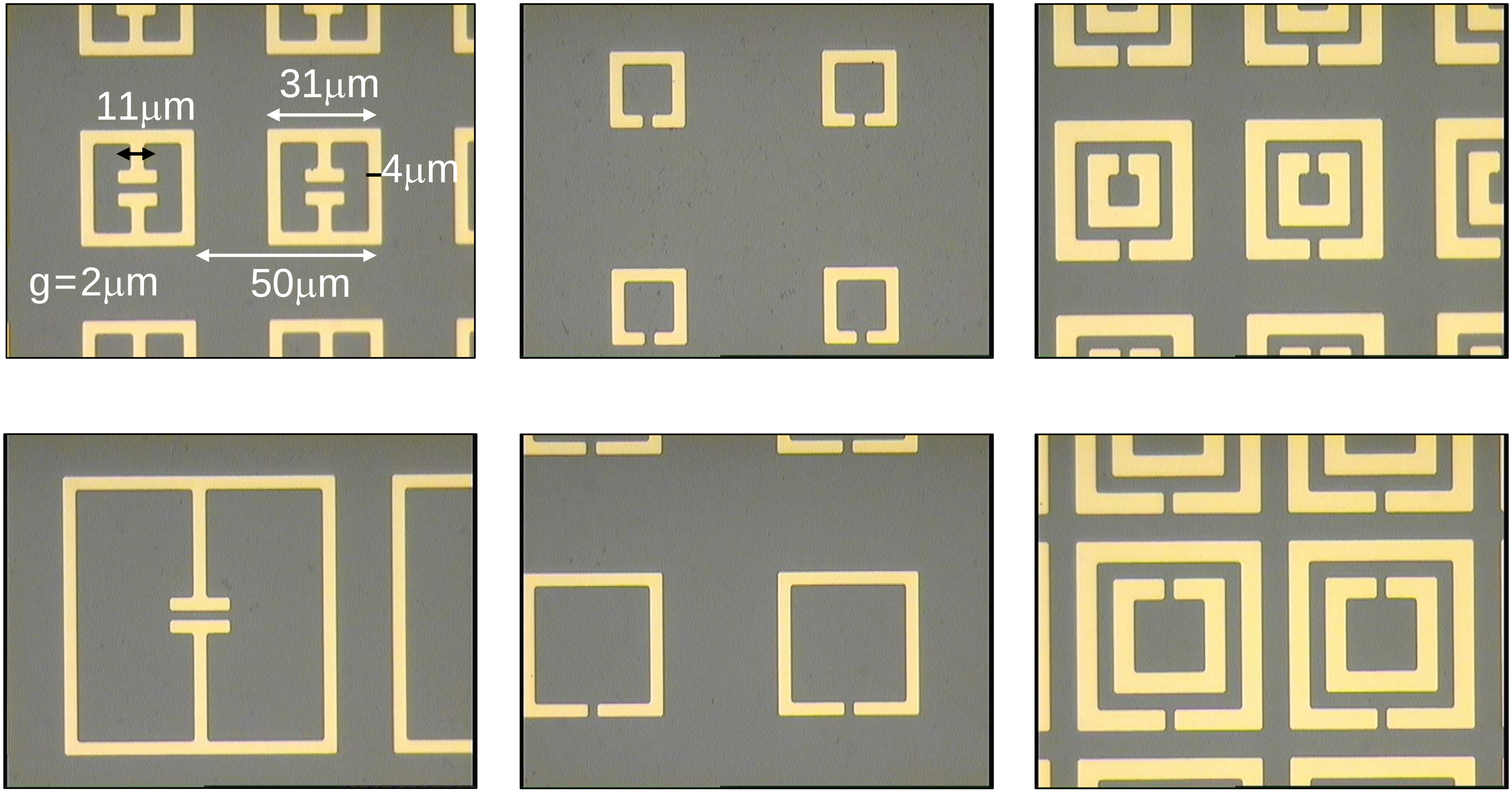
Designed 15 different THz metamaterials per wafer



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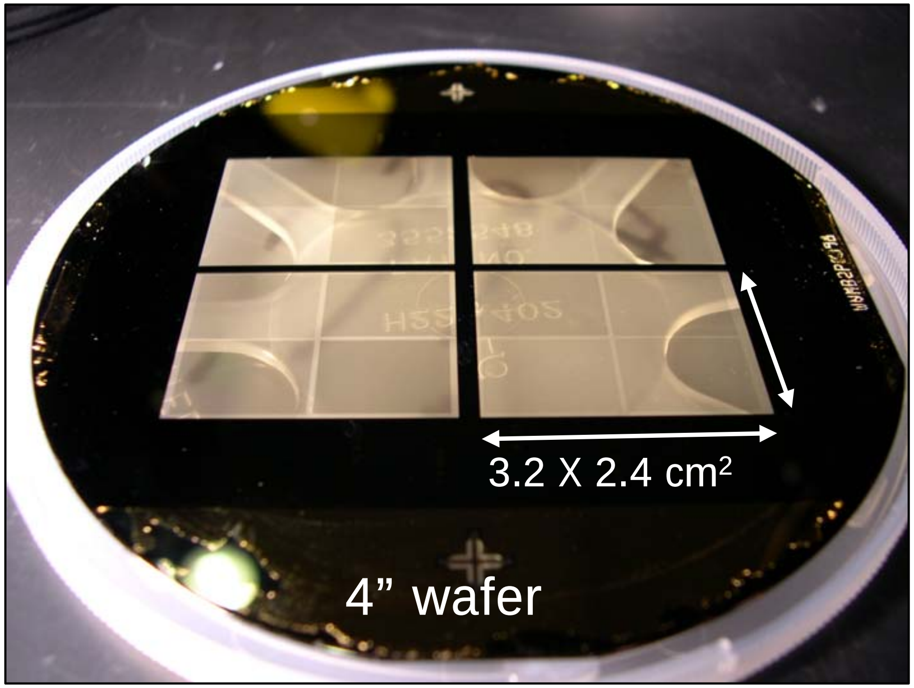
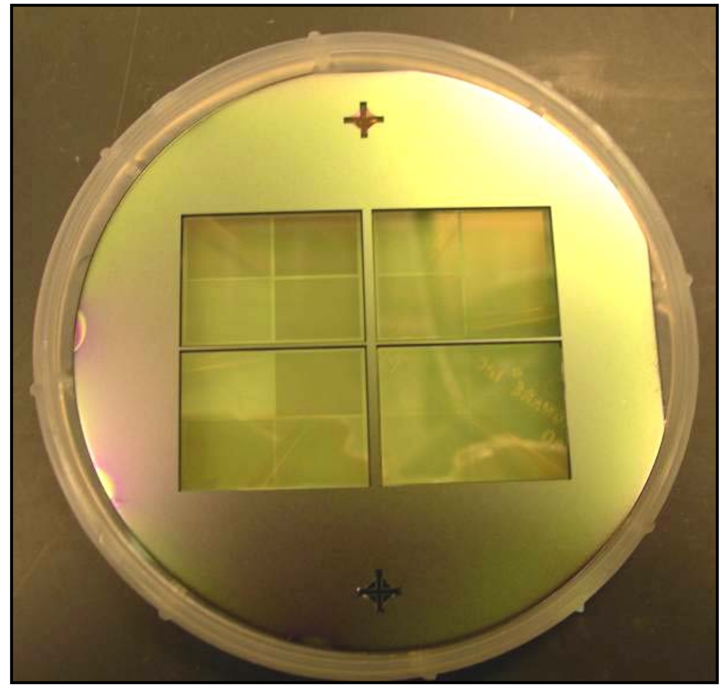
THz metamaterials on four 1μm thick free-standing silicon nitride windows in a 4” wafer



Back side



Front side

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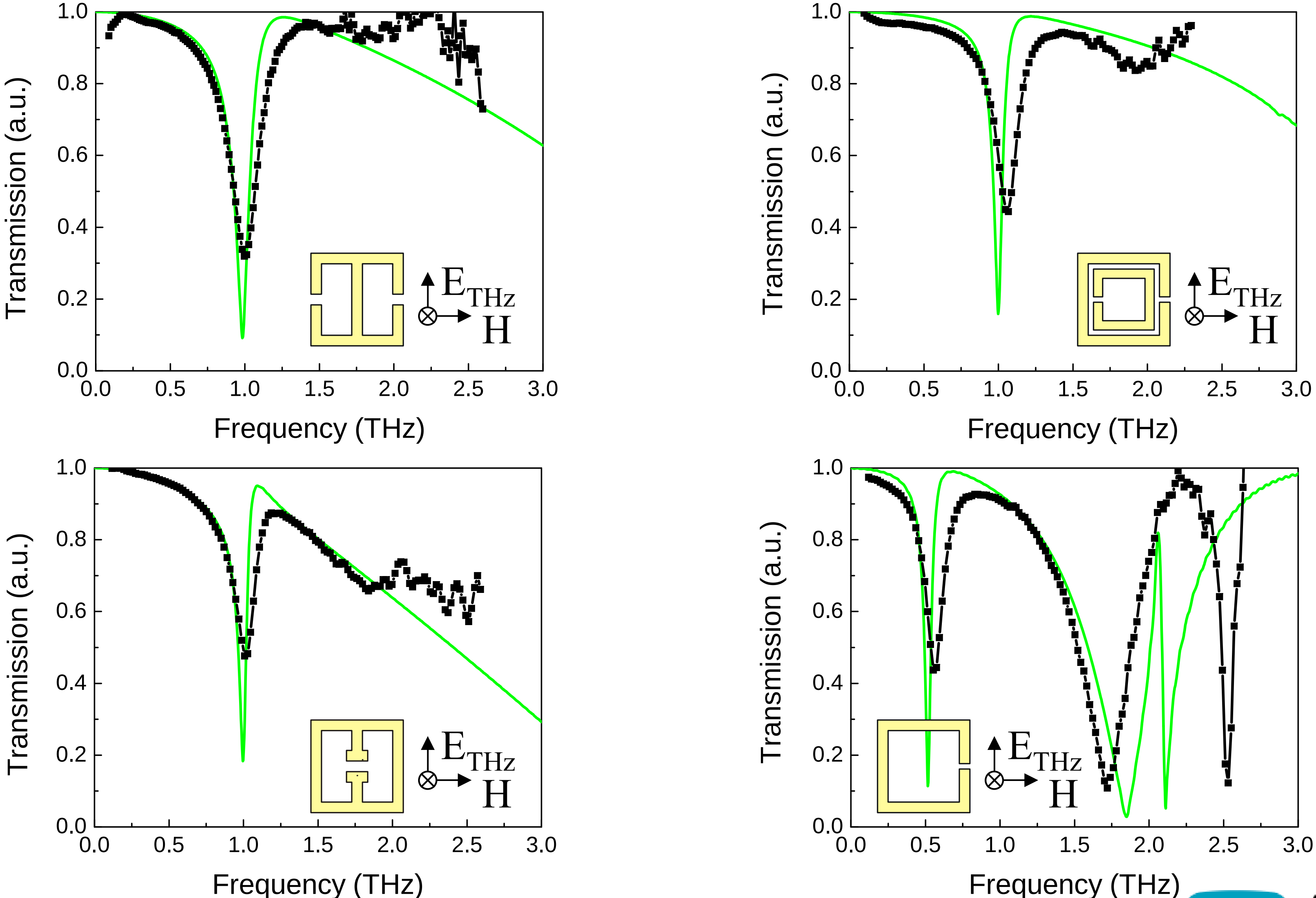
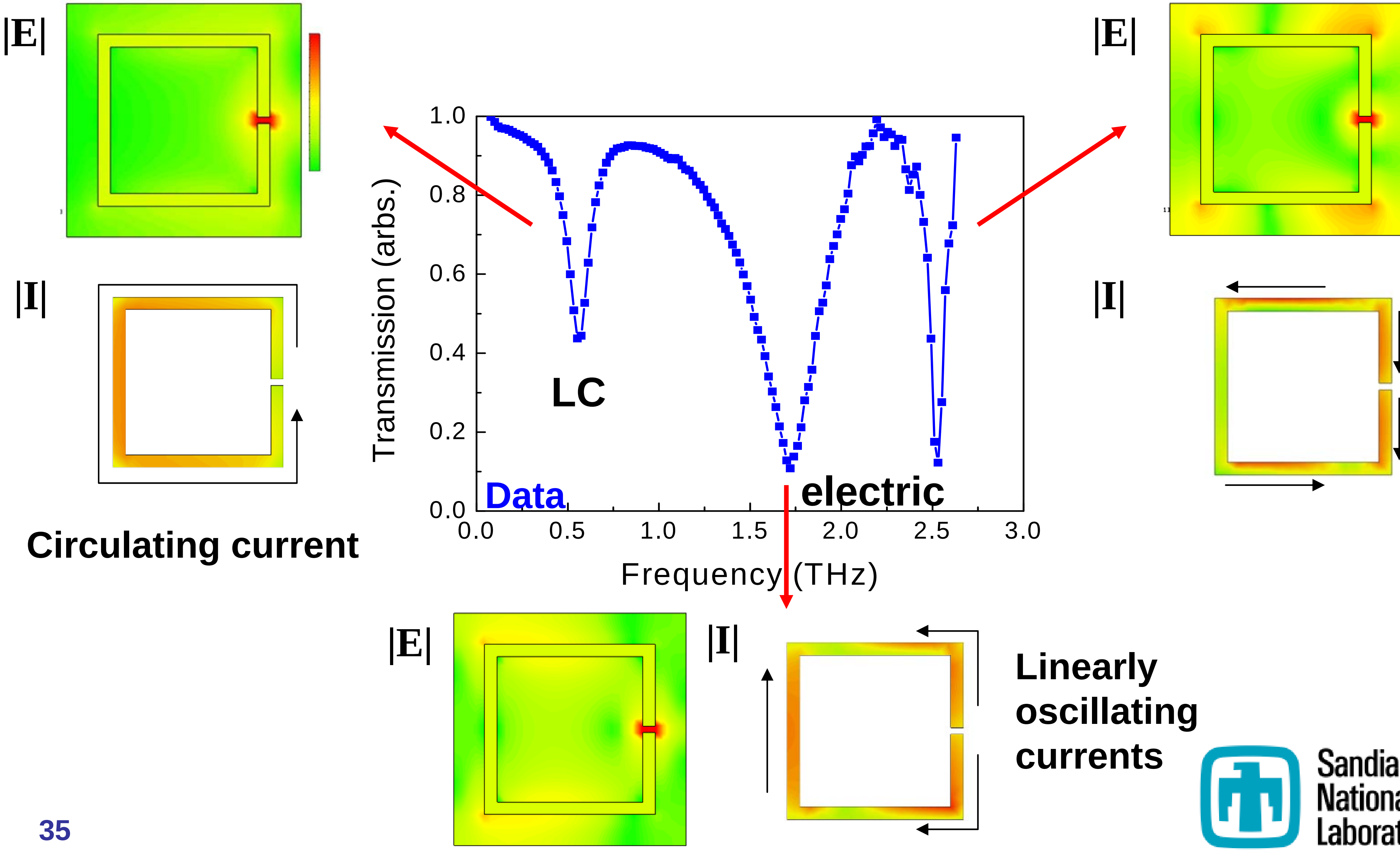
Experiment and electromagnetic modeling of THz transmission spectra

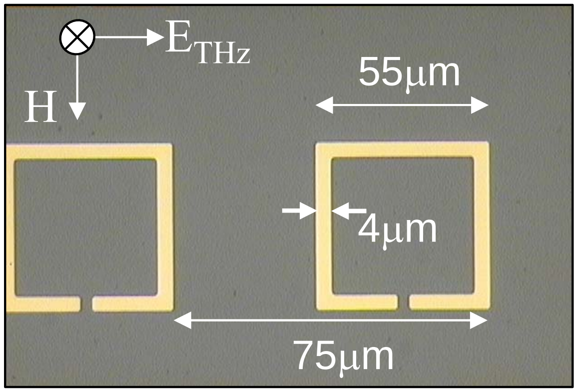


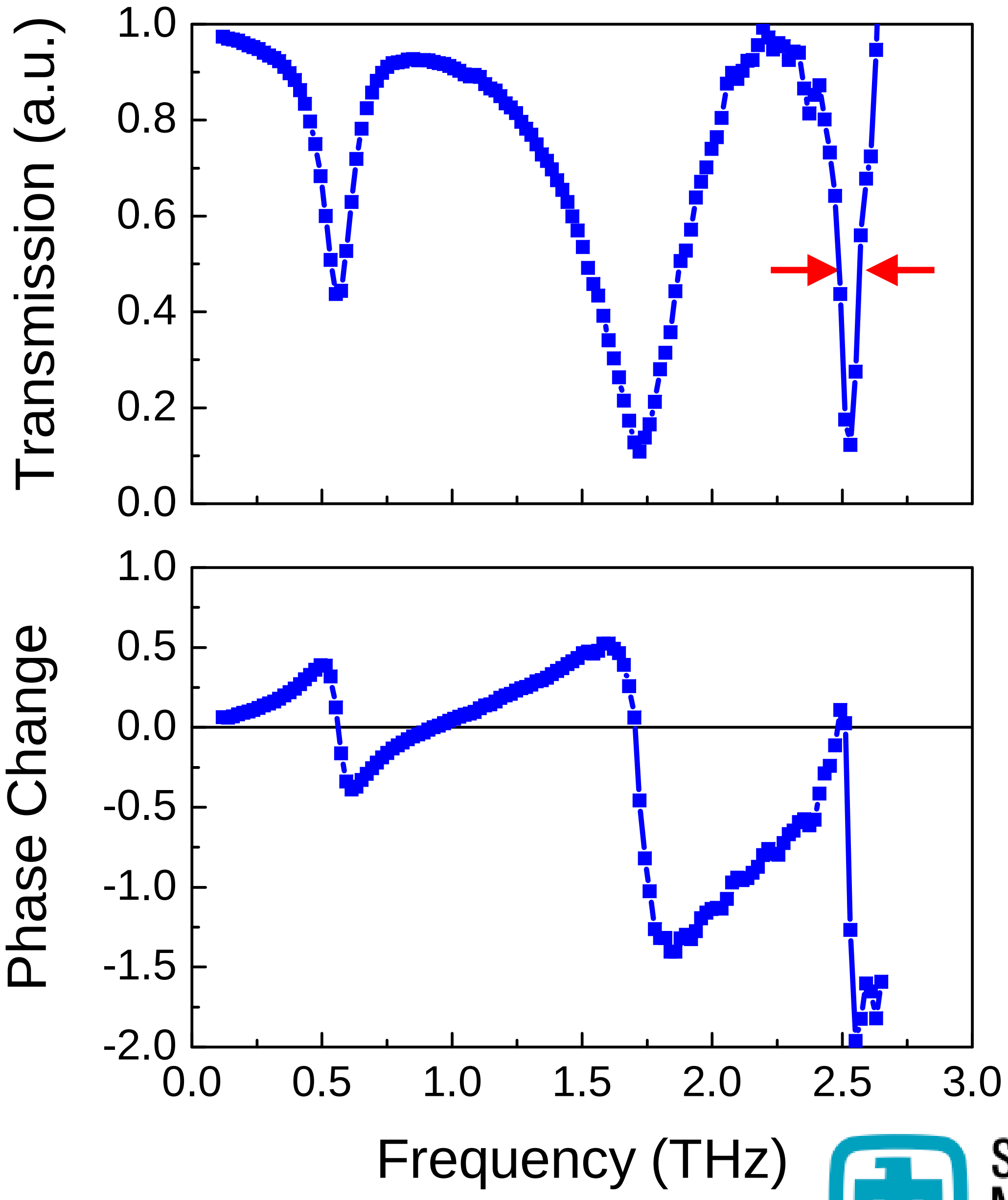
Electromagnetic modeling informs us about the origin of the resonances

E-field enhancement



THz response of a split-ring resonator on silicon nitride has a narrow resonance line width





Dispersive behavior is a signature of a resonance.

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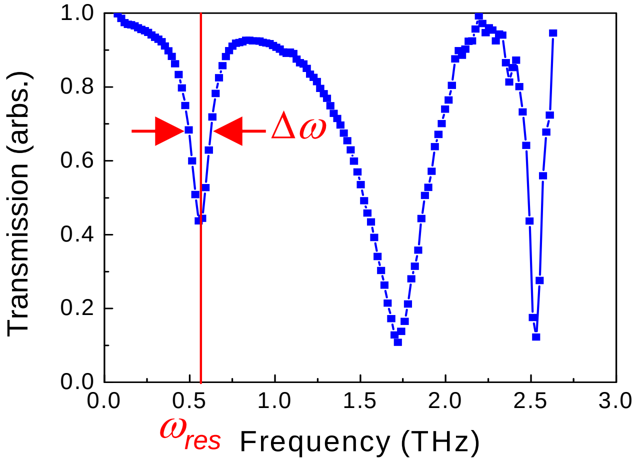
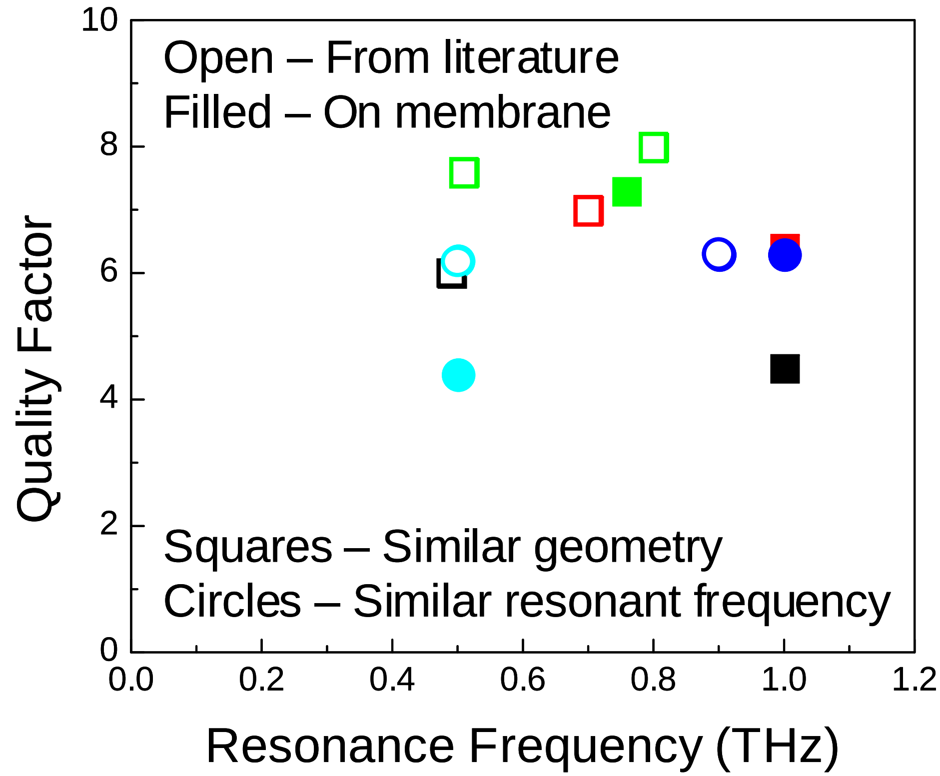
Comparison between metamaterials on thick substrates and on thin membranes



$$Q = \frac{\omega_{res}}{\Delta\omega}$$



	Literature	**Membrane**
Substrate	**Quartz, GaAs, Si**	**Si_3N_4**
Thickness	**1.03 mm – 640 μm**	**1 μm**
Metallization	**3 μm – 200 nm**	**70 nm**

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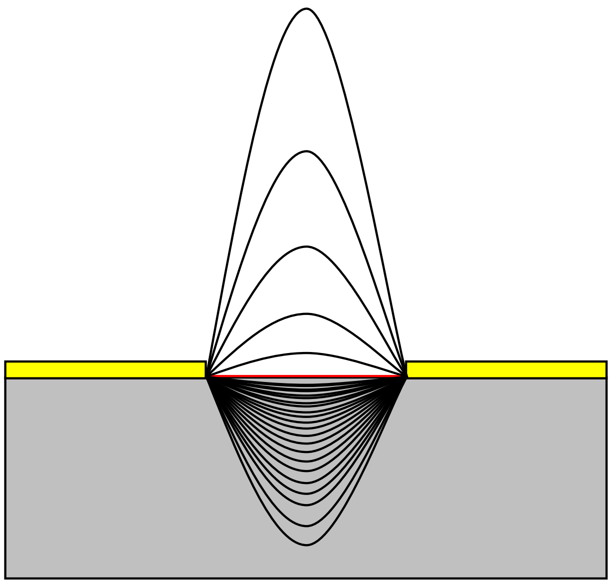
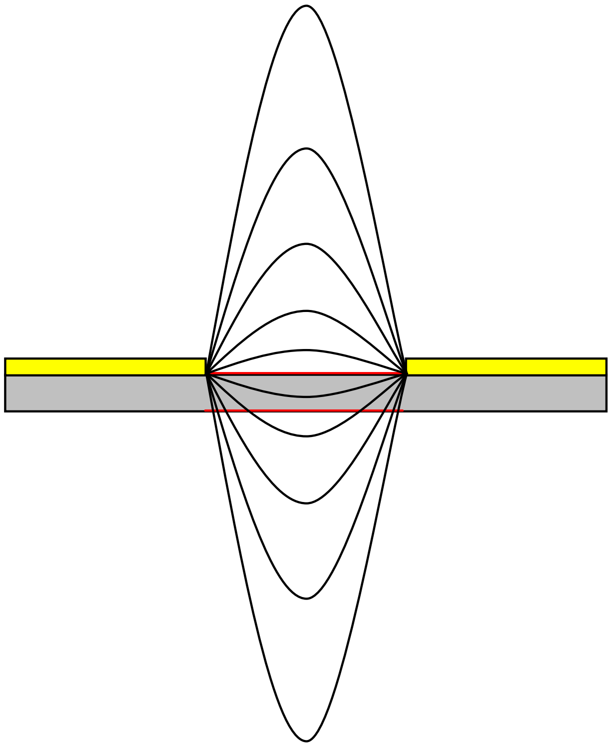
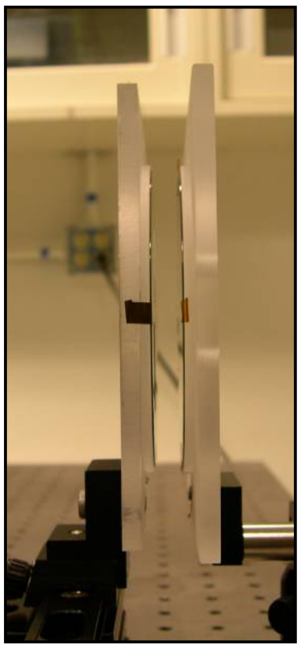
Thin membranes impose symmetry on the electric flux distribution and twice the access to molecules

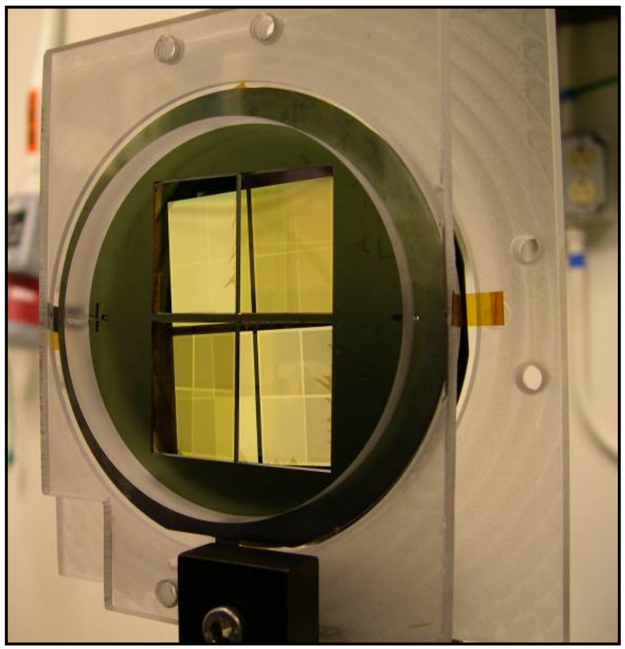


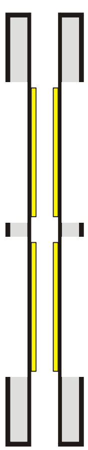


Need to fabricate 3D structures

Metamaterials on thin membranes provide a path towards quasi-3D structures by layering

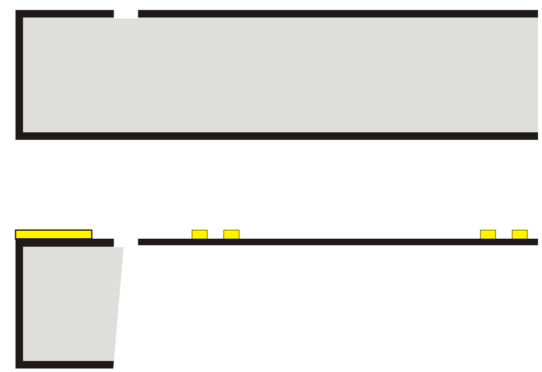






Limited to two layers due to substrate thickness.

Future Work:
Membrane removal



Allows multilayer stacking.

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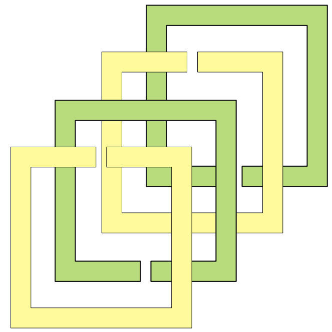
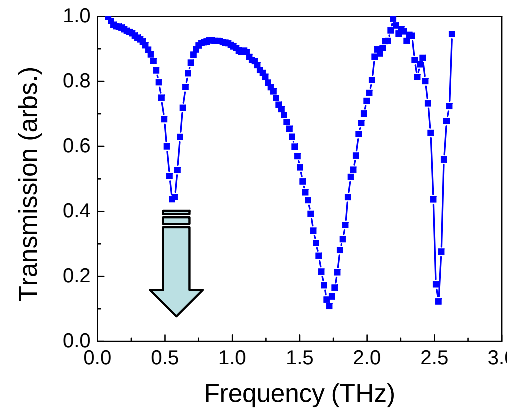
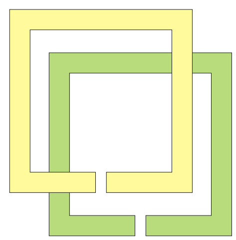
Multi-layer structures allow studies of coupling and symmetry

Number of layers

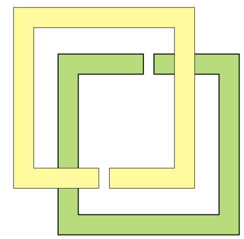




Orientation of the resonators

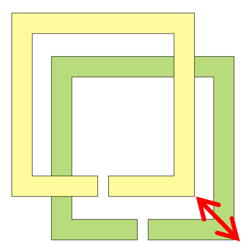


Symmetric



Antisymmetric

Separation between the layers



Periodic

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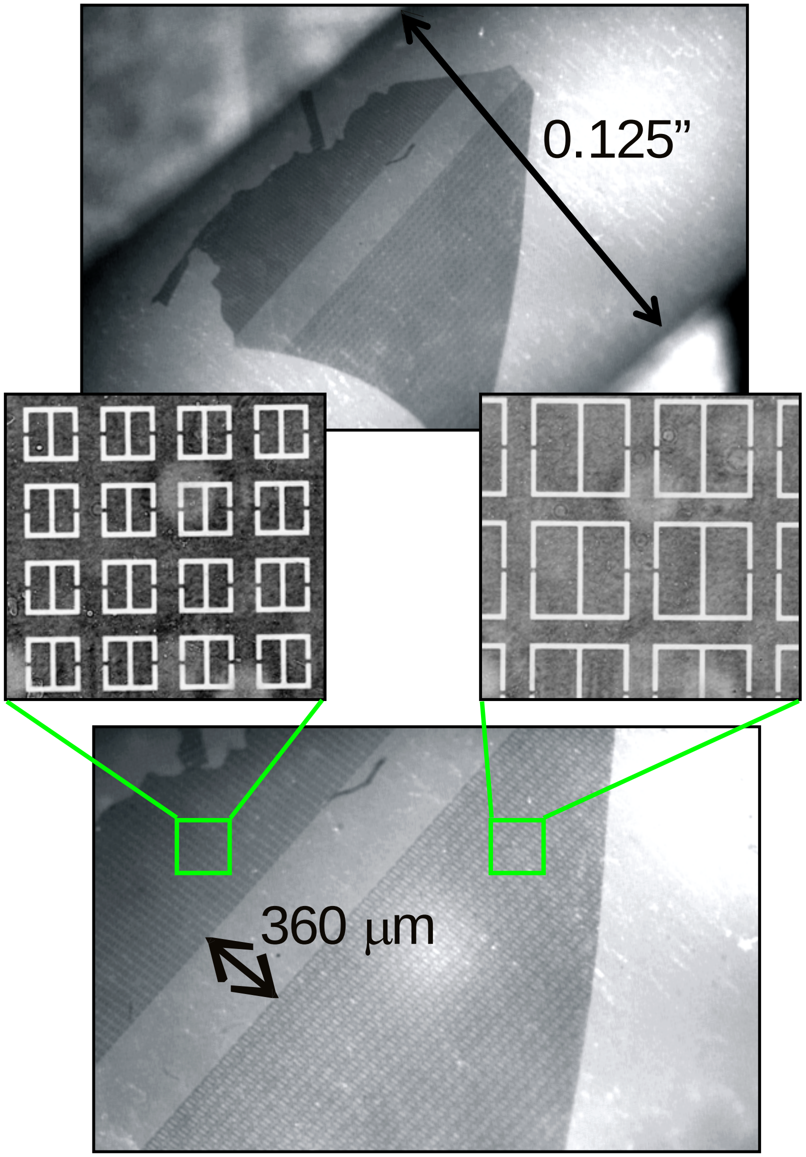
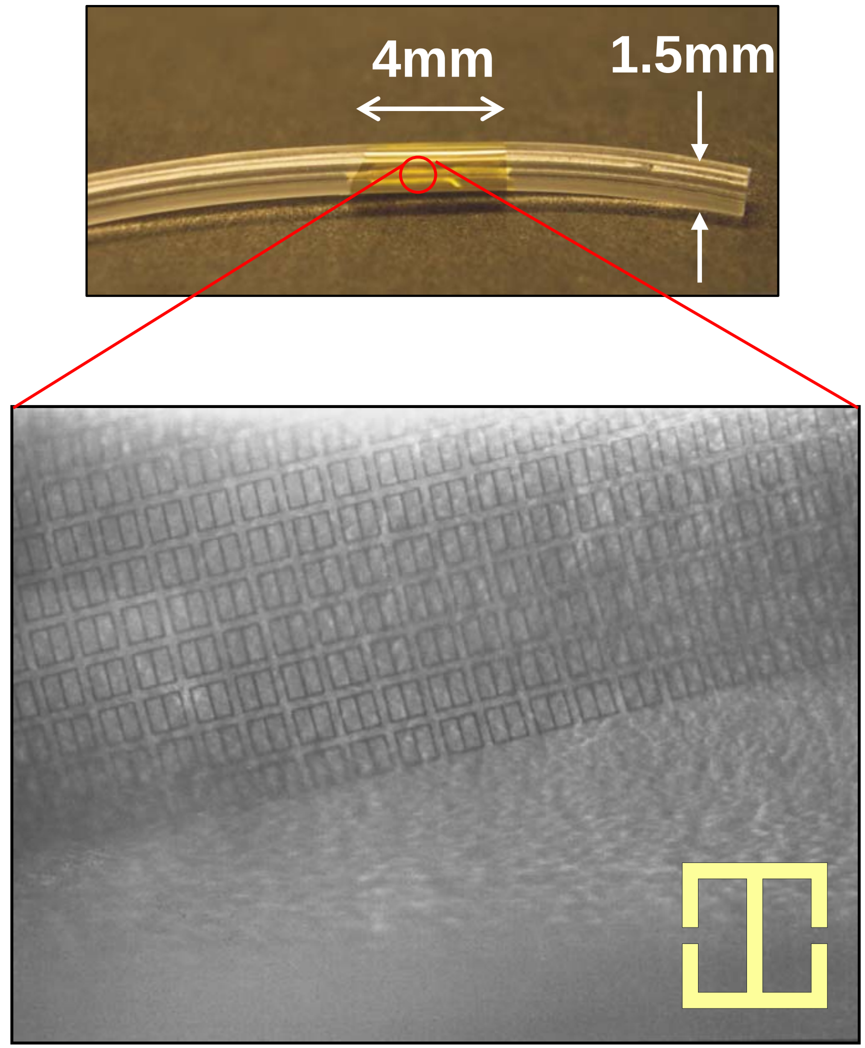
Releasing the membrane allows us to wrap it around curved surfaces





Membranes are ductile!

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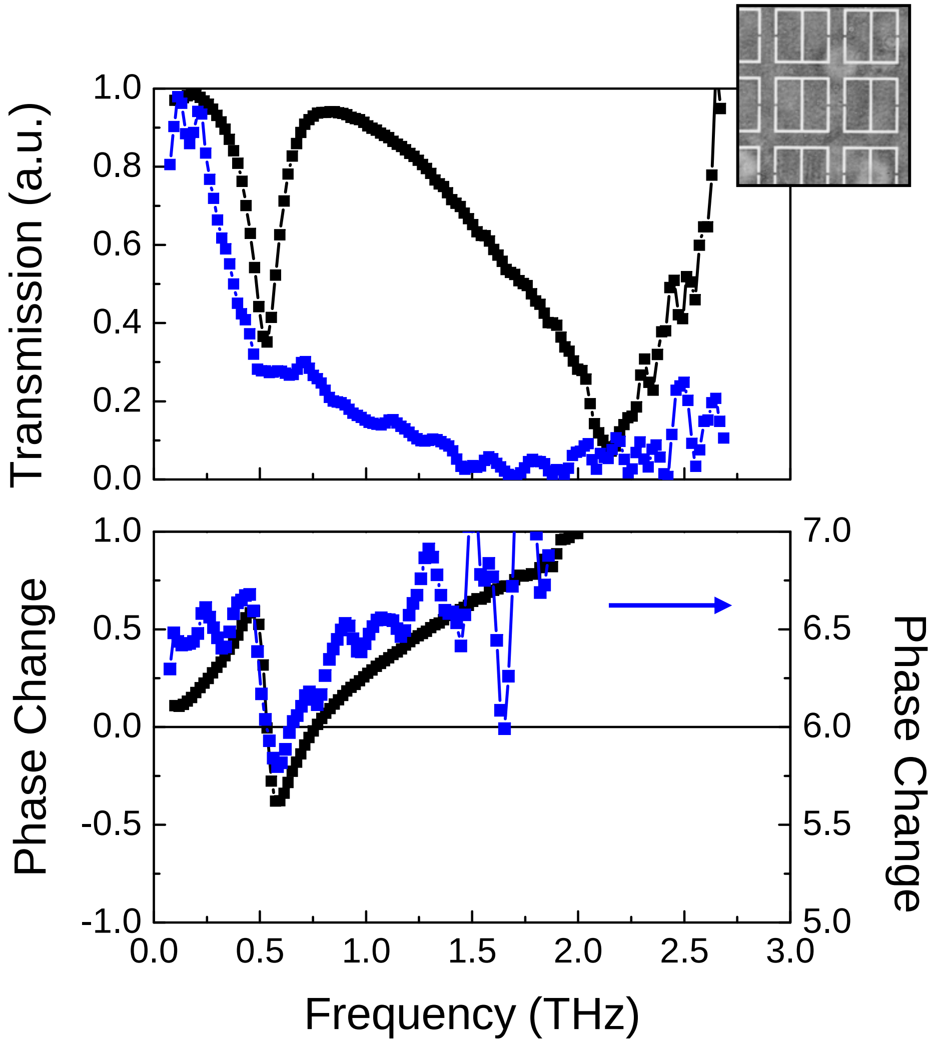
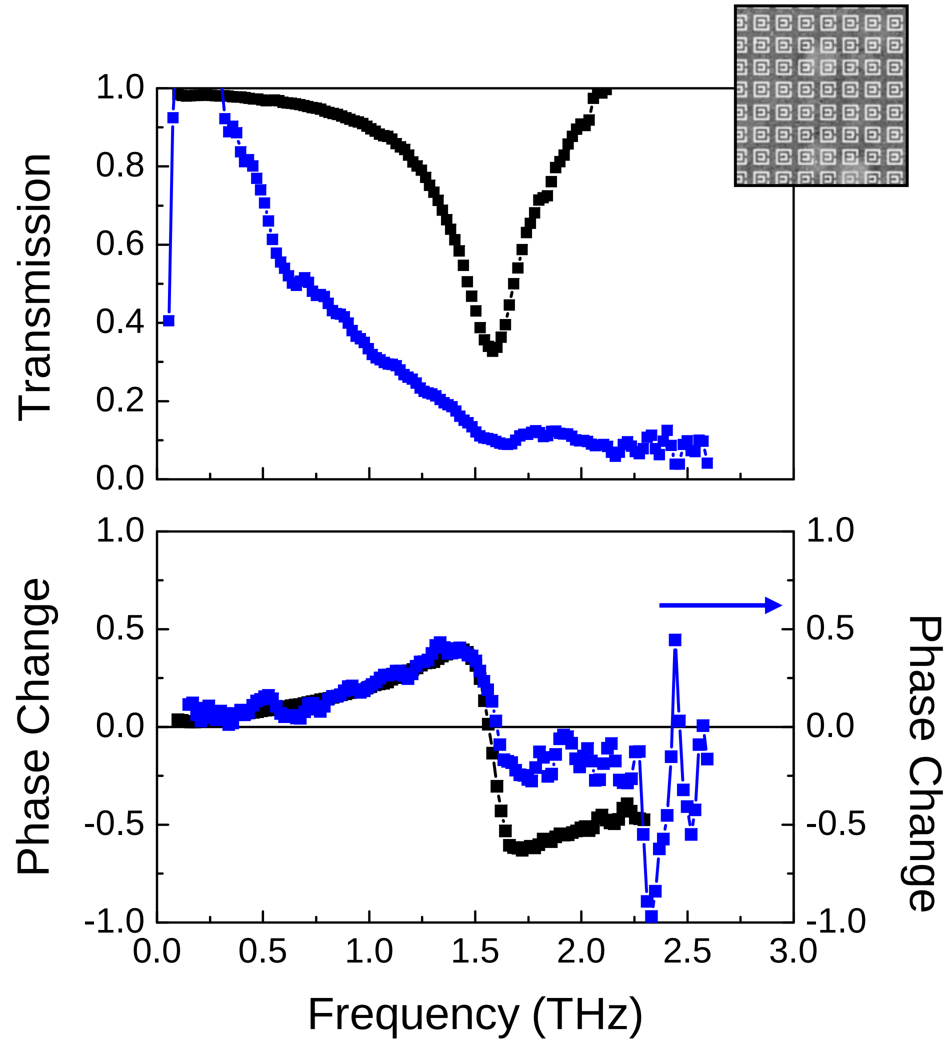
THz transmission spectra of a metamaterial covered membrane on a Teflon tube





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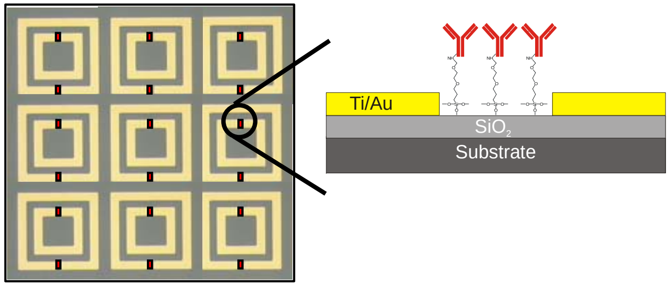
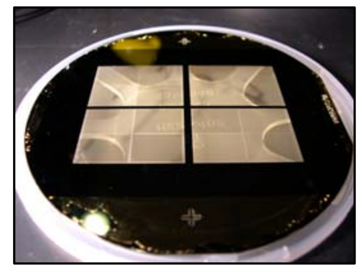
In summary, identification of a biosensing scheme furthers developments in THz metamaterials

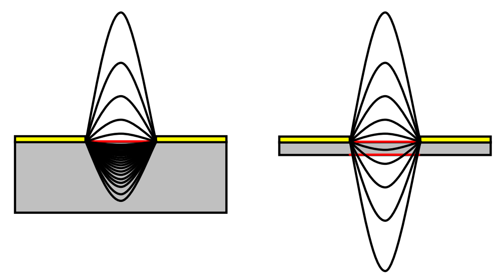


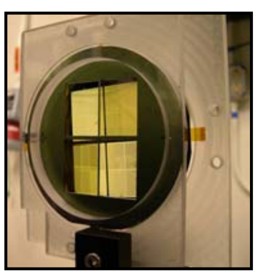
Developed a chem-bio detection scheme based on changes on the dielectric response of a metamaterial.

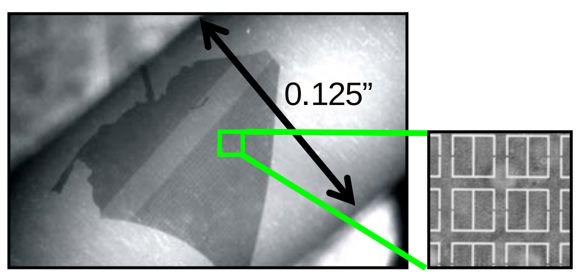


Metamaterials on large-area, free-standing, 1 μm thick silicon nitride membranes.

- **Obtained comparable quality factors to those fabricated on thick substrates.**
- **Implemented a double layer scheme.**
- **Identified a route for membrane liftoff.**
- **First implementation and characterization of curved THz metamaterials.**







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