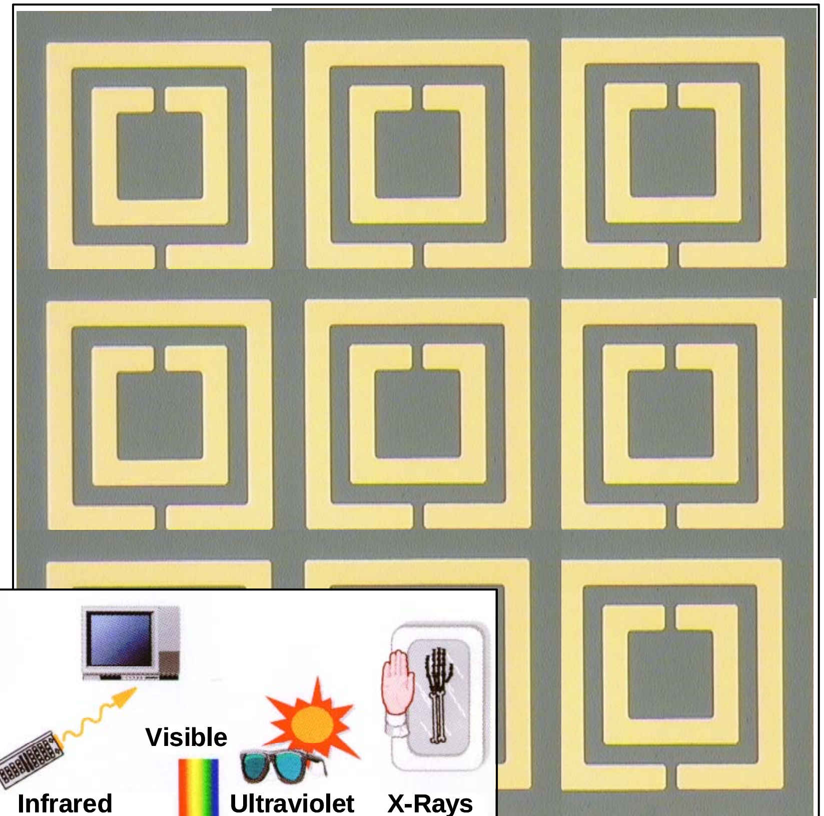
SAND2008-1754P

Harnessing the Electromagnetic Properties of Metamaterials: From Biosensors to Terahertz Devices

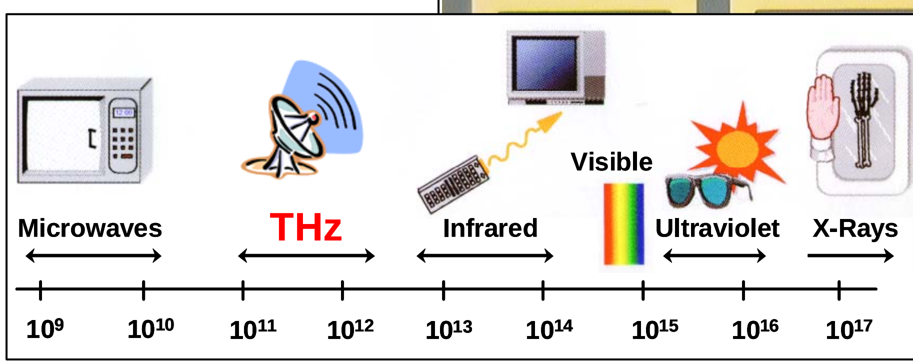


Xomalin G. Peralta, Ph. D.

IC Postdoctoral Fellow

Applied Photonic Microsystems
Sandia National Laboratories

February 22, 2008



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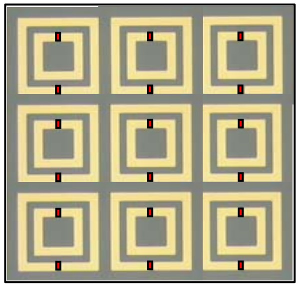
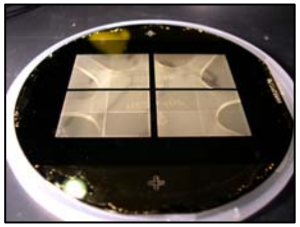
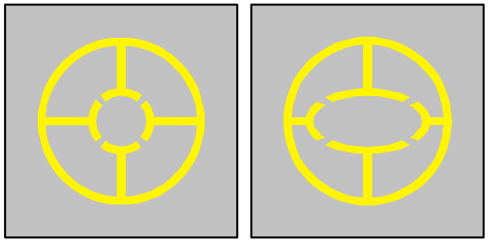
This talk presents metamaterial structures that enable studies of the interaction of light with matter



Metamaterials for chemical or biological sensing



Metamaterials on free-standing silicon nitride membranes



Polarization insensitive and polarization sensitive metamaterials

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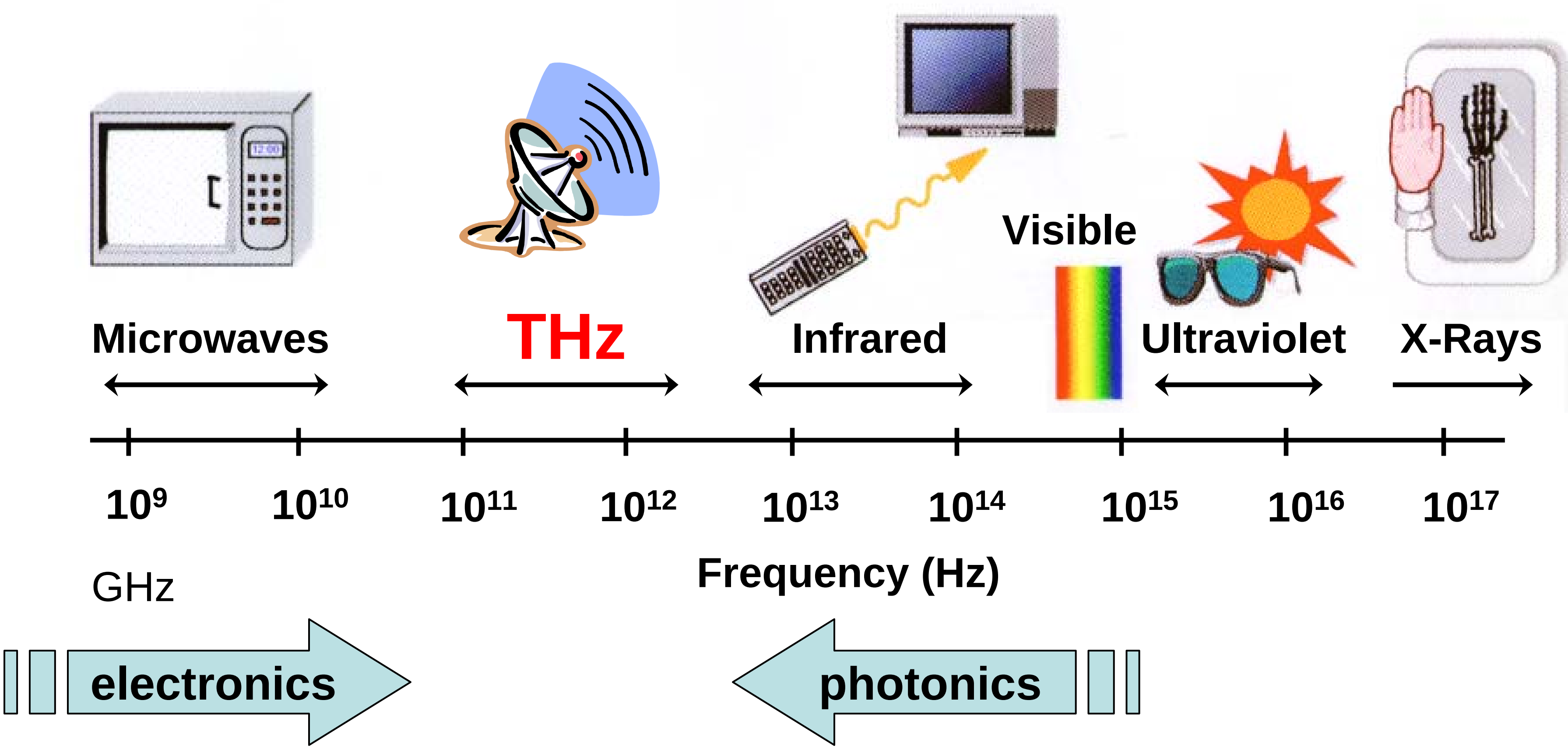
Where is the far-infrared or Terahertz (THz) region?



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

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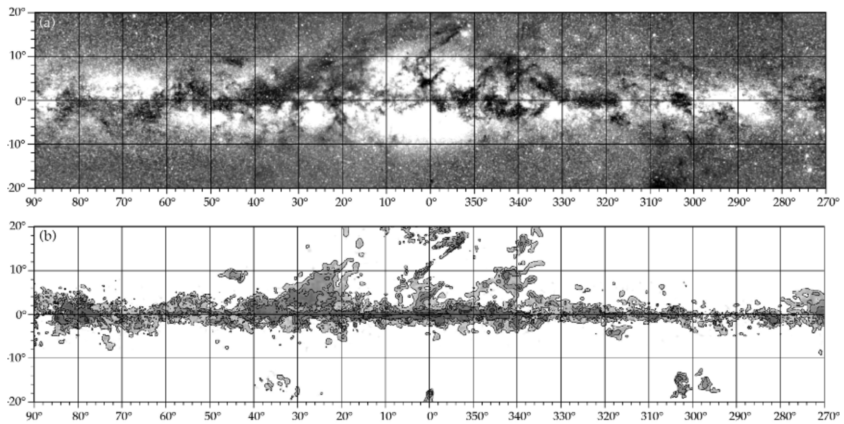
Most physical phenomena at THz frequencies are related to vibrational rotational modes of molecules

Astrophysics

Galactic optical emission and CO emission @ 115GHz



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

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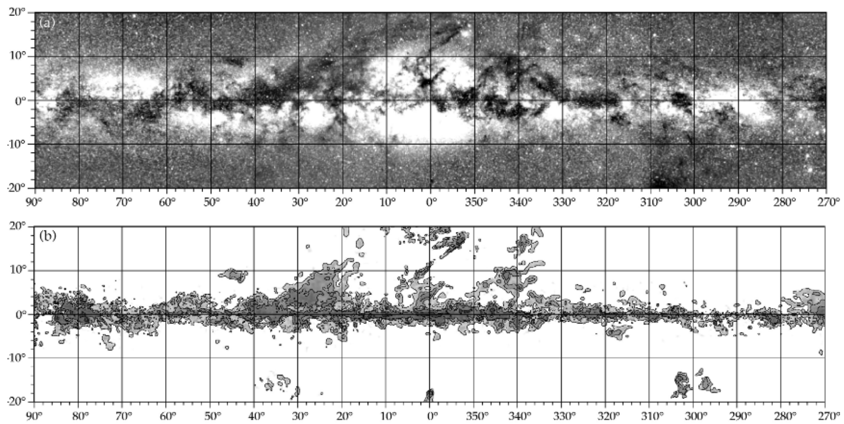
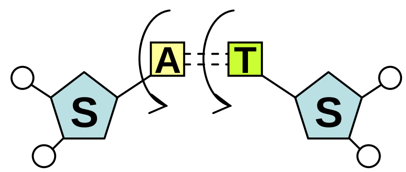


T. M. Dame et al., Astrophys. J. 547, 792 (2001).

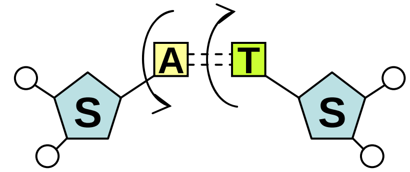
Biology

DNA vibrational modes

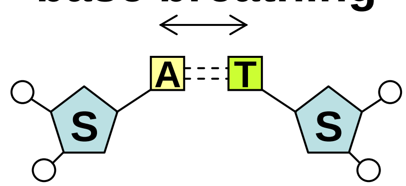
base roll



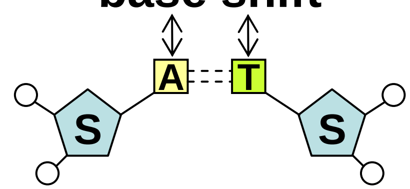
"propeller" twist

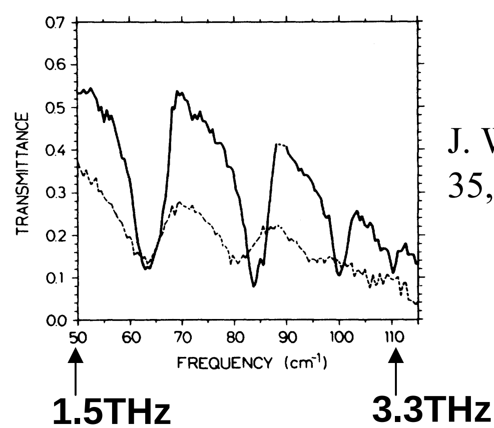


base breathing



base shift





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

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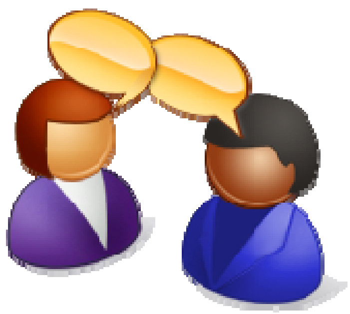
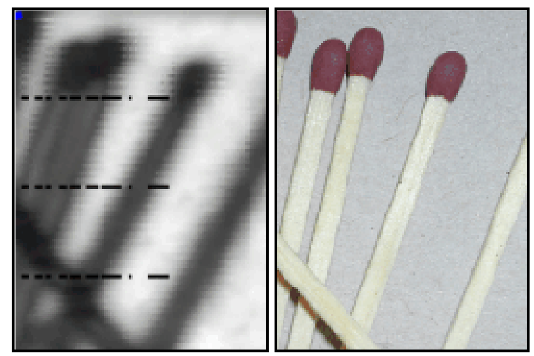
There are some emerging technological applications of THz radiation

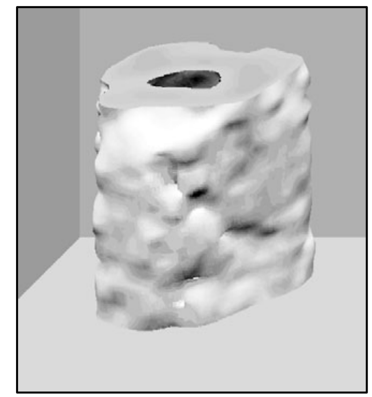
Communications



Imaging and Tomography

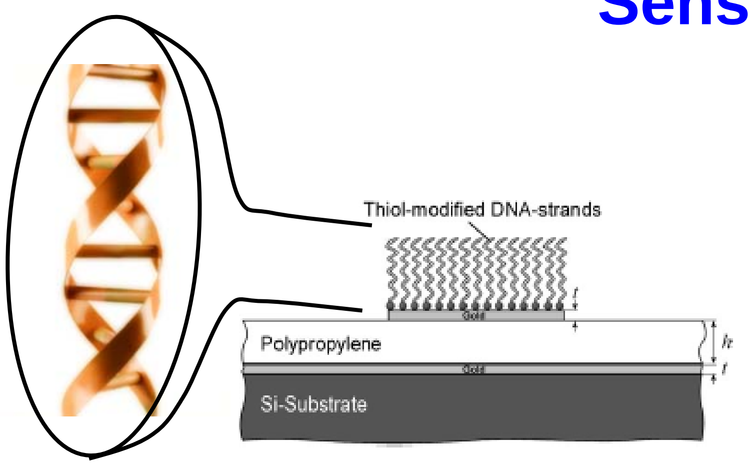


P. Planken, DELFT.

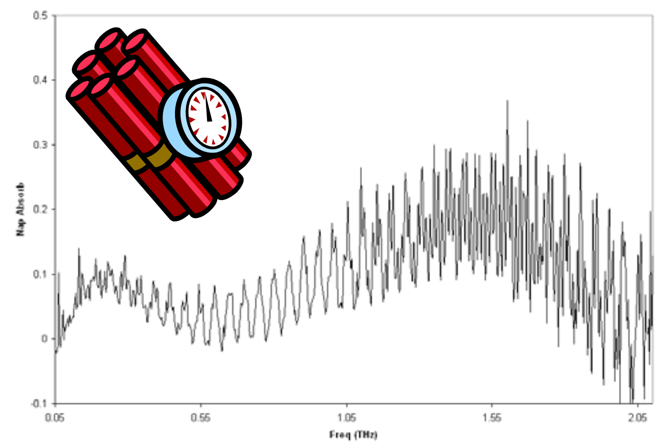


B. Ferguson et. al,
Phys. Med. Bio. (2002).

Sensing

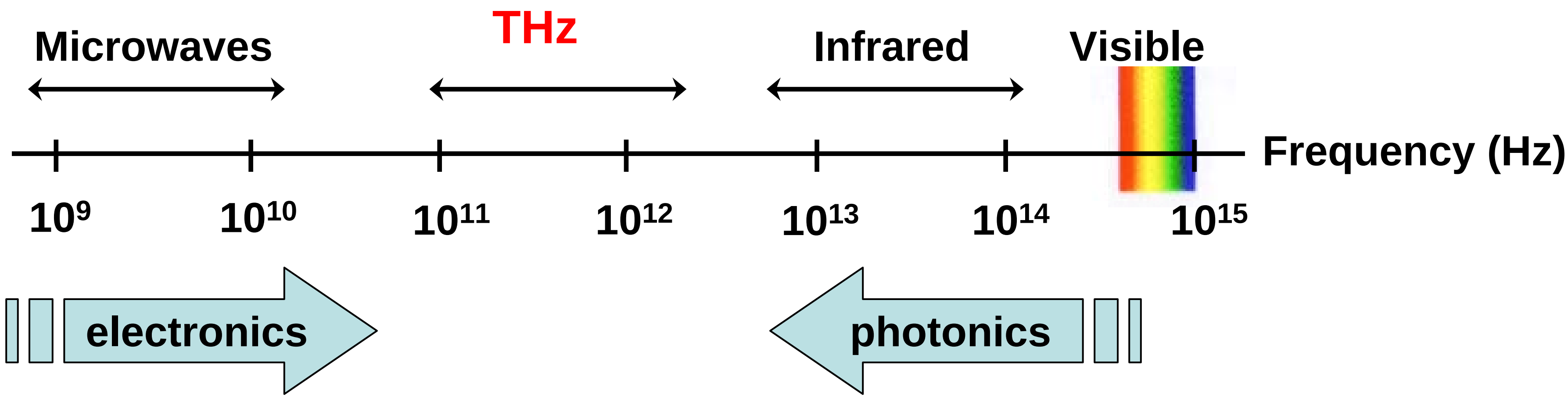


M. Nagel et al., Phys. Med. Biol. **48** (2003) 3652.



Courtesy of M.C. Wanke, SNL

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



Parasitics
Transit times
decrease

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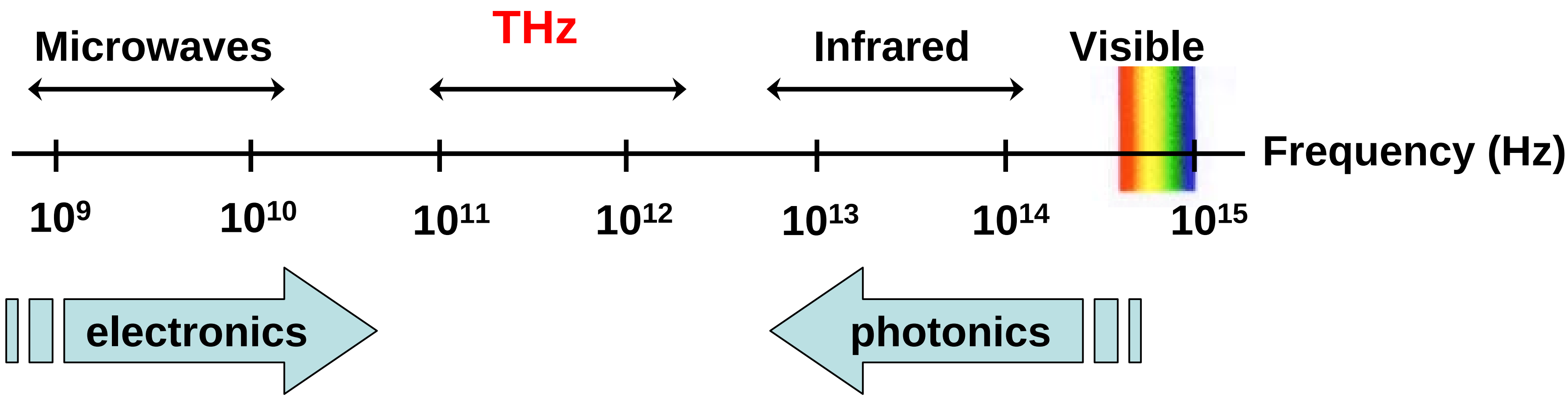
Why is there a void in science and technology at THz frequencies?



Parasitics
Transit times
decrease

Thermal fluctuations
Energy gaps decrease

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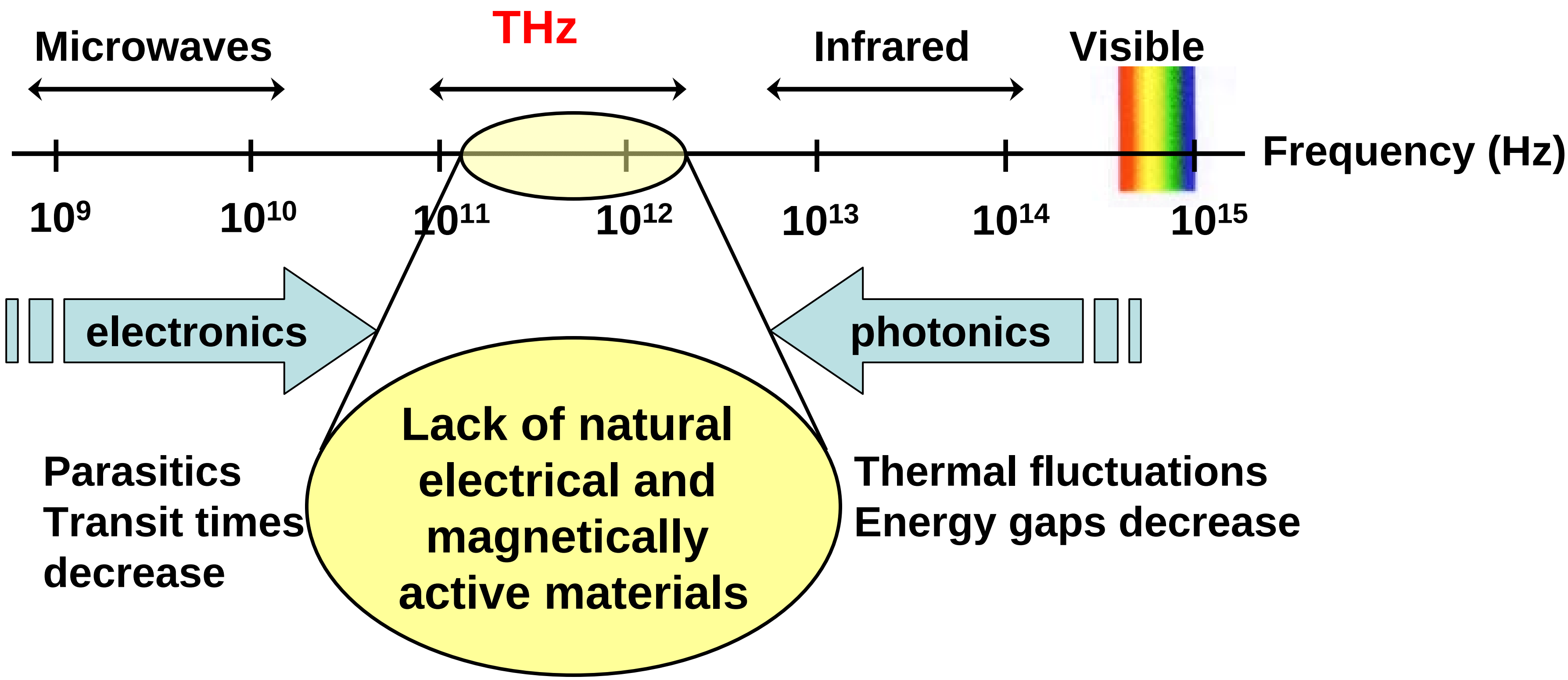
Why is there a void in science and technology at THz frequencies?



Metamaterials can provide tools to solve this problem!

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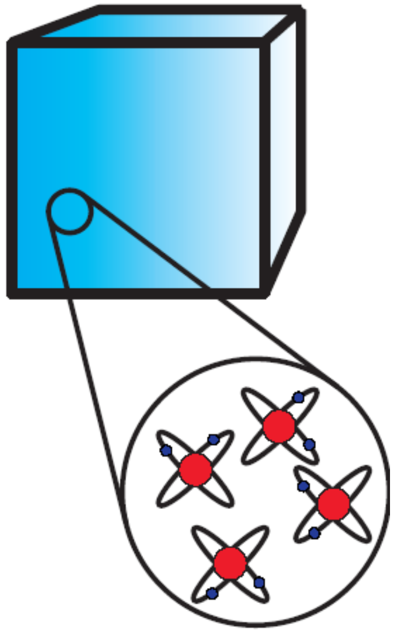
What are metamaterials?

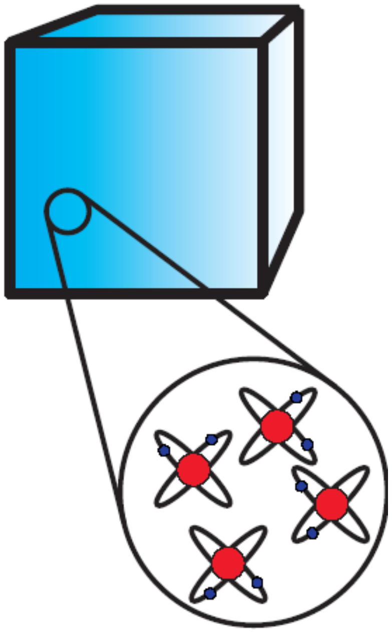
μετα = beyond



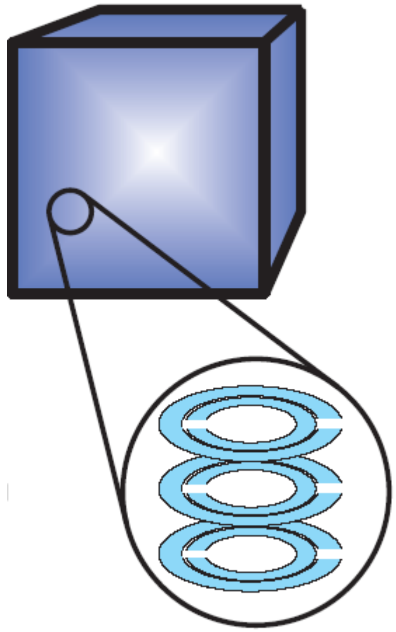
A natural material composed of atoms.

What are metamaterials?

$\mu\epsilon\tau\alpha$ = 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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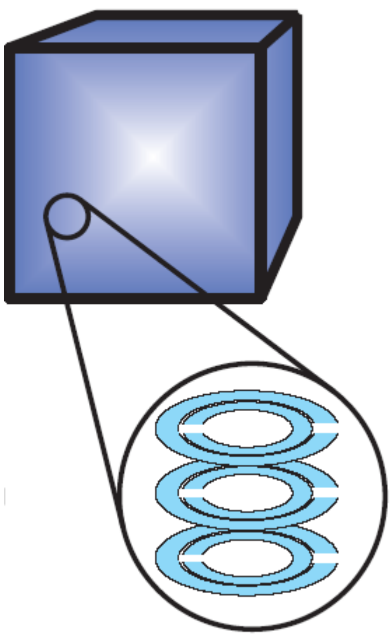
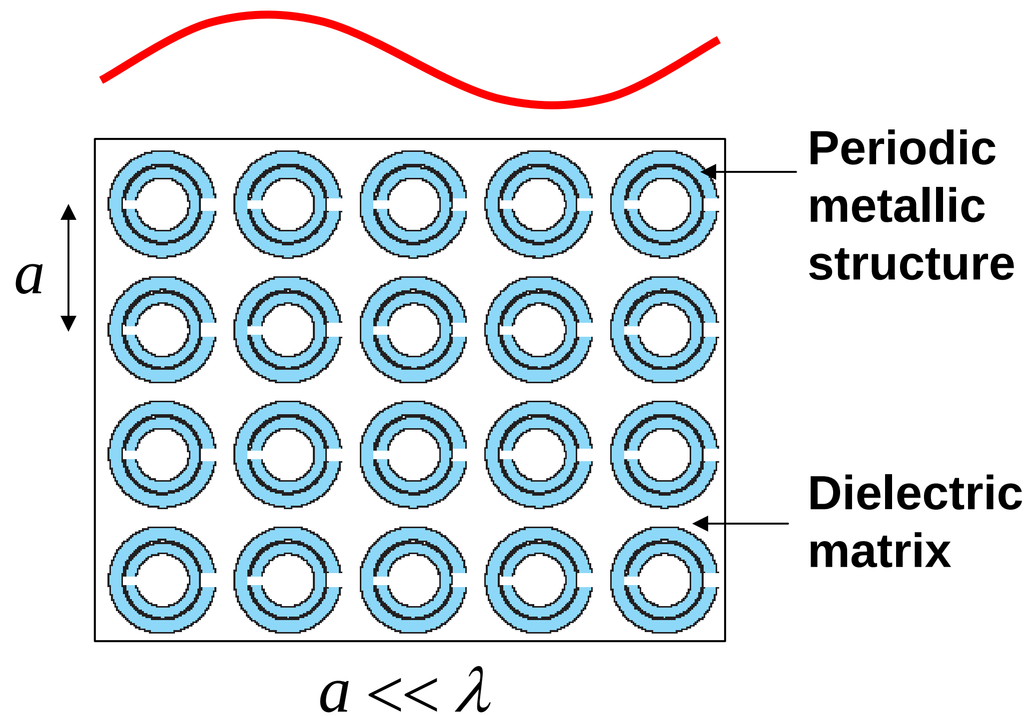
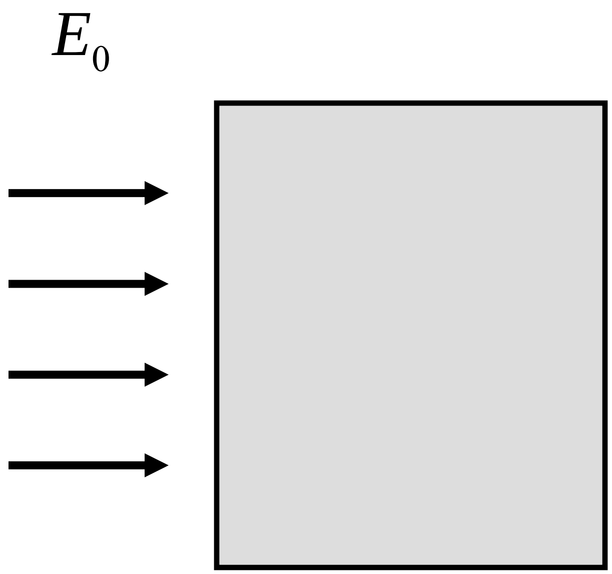
The properties of the “atoms” and their spatial distribution determine the properties of the metamaterial



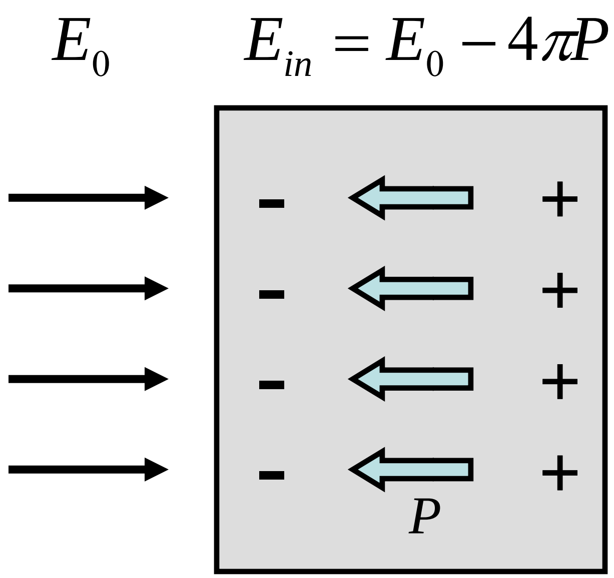


The individual units are designed to have specific electromagnetic properties.

The dielectric permittivity is a measure of the ability of a material to be polarized

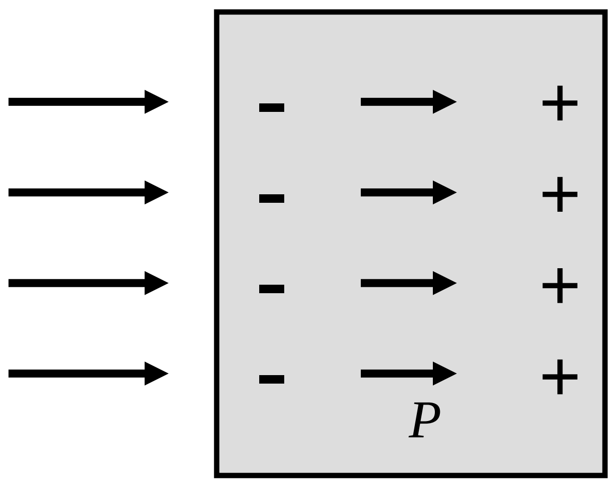


The dielectric permittivity is a measure of the ability of a material to be polarized



The dielectric permittivity is a measure of the ability of a material to be polarized

E_0 $\quad E_{in} = E_0 - 4\pi P$



Dielectric permittivity

$$\varepsilon = \frac{E_0}{E_{in}}$$

In general ε=ε(ω)

The permittivity relates to a material's ability to "permit" an electric field.

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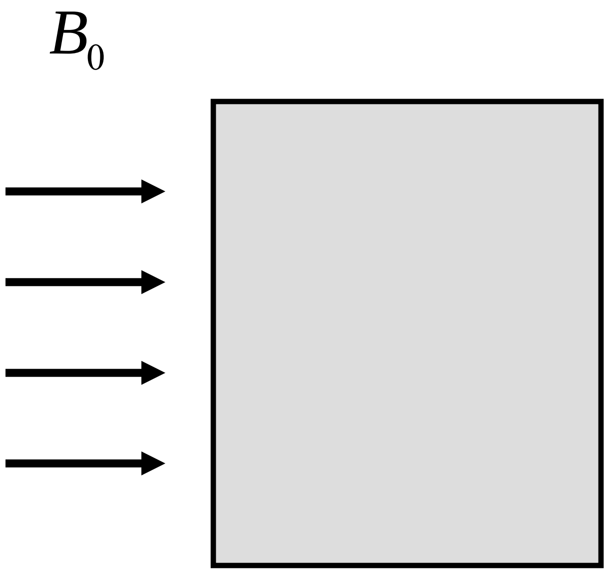
The magnetic permeability is a measure of the degree of magnetization of a material



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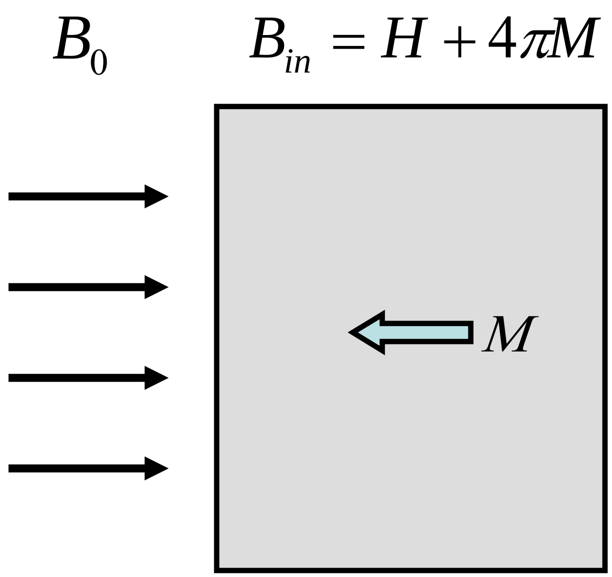

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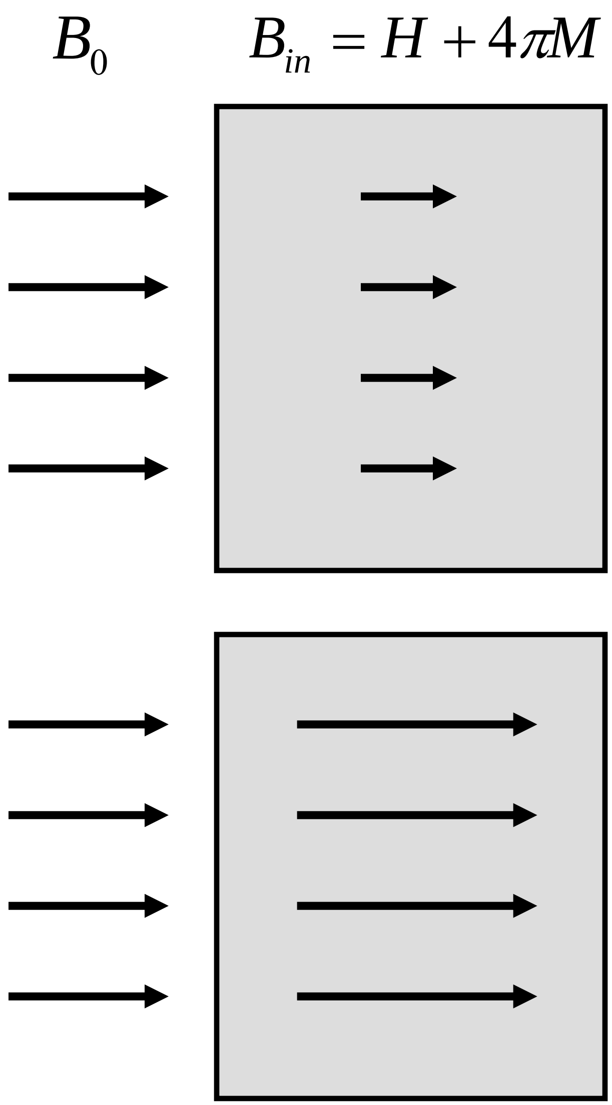
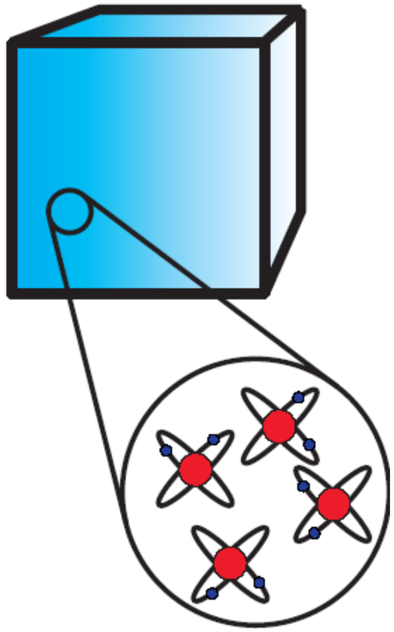


Magnetic permeability

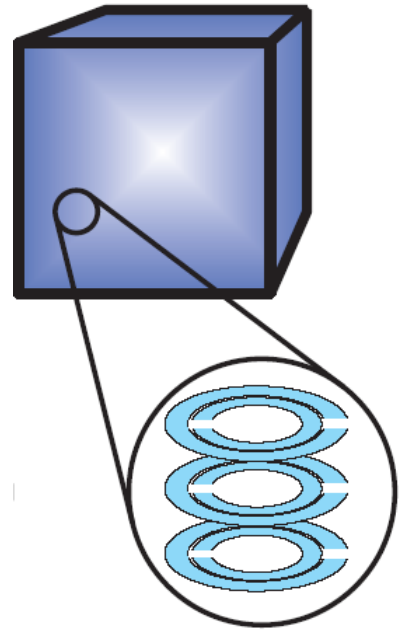
$$\mu = \frac{B_0}{B_{in}}$$

In general, $\mu = \mu(\omega)$

Any material that satisfies $a << \lambda$ is described by the effective medium approximation



a = periodicity



A natural material composed of atoms.

A metamaterial is composed of artificially structured "atoms".

Can be characterized by an effective electric permittivity ε and an effective magnetic permeability μ.

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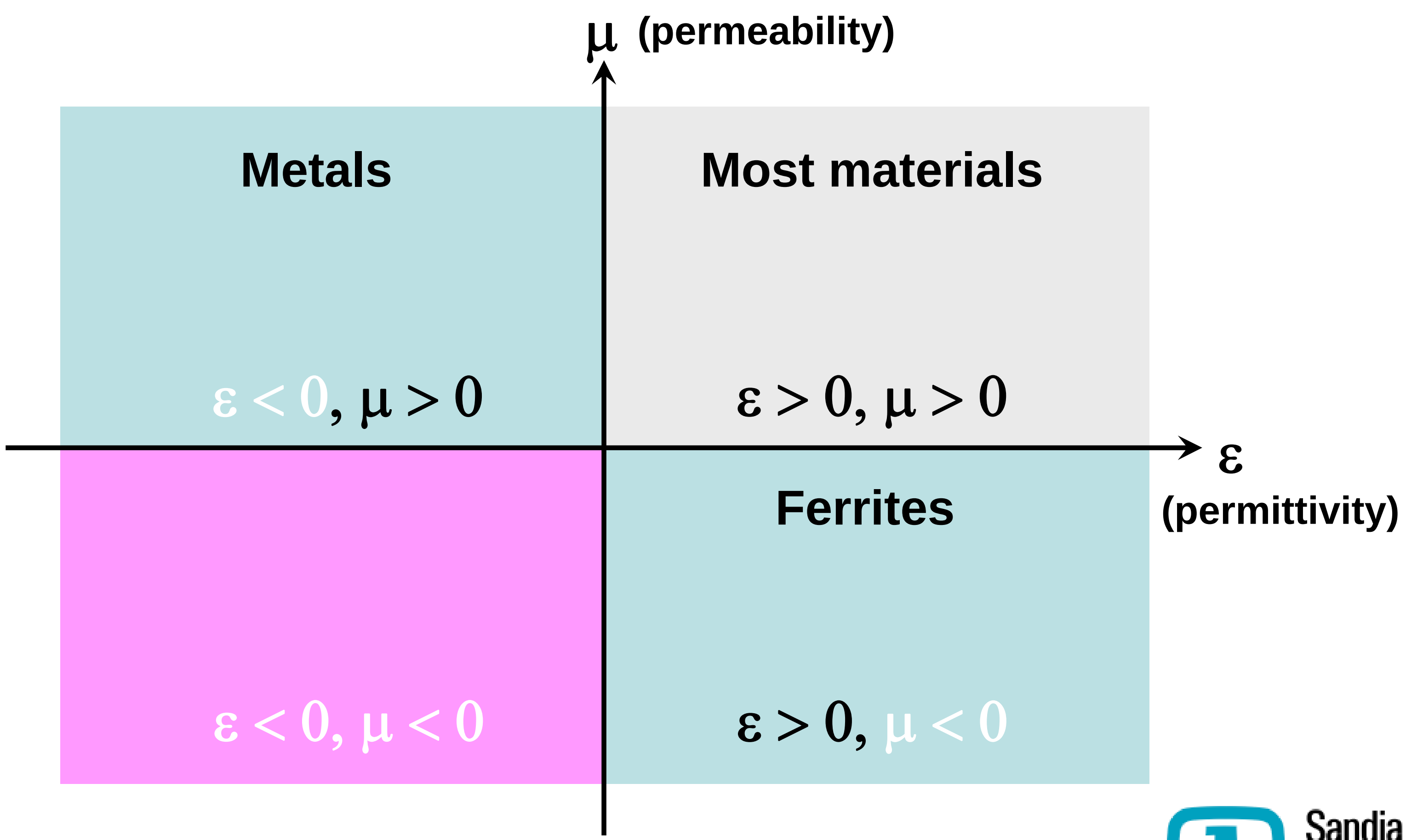
We can organize materials according to their permittivity and permeability



 V. Veselago, Sov. Phys. Usp. 10, 509 (1968)

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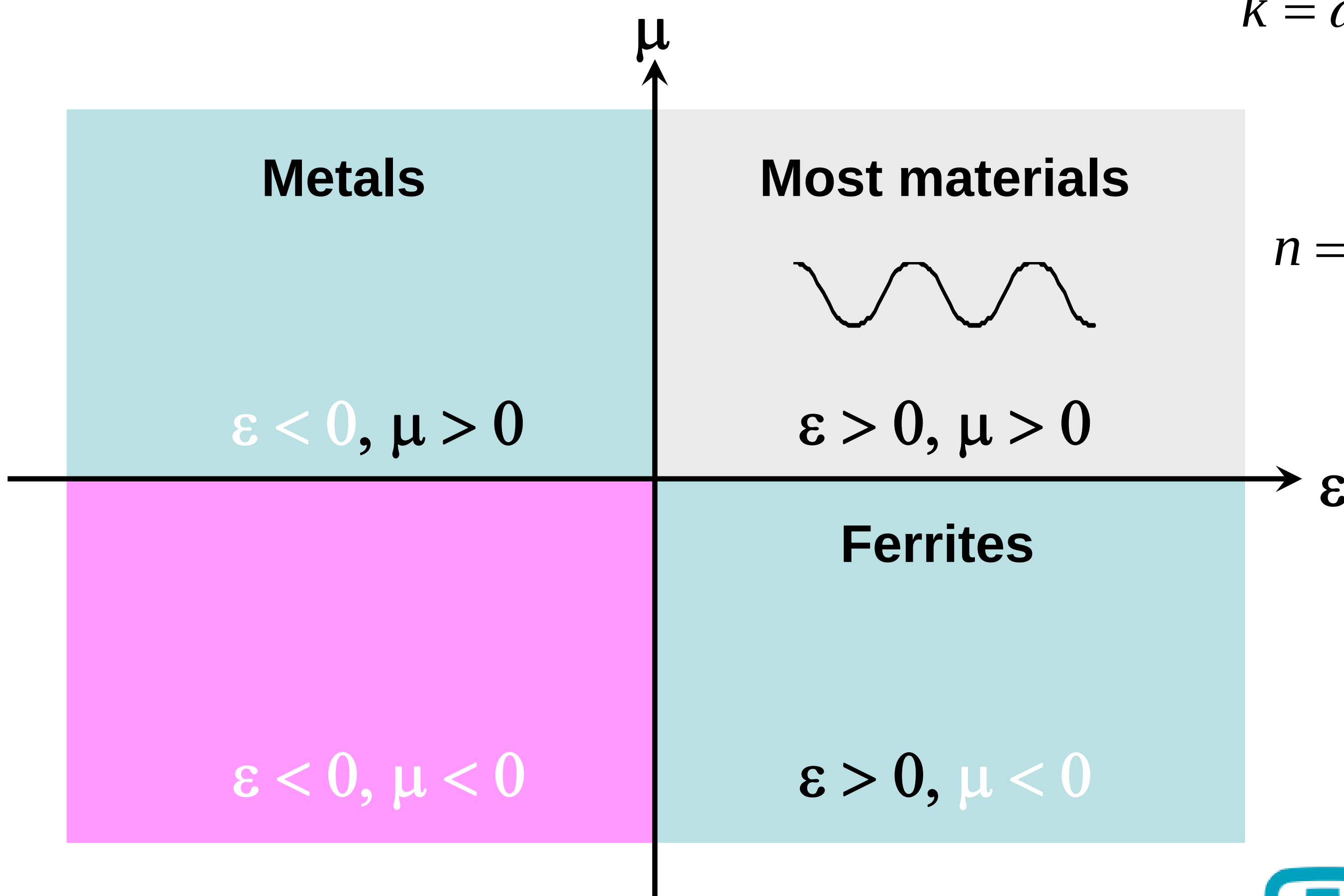
How electromagnetic waves propagate through a material is given by solutions to the wave equation

Wave equation: $\nabla^2 E = \varepsilon\mu \frac{\partial^2 E}{\partial^2 t}$

Solution: $E = E_0 e^{-i(\omega t - kx)}$

$k = \omega\sqrt{\varepsilon\mu}$



$n = +\sqrt{\varepsilon\mu}$

How electromagnetic waves propagate through a material is given by solutions to the wave equation

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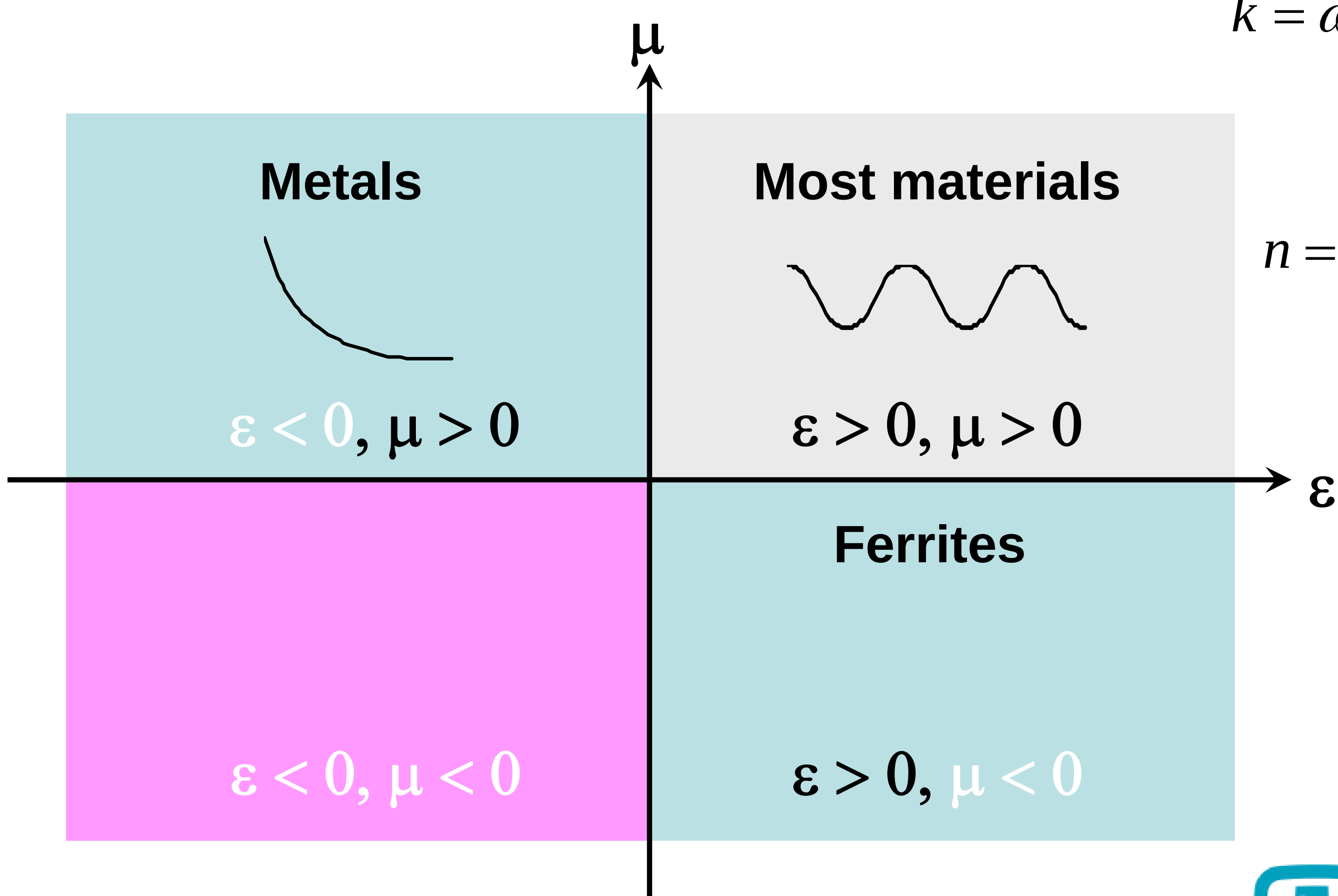

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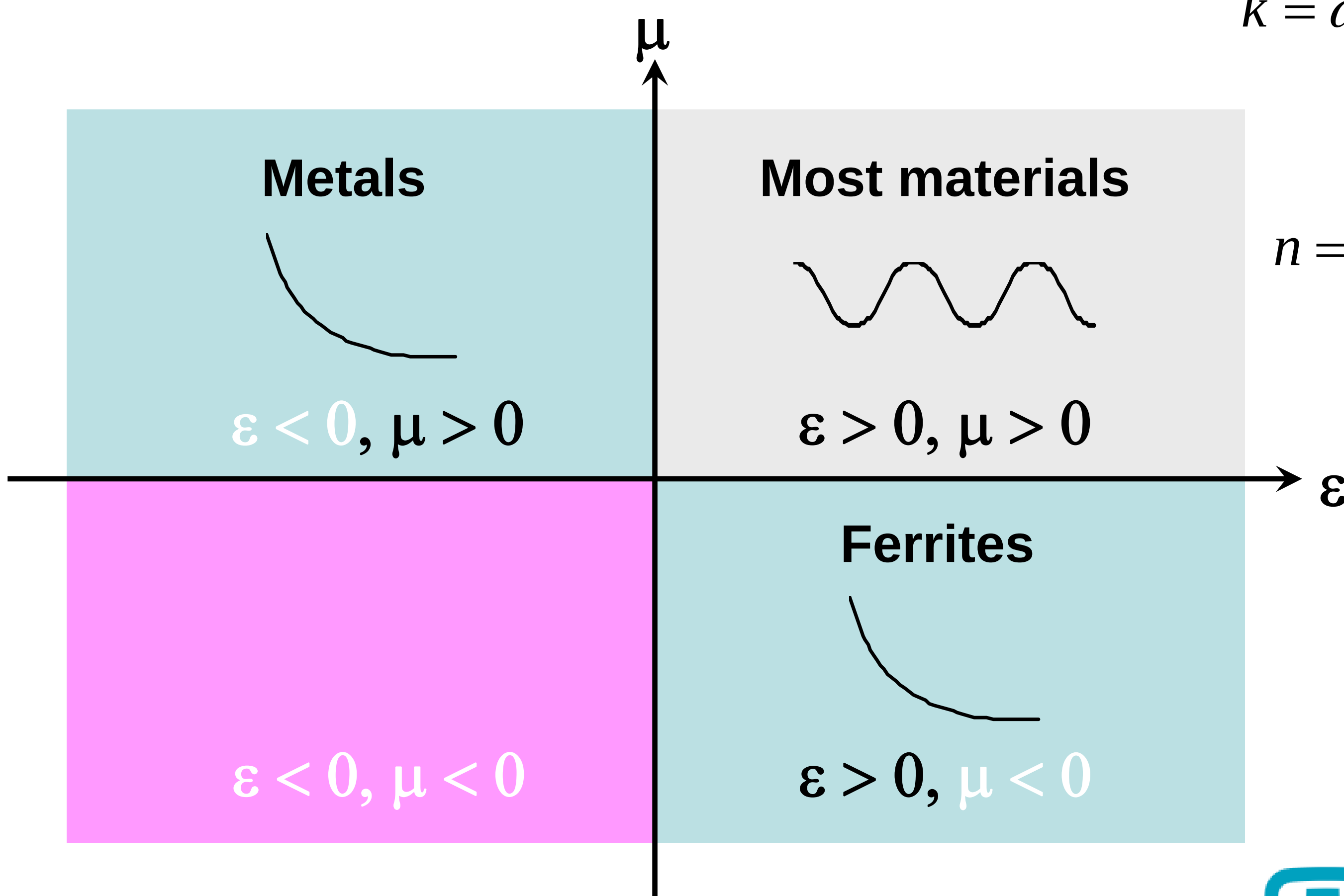

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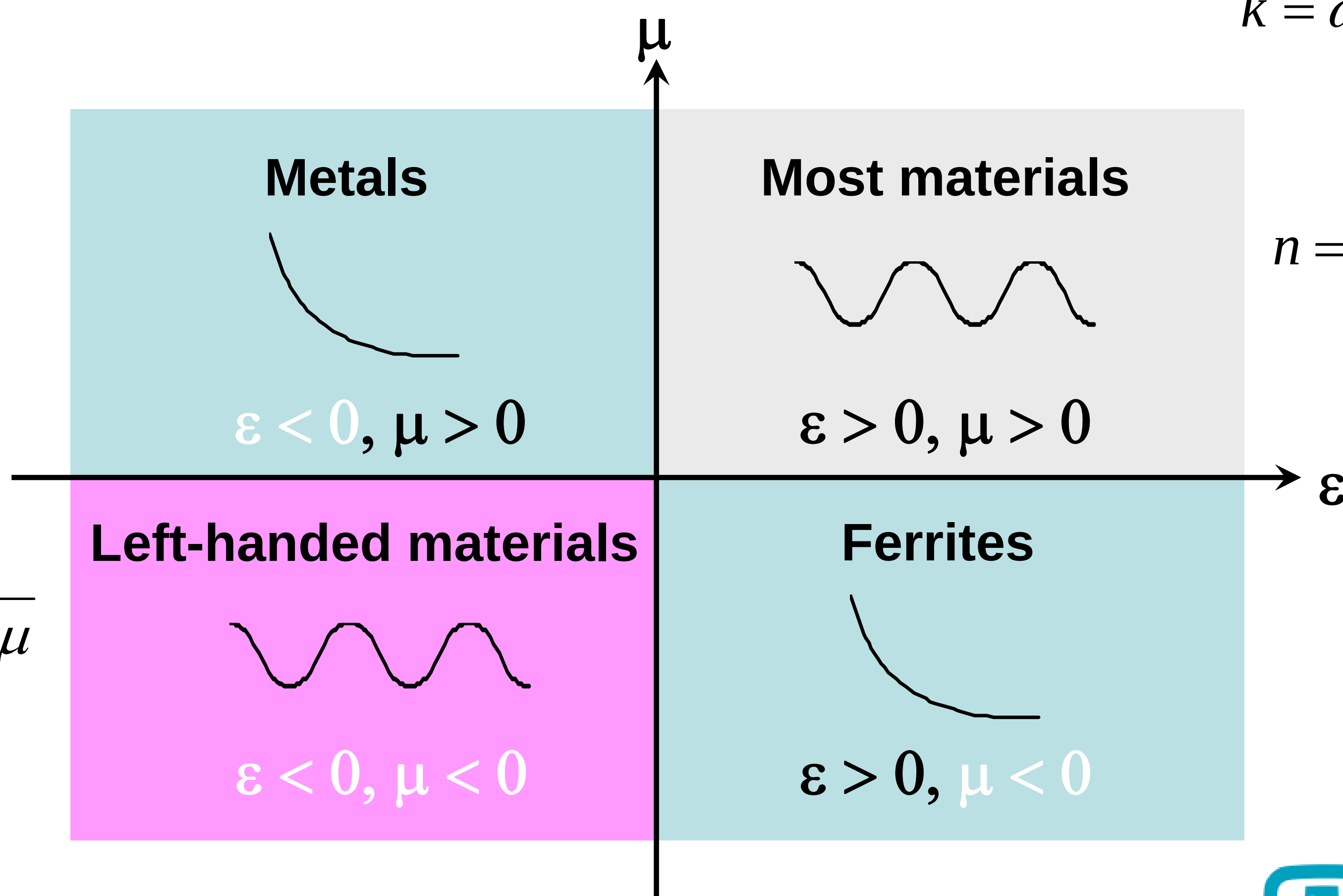

$n = -\sqrt{\varepsilon\mu}$

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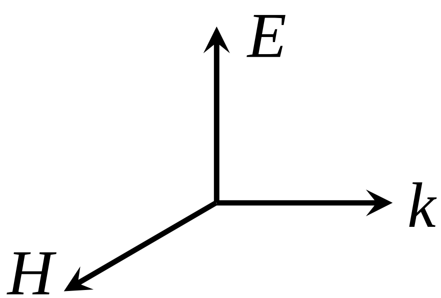
Why are they called left-handed materials?

Maxwell's equations:

$$\begin{cases} k \times E = \dfrac{\omega}{c}\mu H \\ k \times H = -\dfrac{\omega}{c}\varepsilon E \end{cases}$$

If $\varepsilon>0$ and $\mu>0$ then it is a right-hand set of vectors:



$$n = +\sqrt{\varepsilon\mu}$$

Why are they called left-handed materials?

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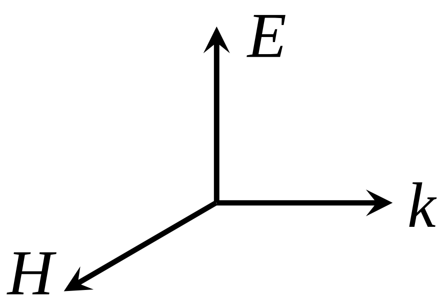
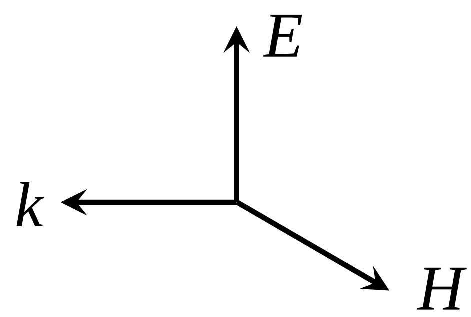


$$n = +\sqrt{\varepsilon\mu}$$

If ε<0 and μ<0 then it is a left-hand set of vectors:



$$n = -\sqrt{\varepsilon\mu}$$

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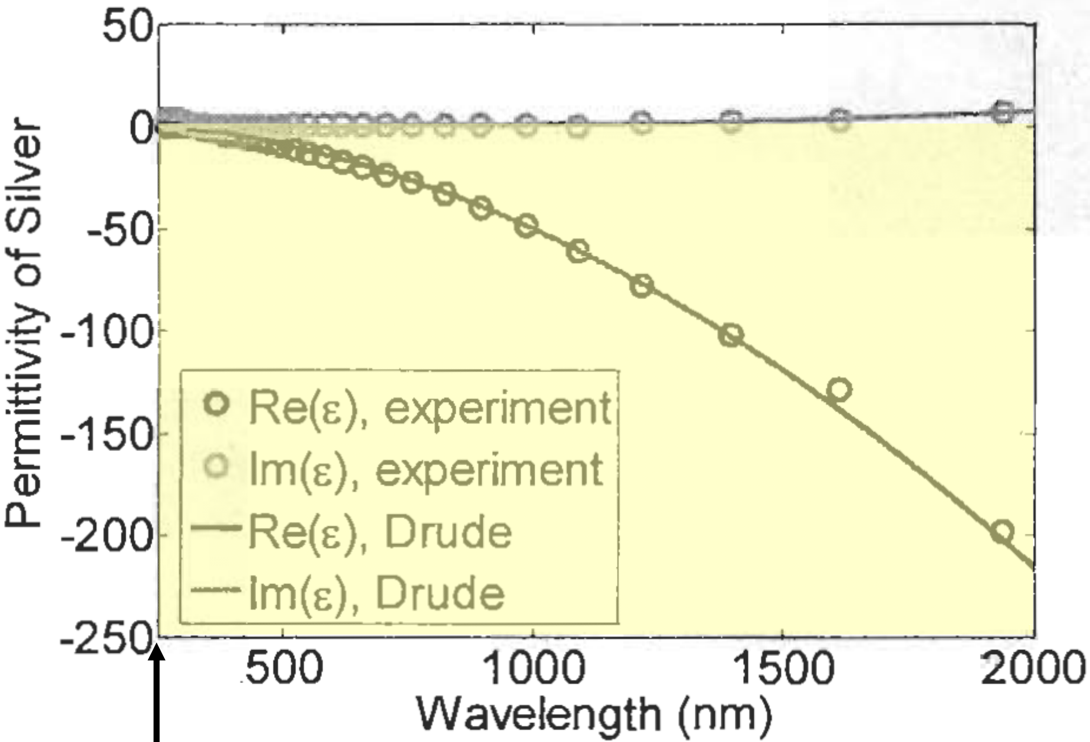
How do you get $\varepsilon < 0$?

Bulk metals naturally have ε < 0 in the UV

Drude free electron theory: $\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$

$$\omega_p^2 = \frac{4\pi N e^2}{m_0}$$

$N \sim 10^{22}$ cm^3



ω_p**~10^{15}Hz**

10^{14}Hz

If $\omega < \omega_p$ then $\varepsilon < 0$

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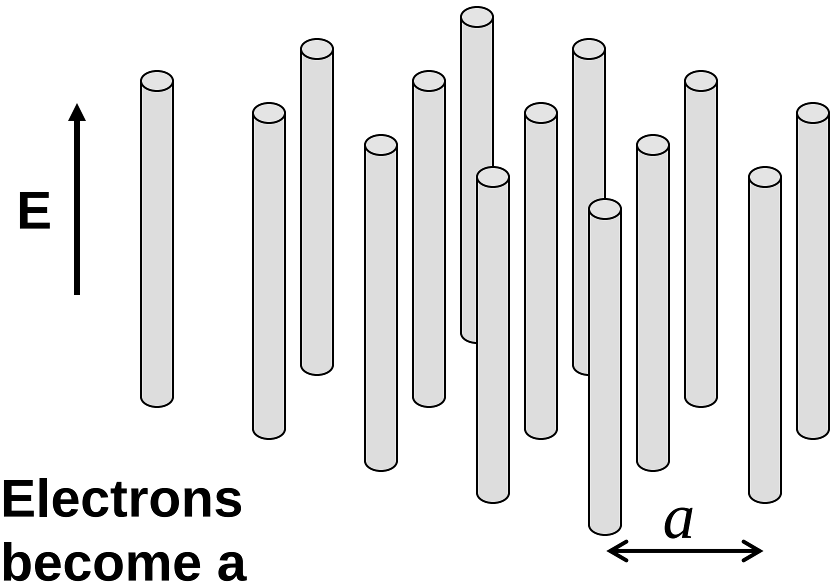
In an array of thin metal wires, the region where $\varepsilon < 0$ can be tuned by the geometry



Electrons become a dilute plasma

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

$$\omega_p^2 = \frac{2\pi c^2}{a^2 \ln(a/r)}$$

depends on the geometry

J. Pendry et al., PRL 76, 4773 (1996)

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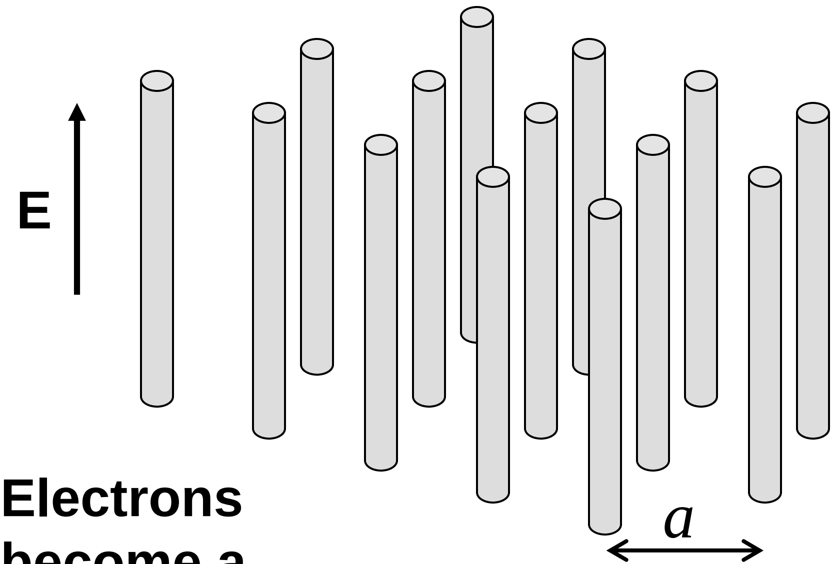

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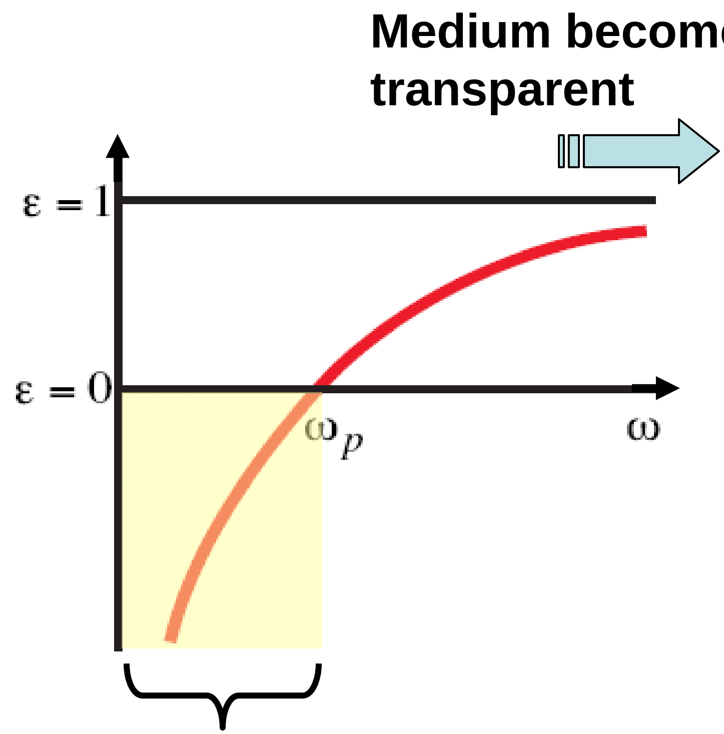

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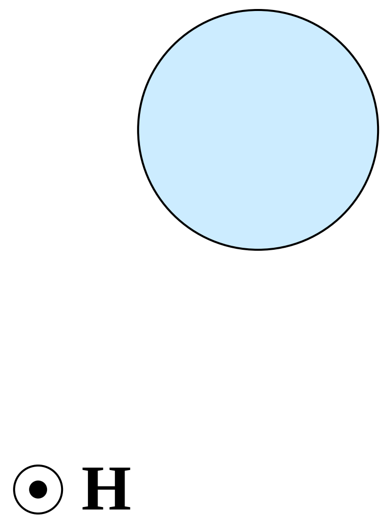
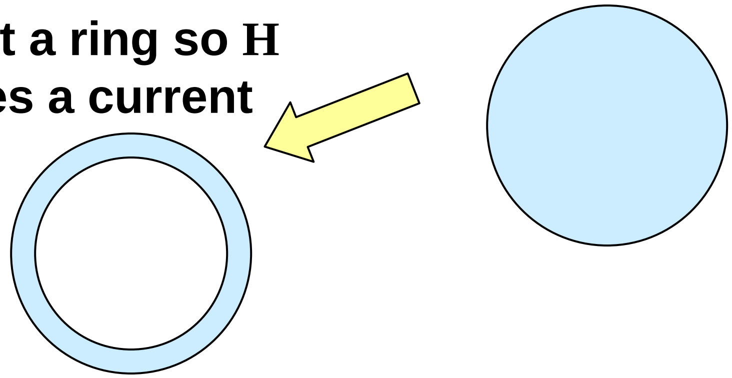
How do you get $\mu < 0$?

First metamaterials with μ < 0 were double circular split-ring resonators

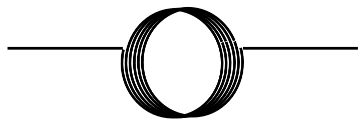


First metamaterials with μ < 0 were double circular split-ring resonators

Make it a ring so H induces a current



⊙ **H**

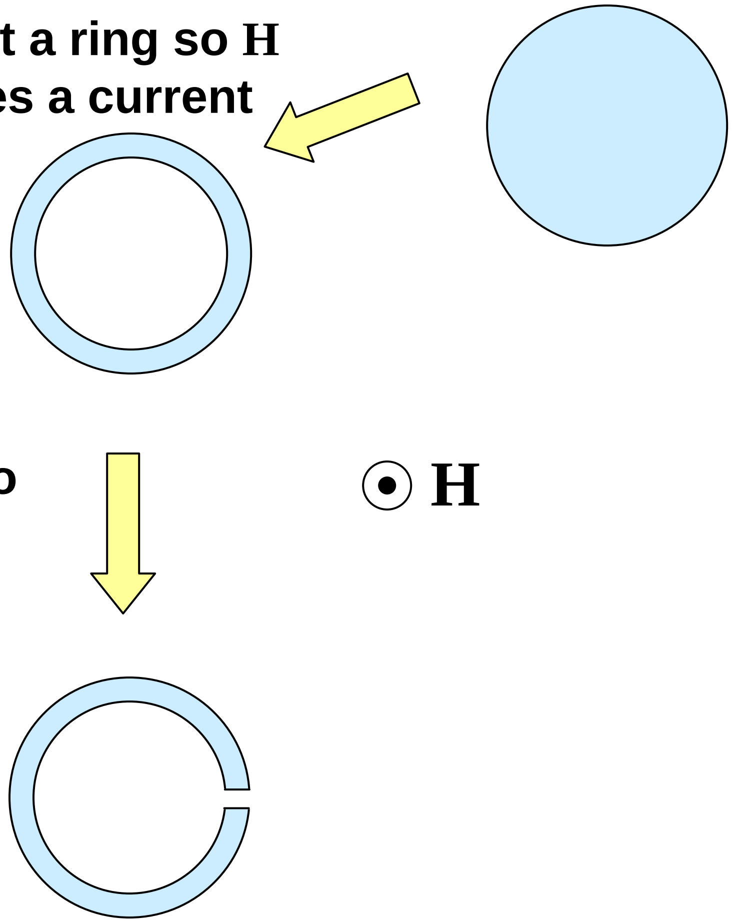


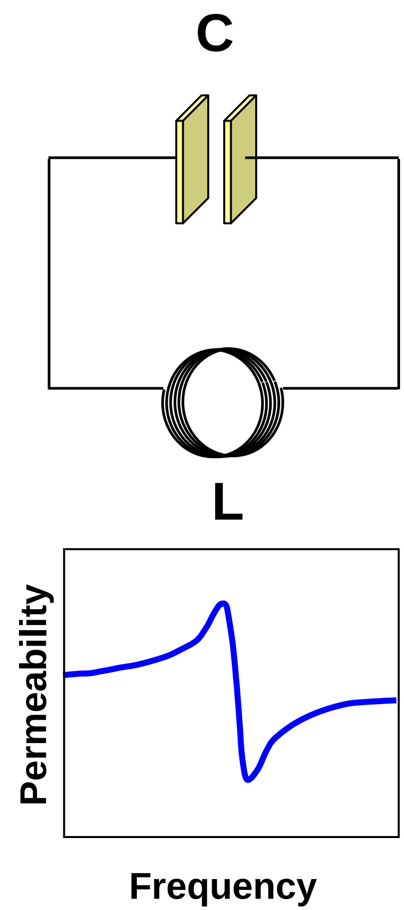
L

First metamaterials with μ < 0 were double circular split-ring resonators

Make it a ring so H induces a current

Cut the ring to introduce a capacitance





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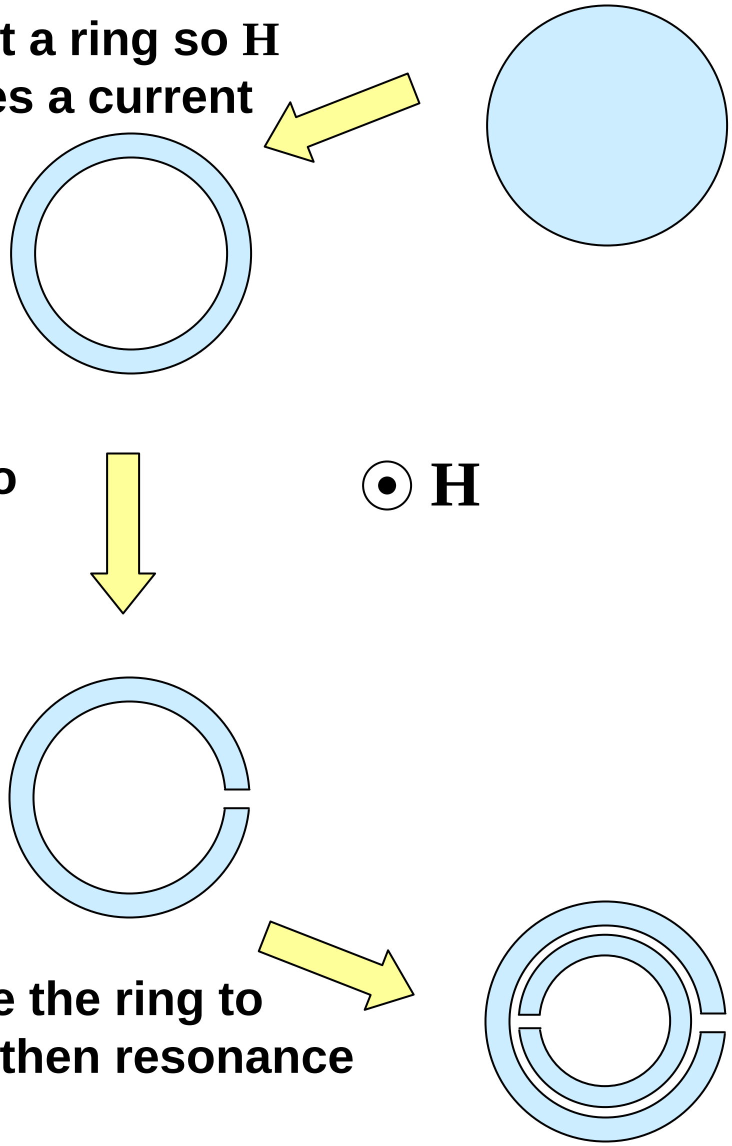
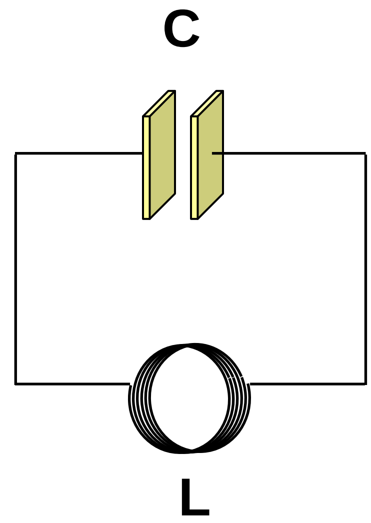
First metamaterials with μ < 0 were double circular split-ring resonators

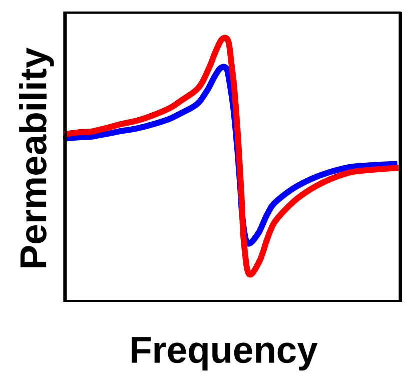
Make it a ring so H induces a current

Cut the ring to introduce a capacitance

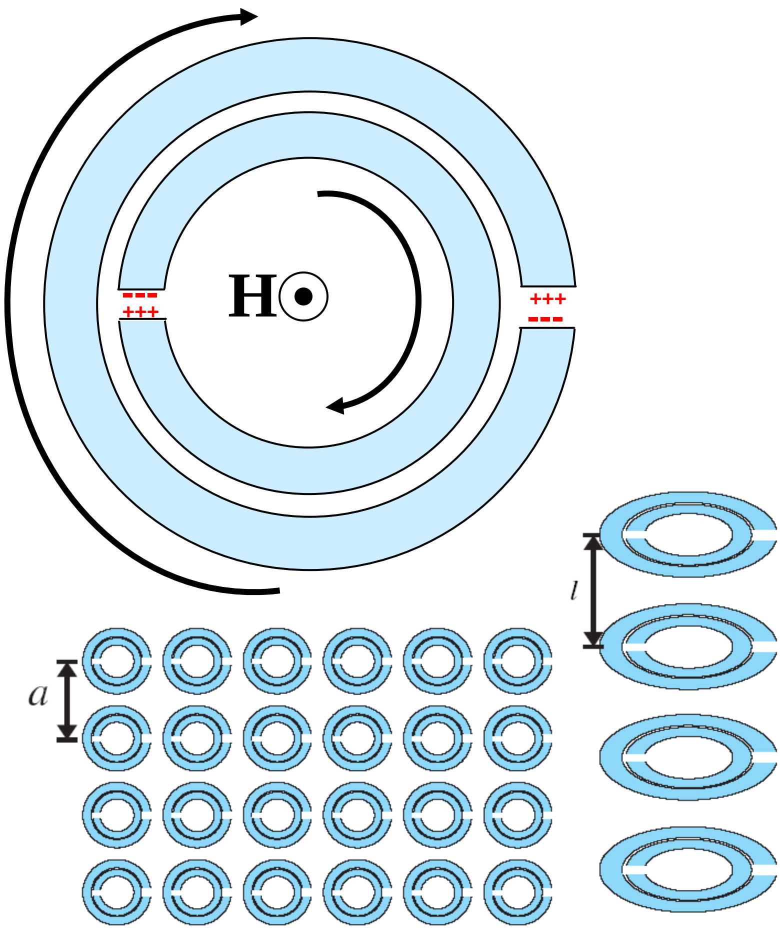
Double the ring to strengthen resonance

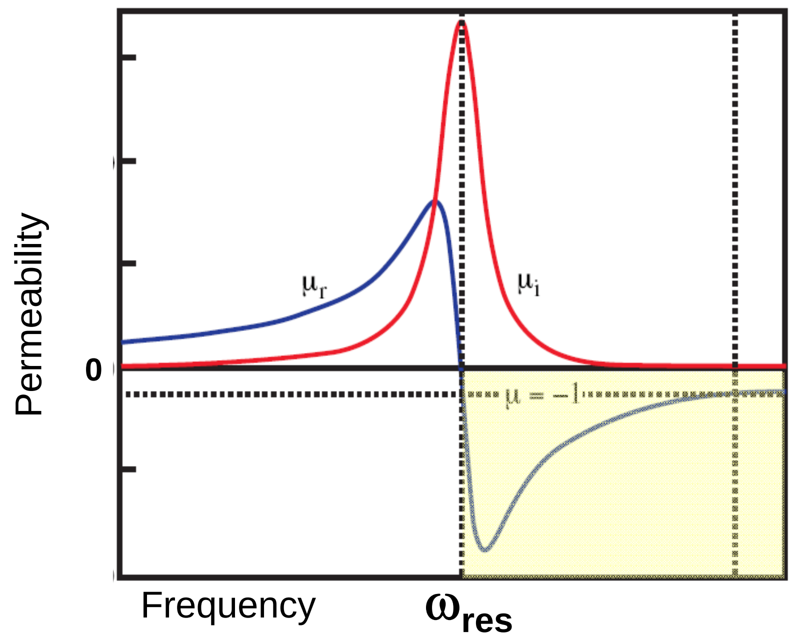






The geometry of the split-ring resonators can control the magnetic permeability ($\mu < 0$)





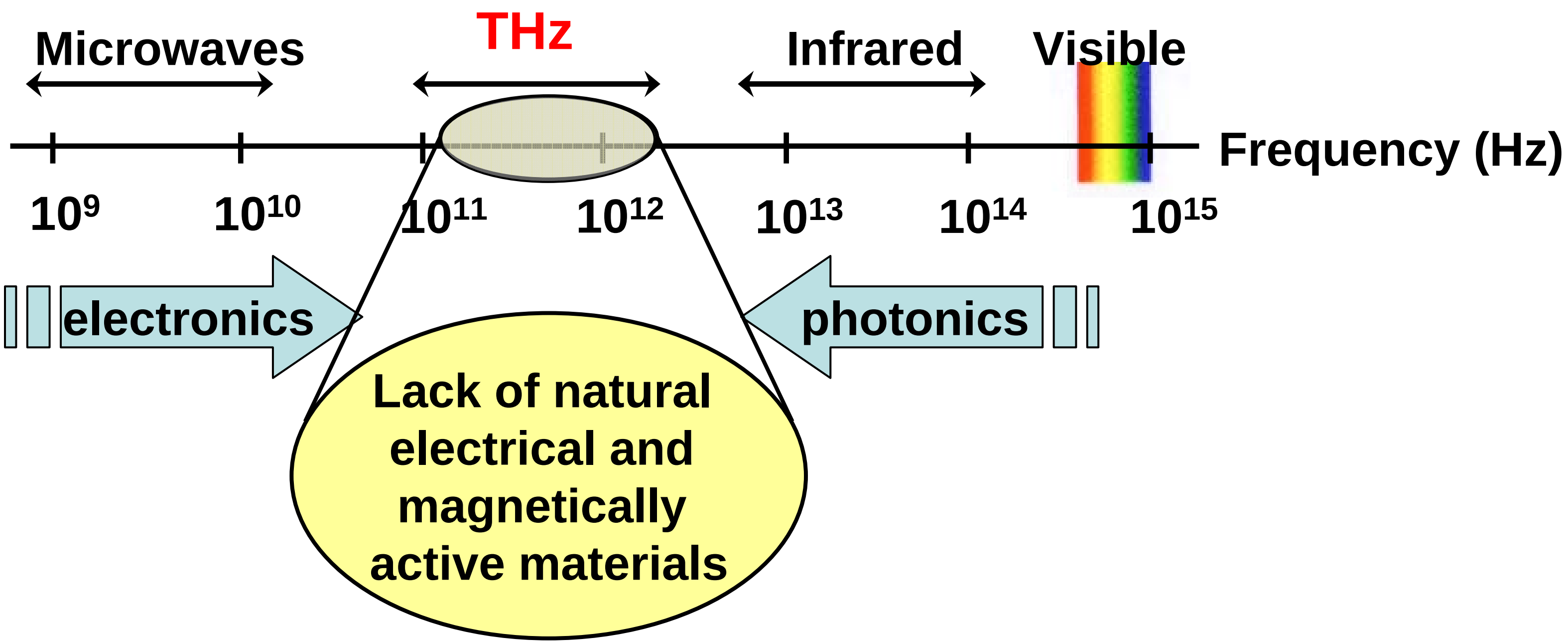
$$\mu(\omega) = 1 + \frac{\omega_{res}^2}{\omega_0^2 - \omega^2 - i\omega\gamma}$$

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

depends on the geometry

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

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



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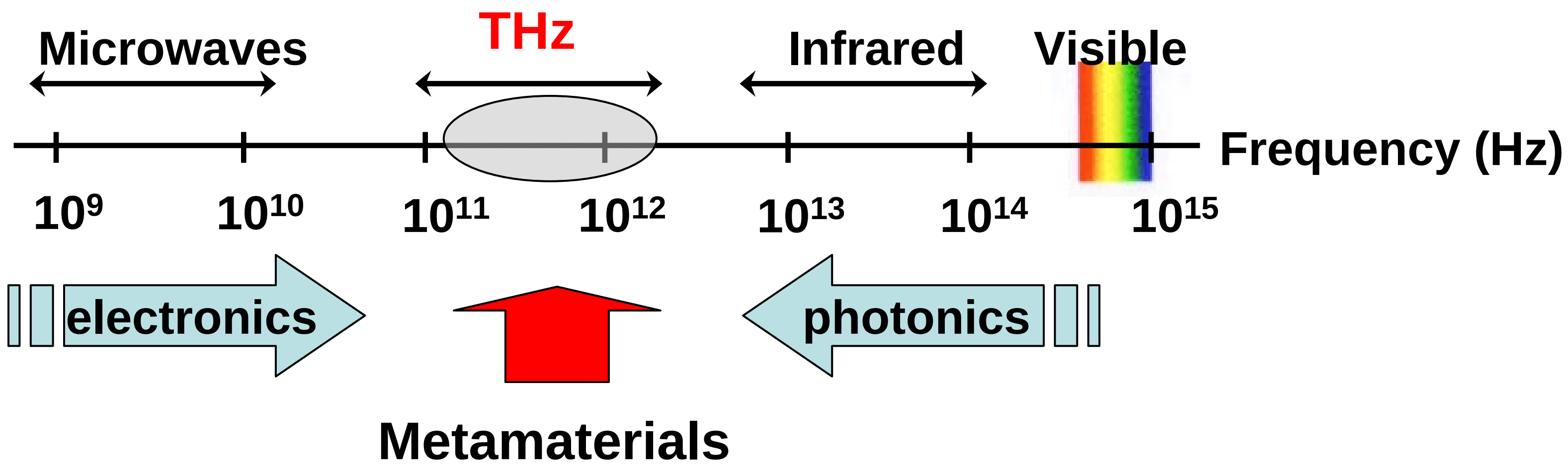
Metamaterials can help bridge the THz gap and interrogate biomolecules is new ways



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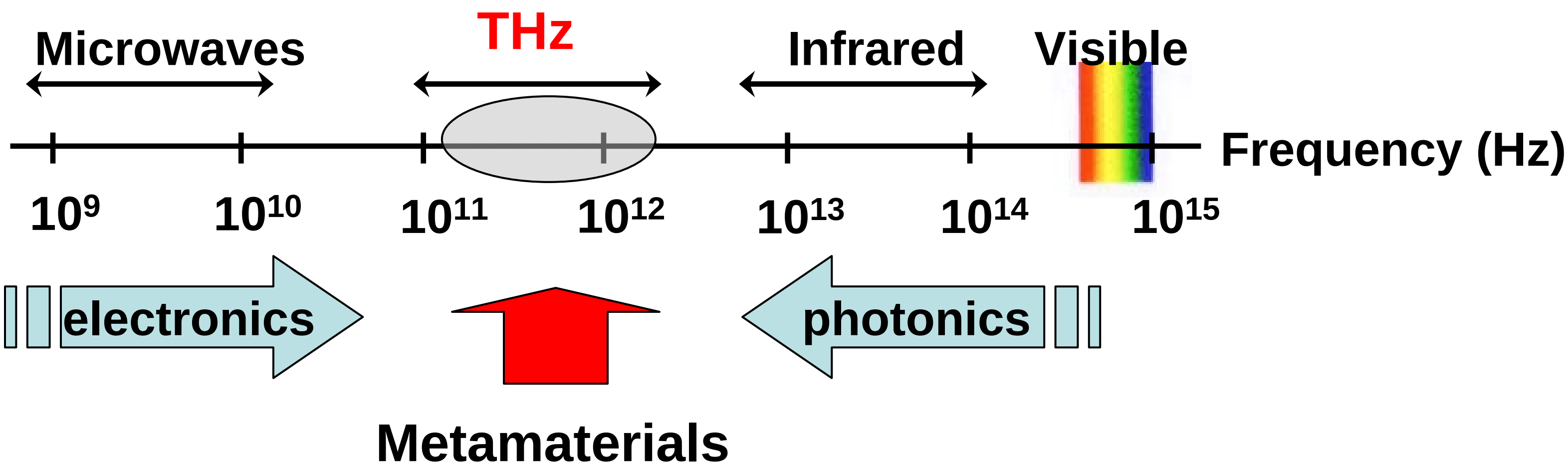
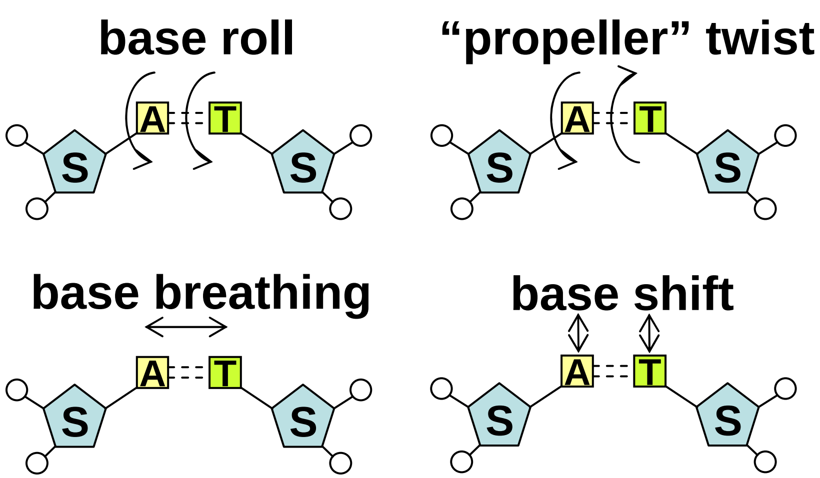
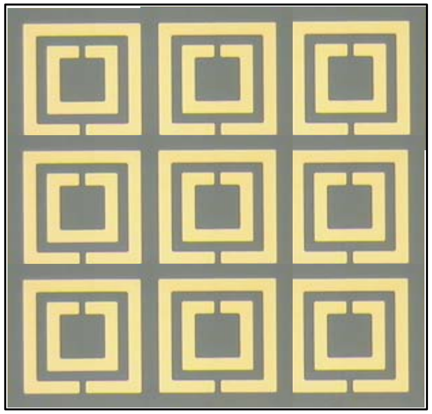
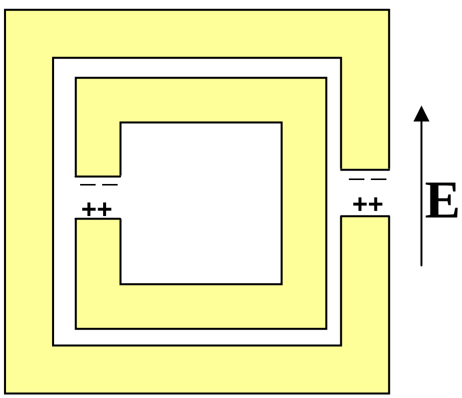


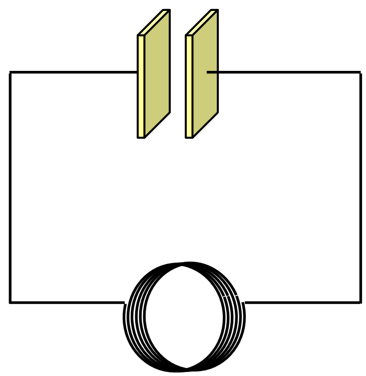


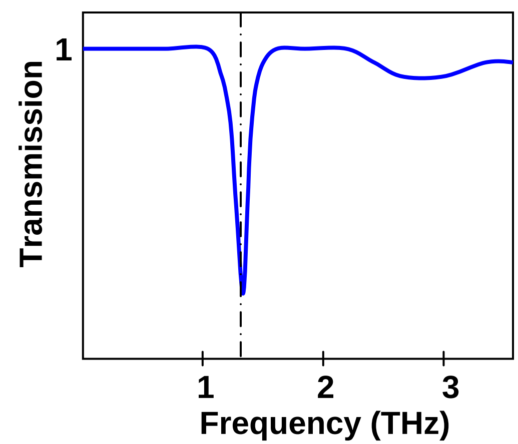
Can we use the change in capacitance as a sensing mechanism for chem-bio molecules?



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







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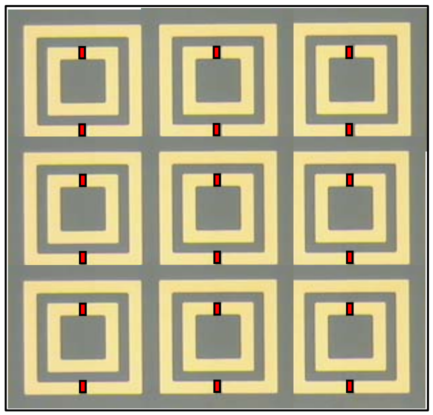

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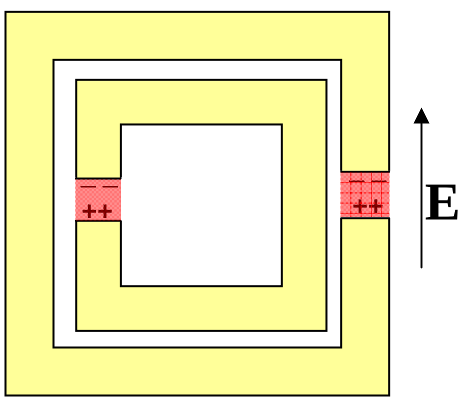

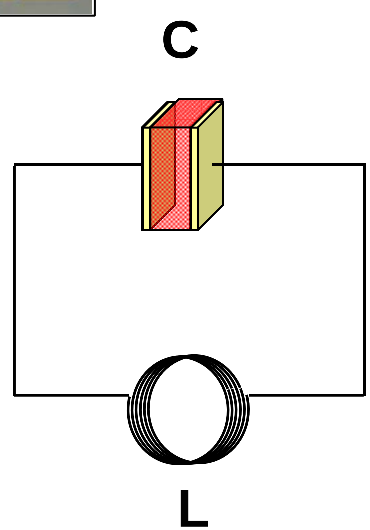

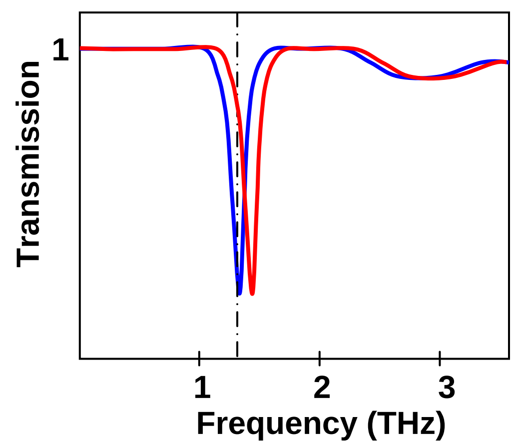

There is a shift in the resonance due to a change in C.

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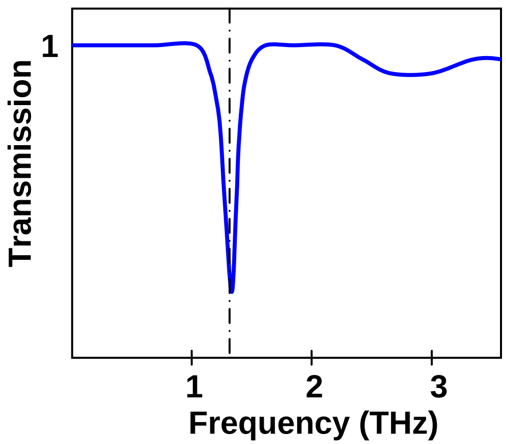
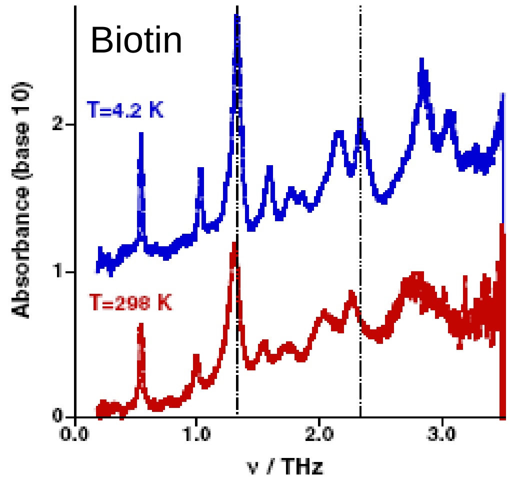
Change in capacitance combined with resonant detection or absorption enhances detection



+



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

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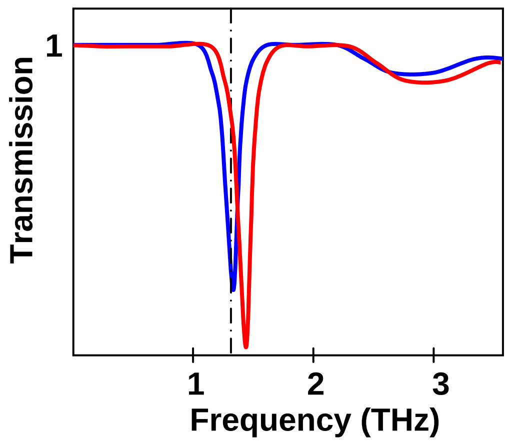
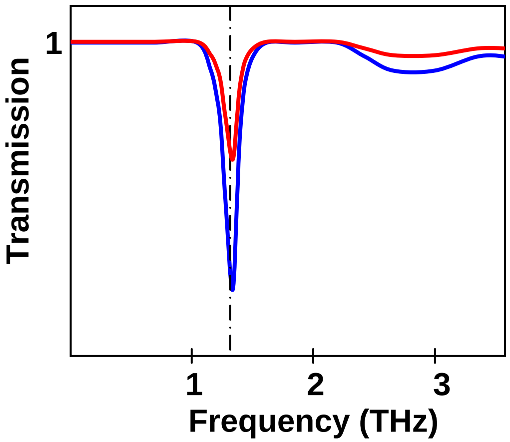


Absorption causes a decrease in transmission



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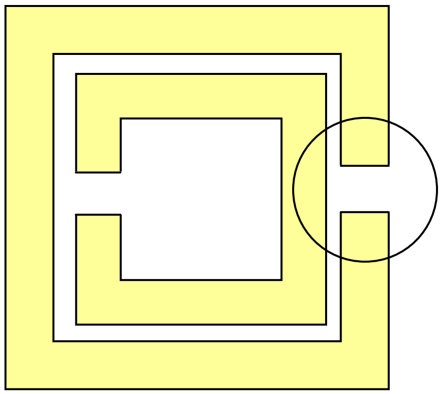
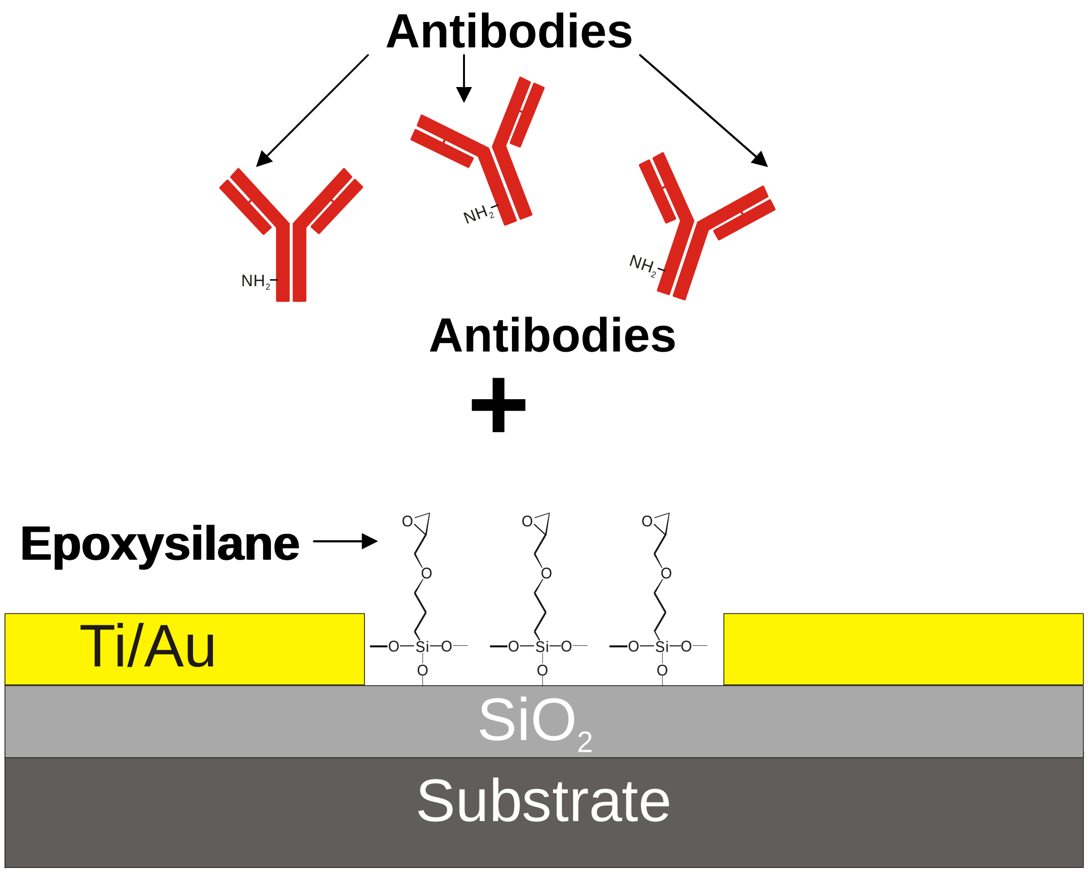
Surface functionalization uses linker molecules to attach biomolecules to inorganic surfaces

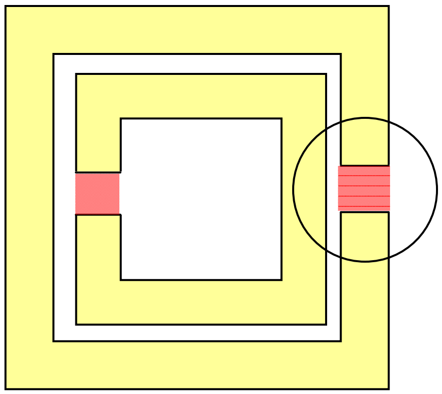


Top view

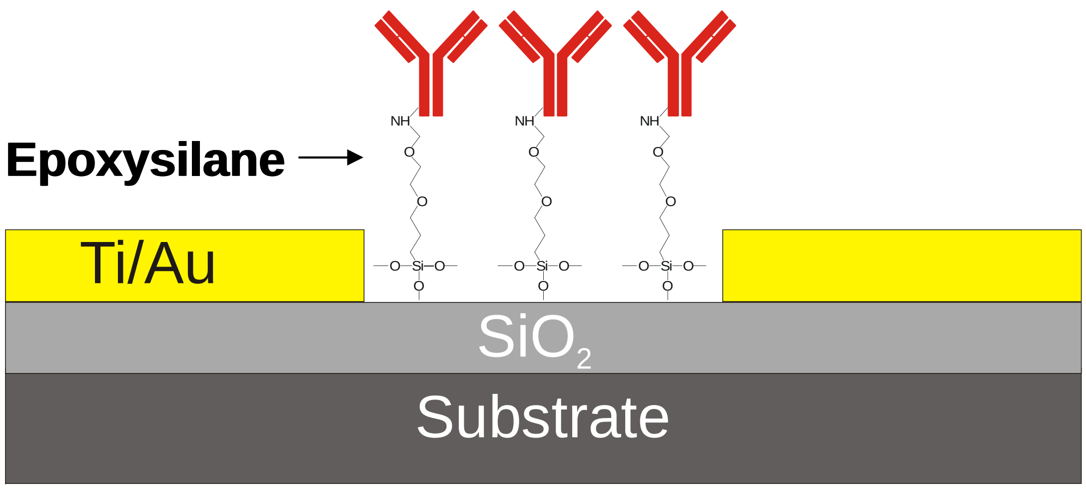


Side view

Surface functionalization uses linker molecules to attach biomolecules to inorganic surfaces



Top view



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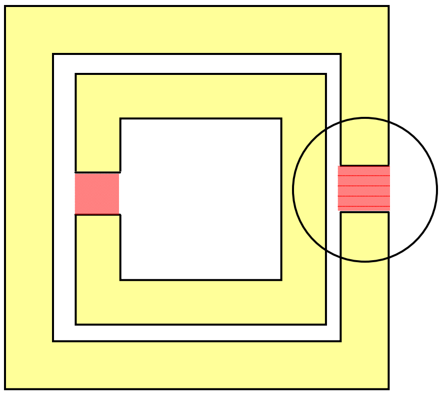
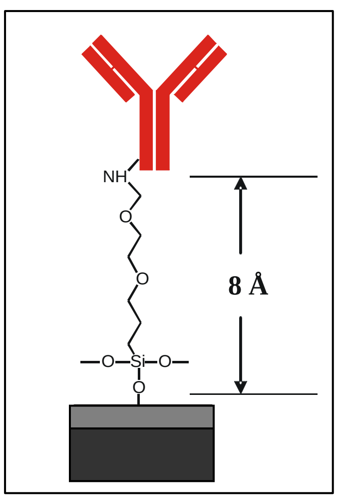
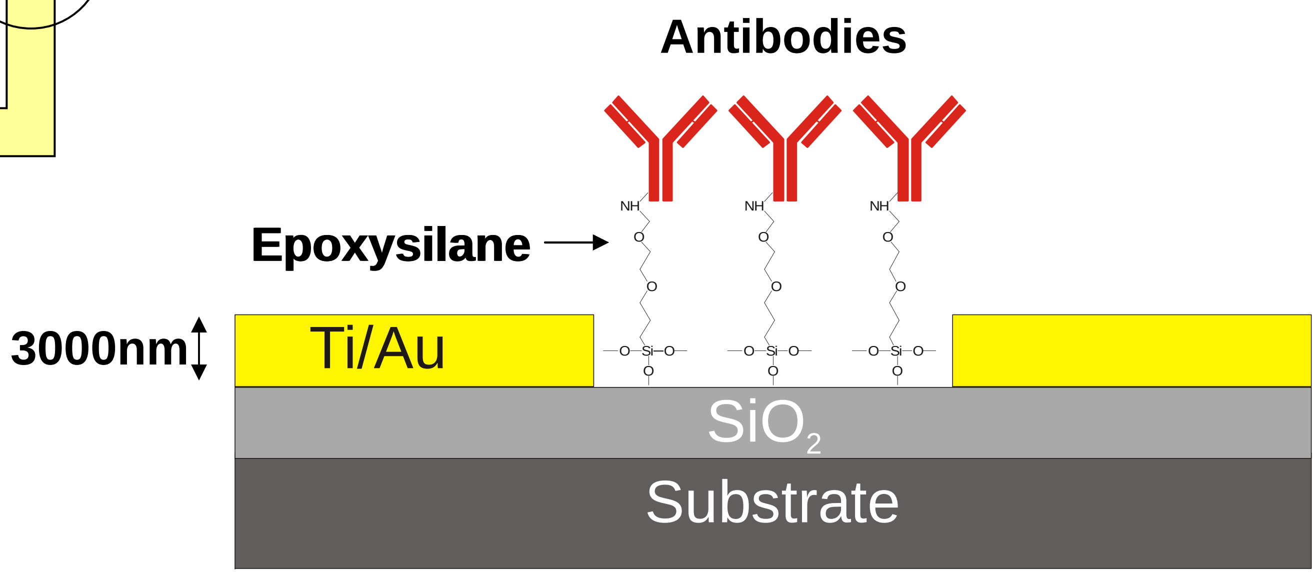


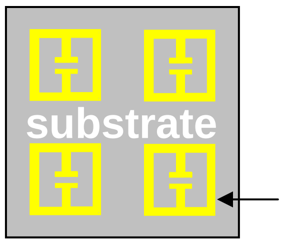
Top view



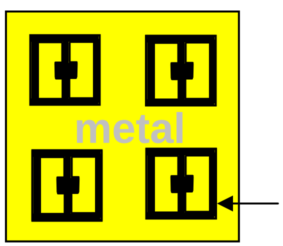


Side view

Demonstration of surface functionalization

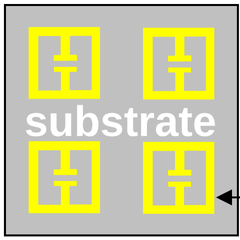


Regular metamaterial



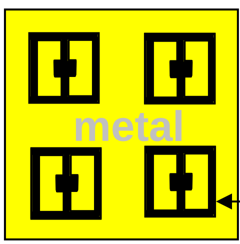
Complementary pattern for functionalization

Demonstration of surface functionalization



metal

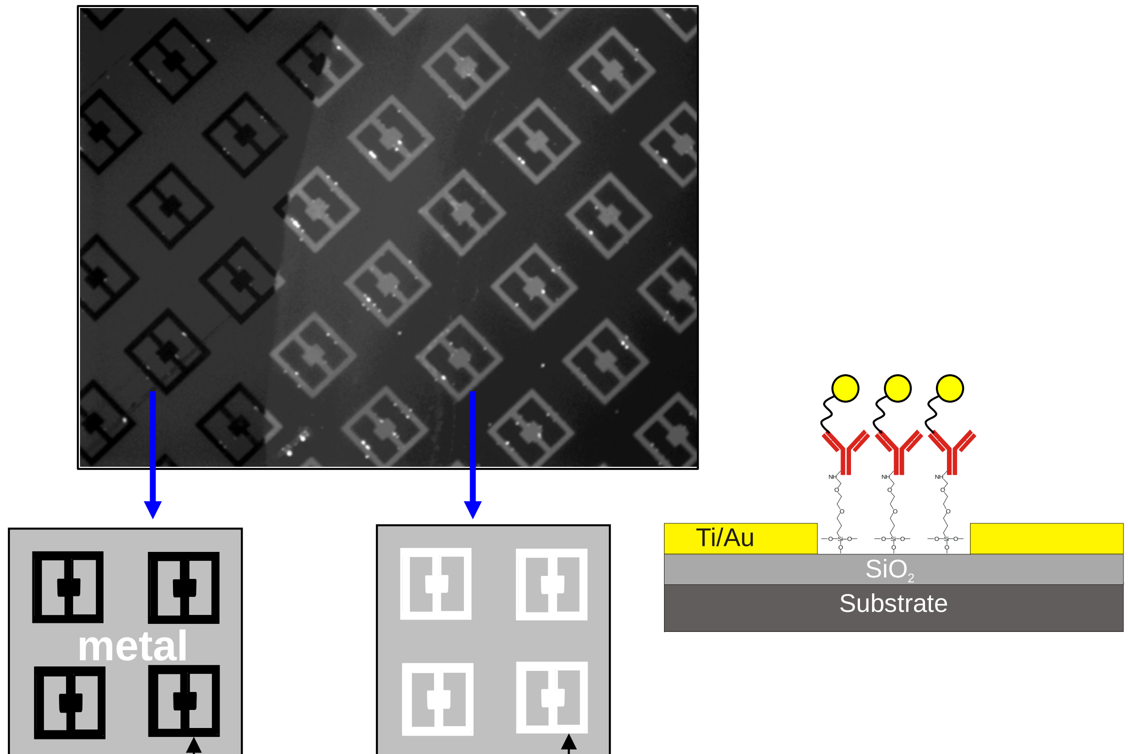
Regular metamaterial



opening

Complementary pattern for functionalization

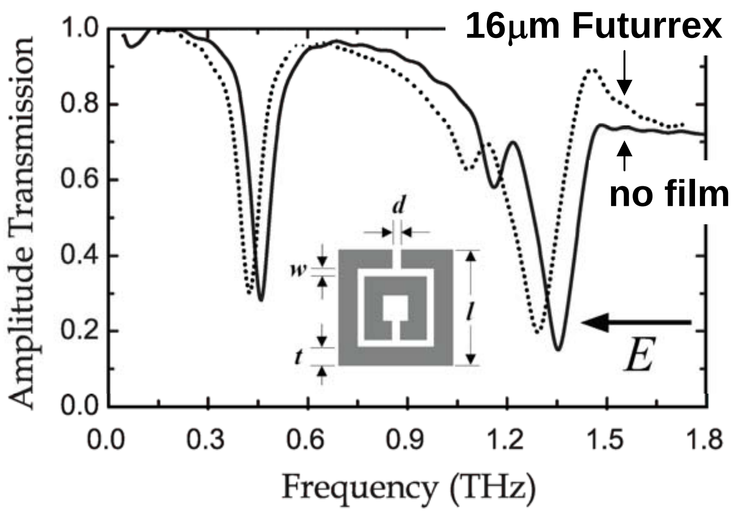
Functionalized metamaterial



epoxysilane

epoxysilane + avidin fluorescein conjugated

There exist several challenges in detecting a monolayer of biomolecules



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

Line width limits sensitivity

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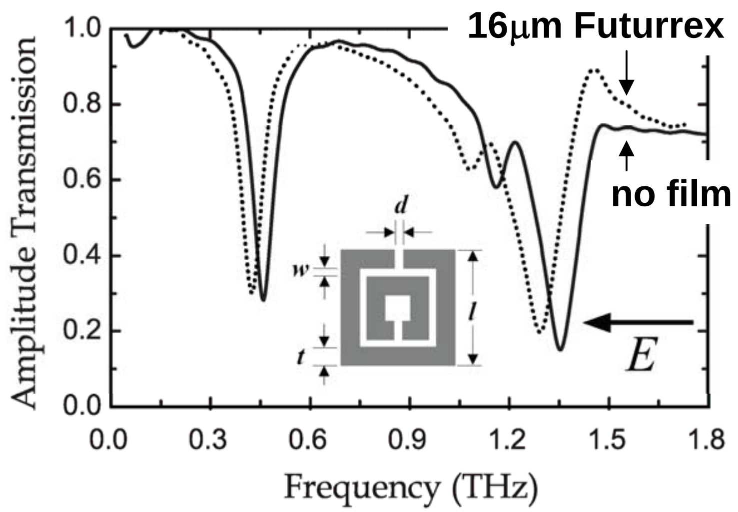

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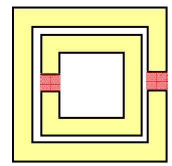

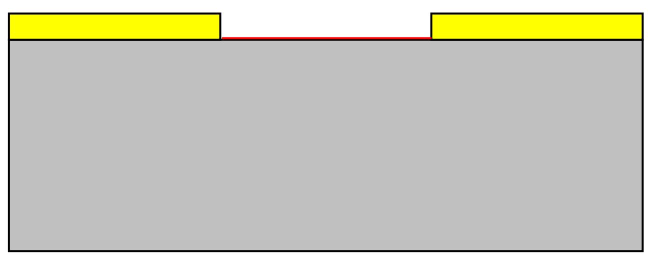

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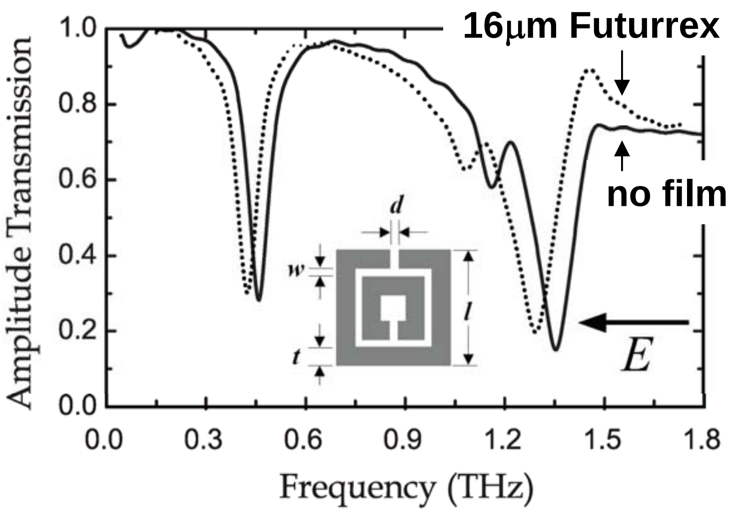

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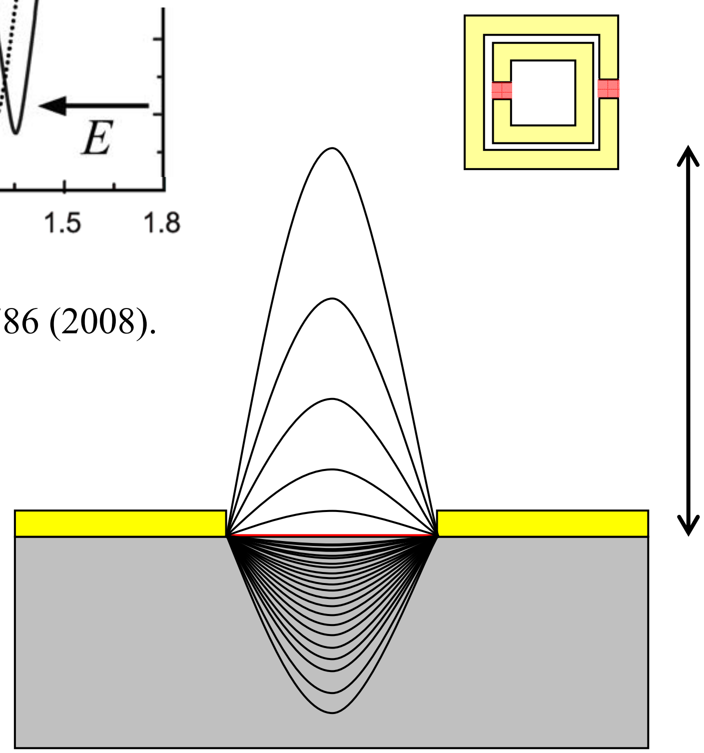

Fringing fields extend ~20μm

Concentration of electric flux in the substrate

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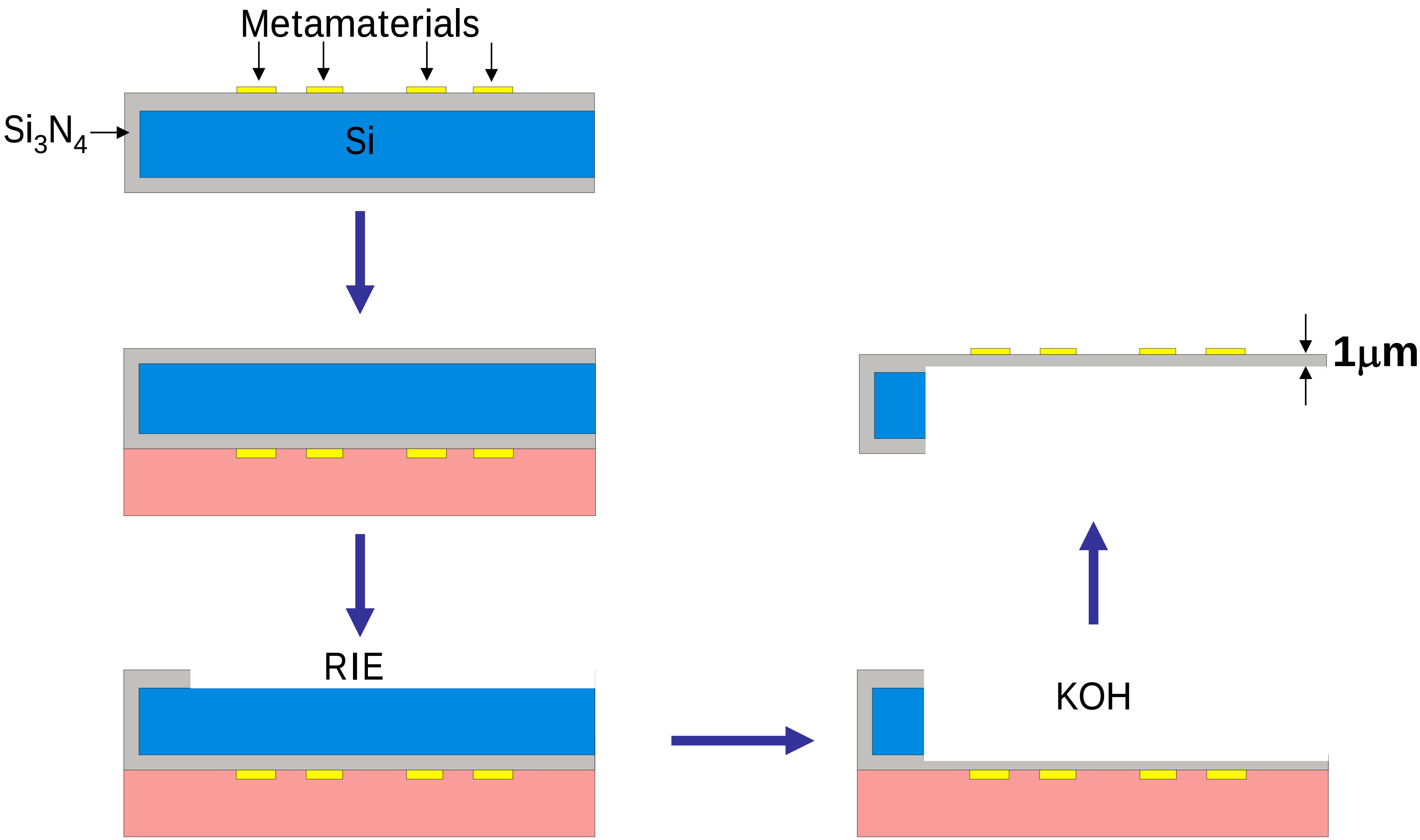
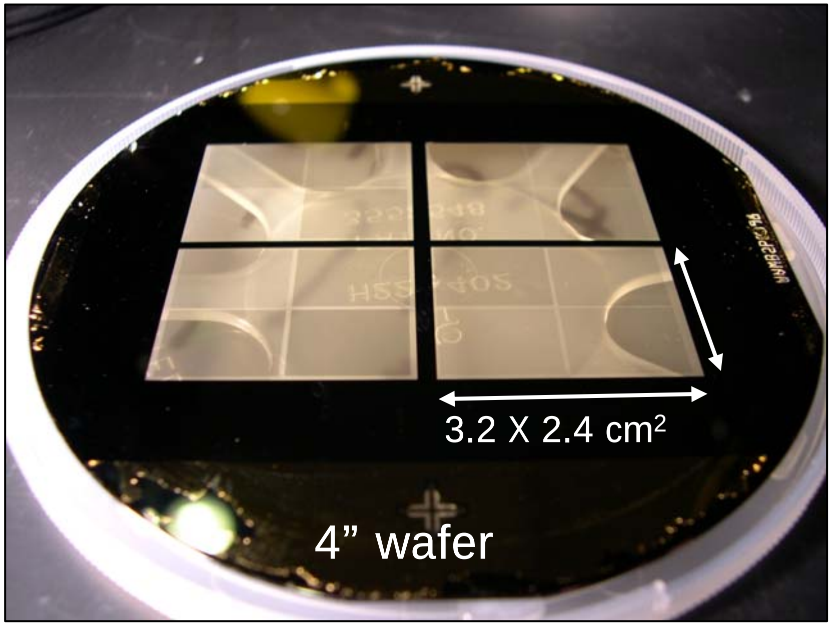
One solution is to eliminate the substrate!

➡ **Can we fabricate metamaterials on thin membranes?**

YES! THz metamaterials on silicon nitride membranes



A 4” wafer showing 4 windows in a 1μm thick free-standing silicon nitride membrane



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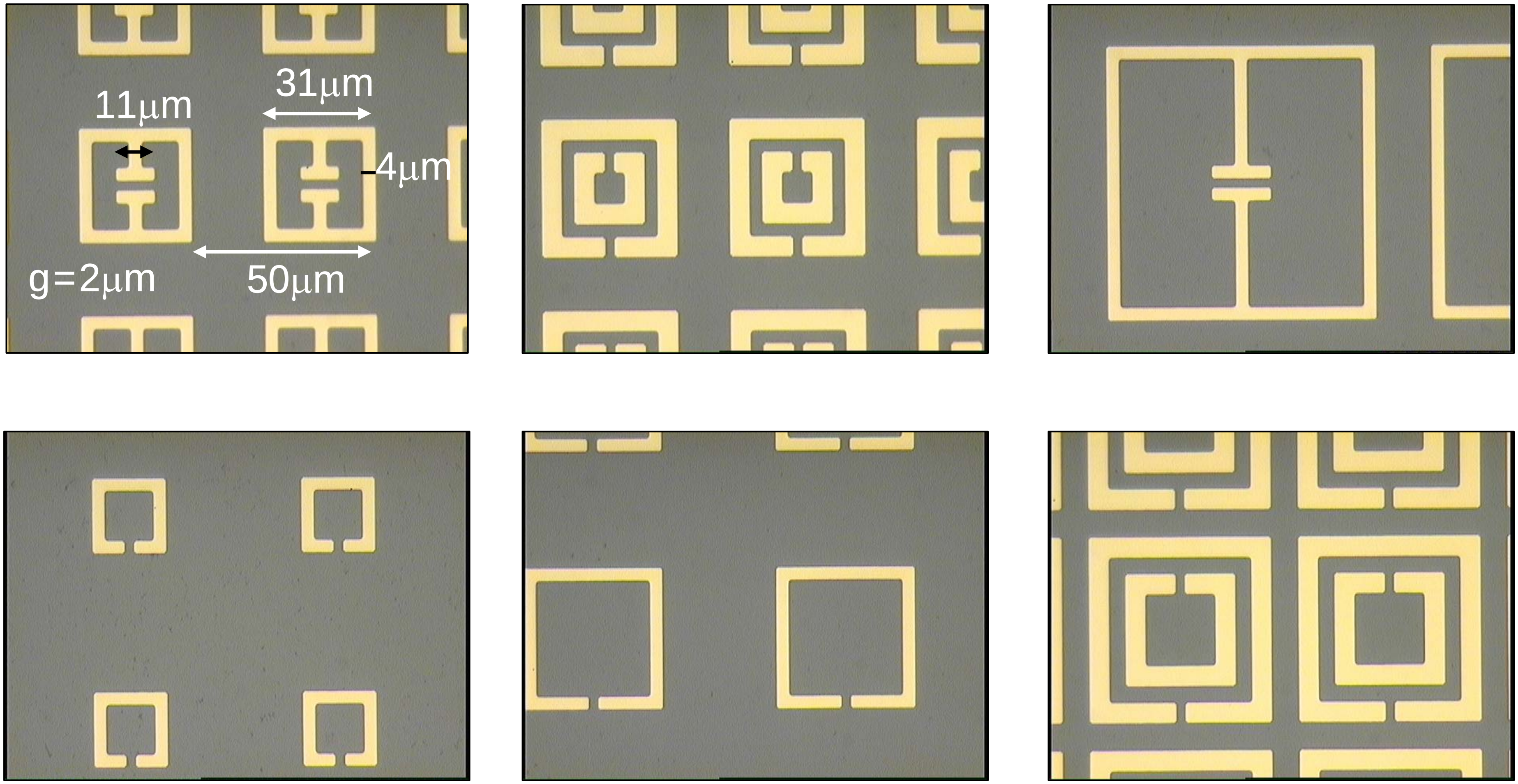
Designed 15 different metamaterials per wafer



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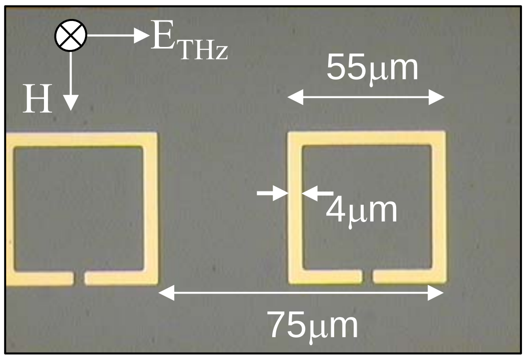
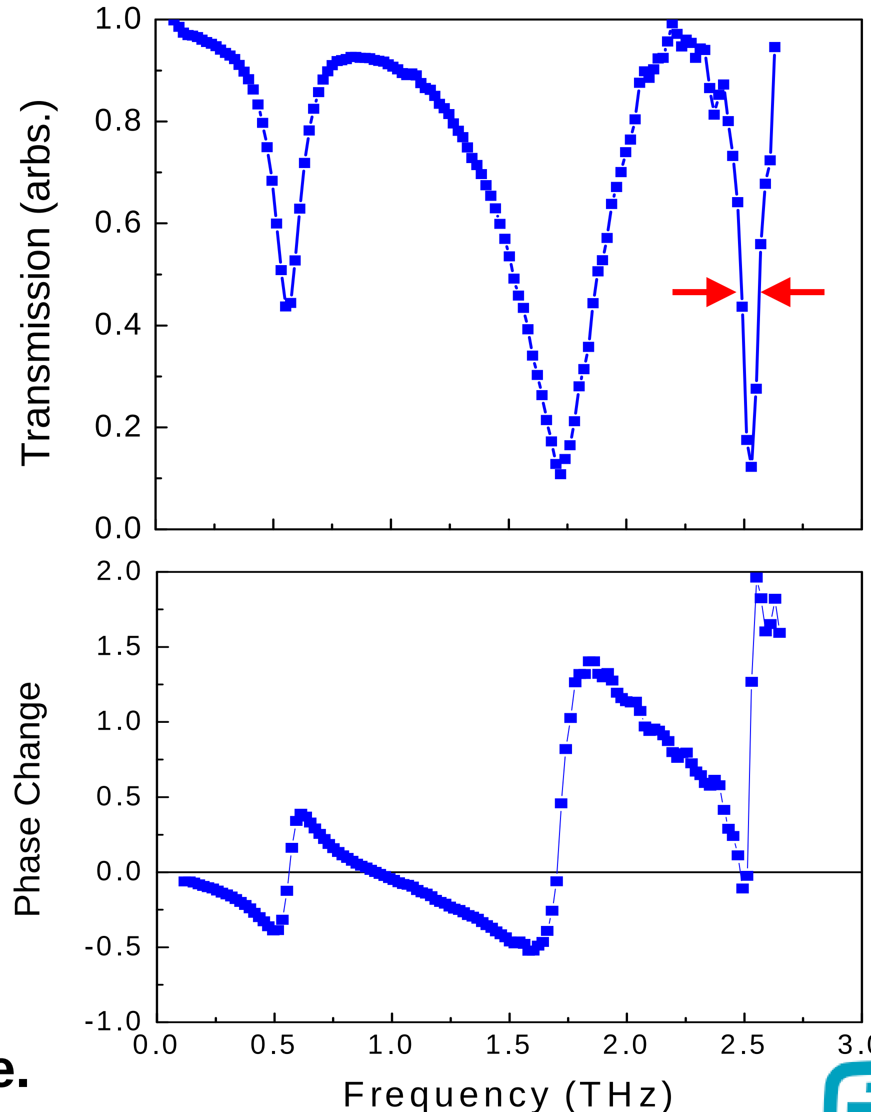
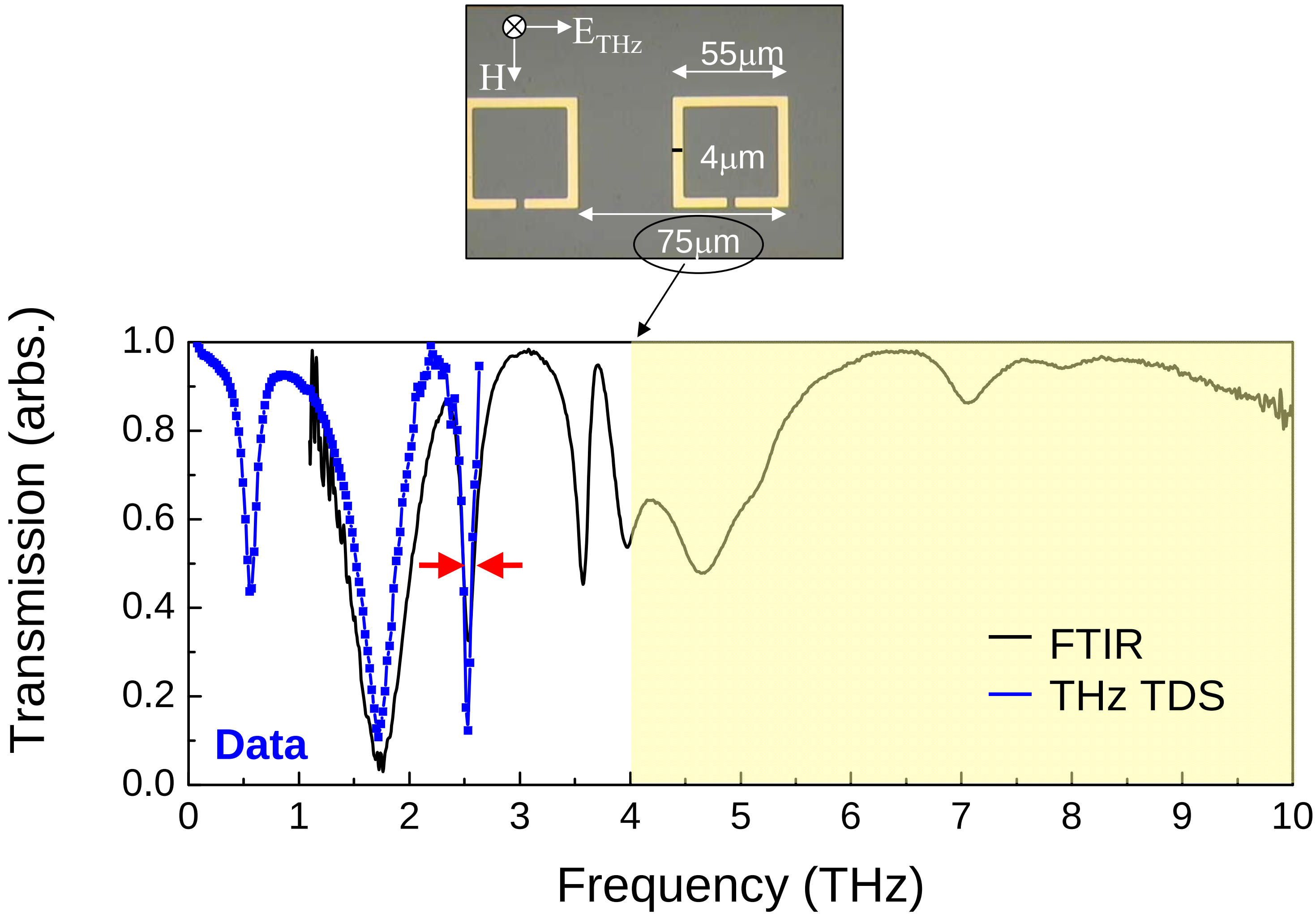
THz response of a split-ring resonator on silicon nitride has a narrow resonance line width





Dispersive behavior is a signature of a resonance.

Removing the substrate allows higher frequency measurements with an IR spectrometer (FTIR)

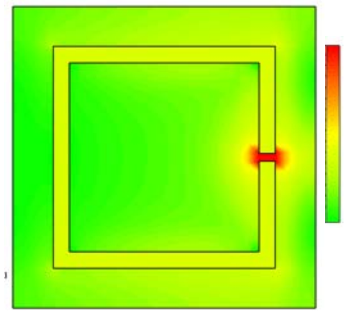


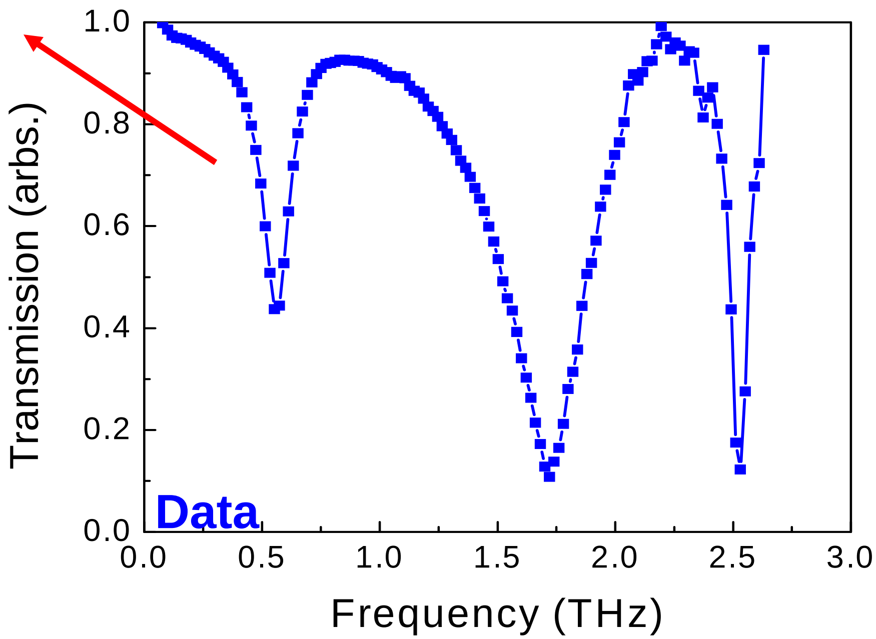
Only gives amplitude information.

Electromagnetic modeling informs us about the origin of the resonances

E-field enhancement

|E|





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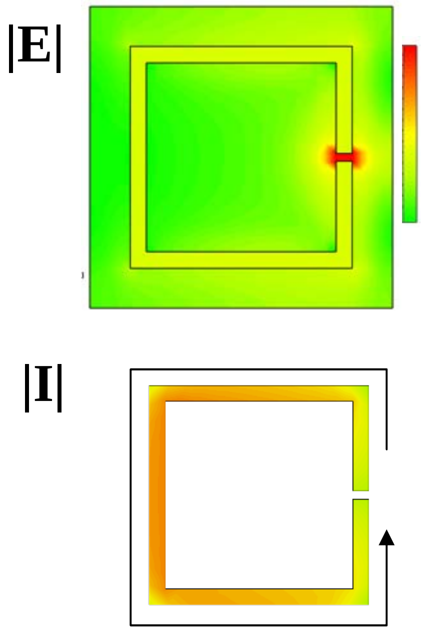
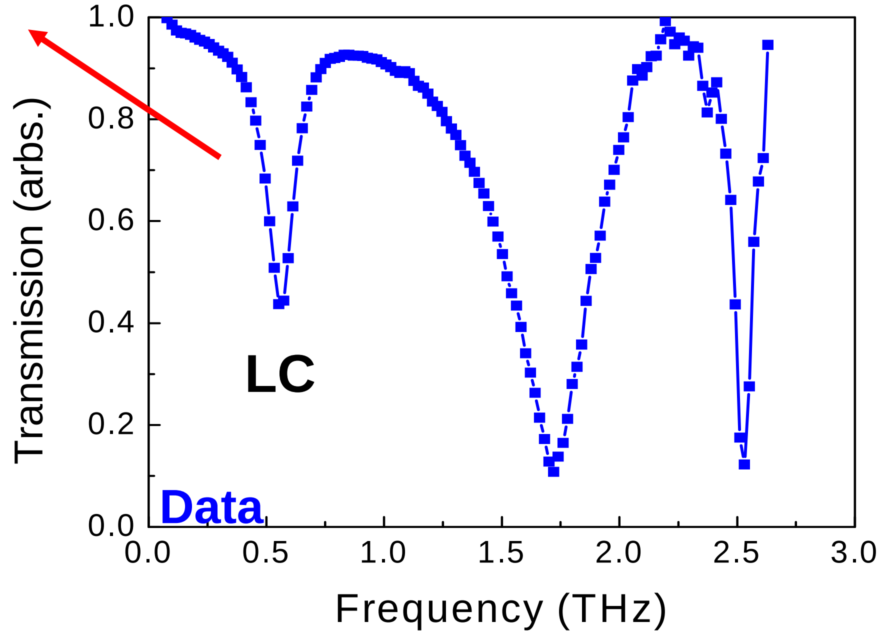
Electromagnetic modeling informs us about the origin of the resonances

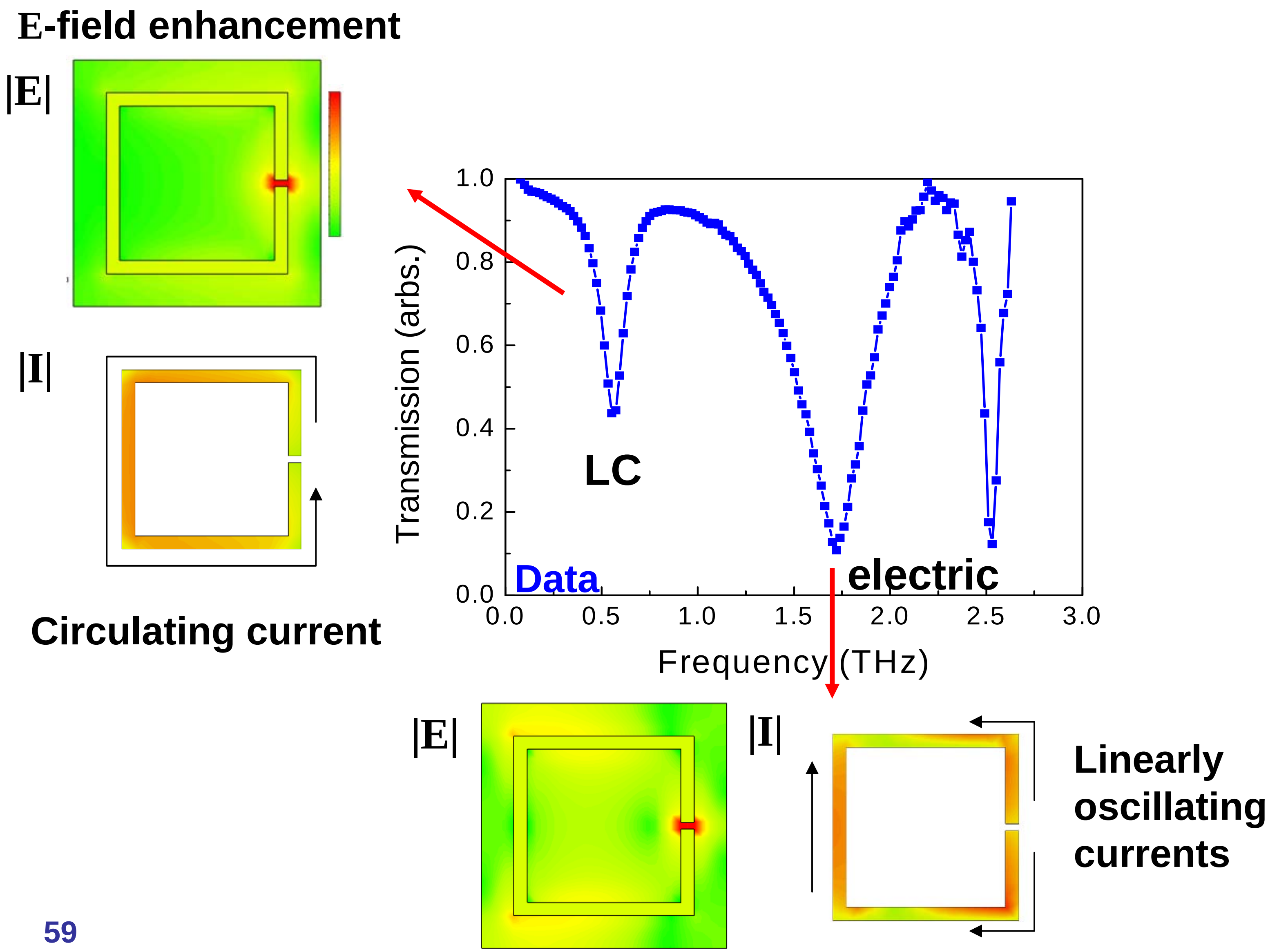
E-field enhancement



Circulating current



Electromagnetic modeling informs us about the origin of the resonances



Electromagnetic modeling informs us about the origin of the resonances

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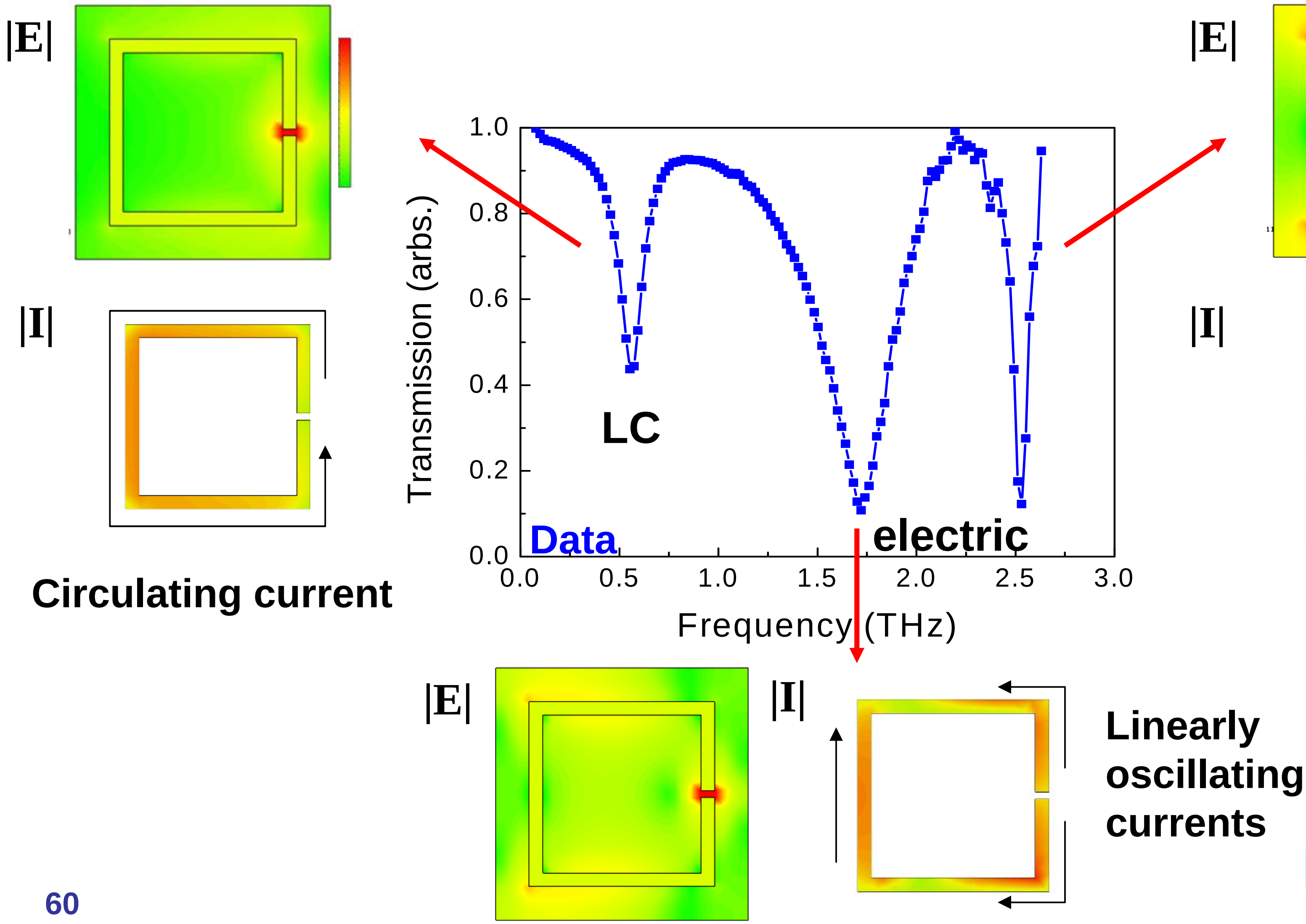

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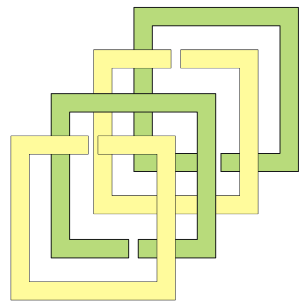
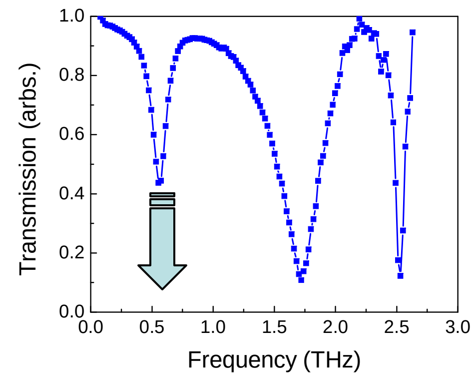
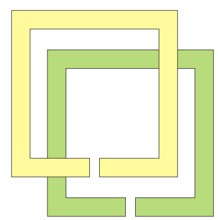
Thin membranes allow studies of coupling and symmetry in multi-layer structures

Number of layers

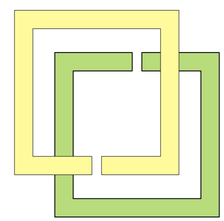




Orientation of the resonators

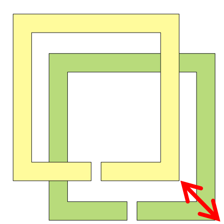


Symmetric



Antisymmetric

Separation between the layers



Periodic

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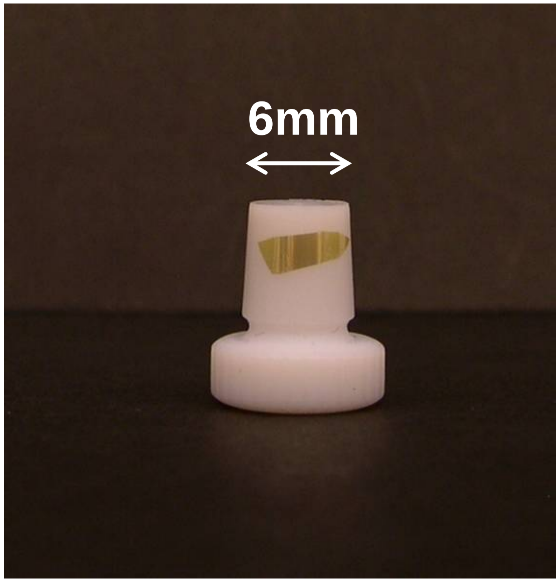
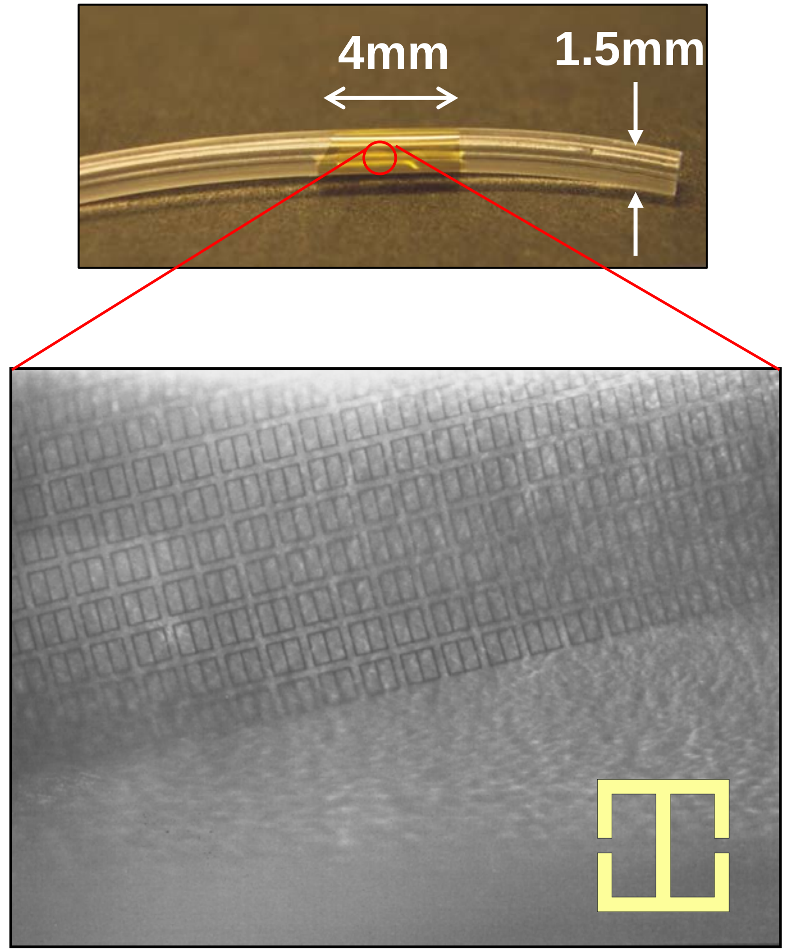
We can also release the membrane and wrap it around curved surfaces





This opens the possibility of creating 3D structures by covering curved surfaces.

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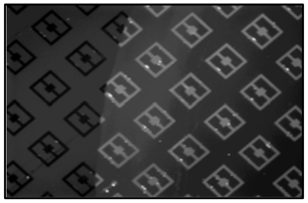
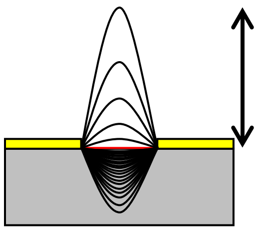
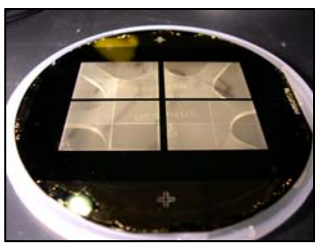
Summary covering the biosensor and thin membrane work



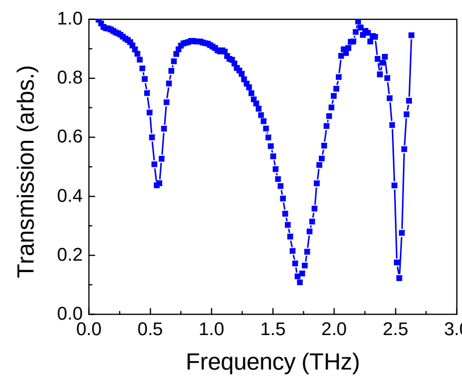
Developed a chem-bio detection scheme based on changes on the dielectric response of a metamaterial.

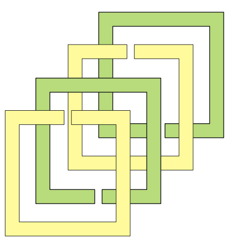


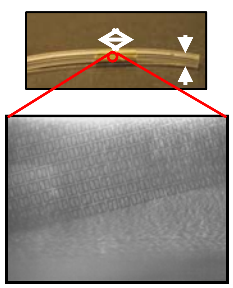
Reduced the effect of the substrate by implementing metamaterials on thin silicon nitride films.



Obtained narrow line widths from higher order modes.







Enabled studies of coupling between layers and the effects of curvature.

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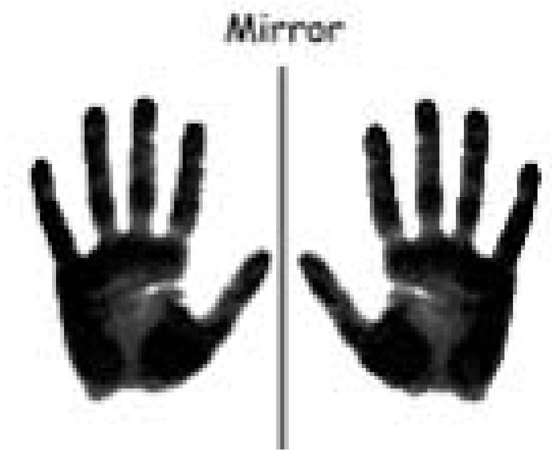
Chirality plays a role in biological systems

χειρ = hand



Chiral object cannot be superposed on its mirror image.

Many biomolecules are chiral, *e.g.,* sugars, aminoacids, enzymes...

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Chirality plays a role in biological systems

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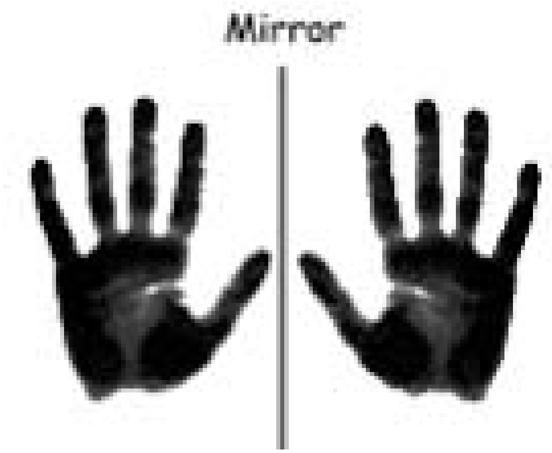
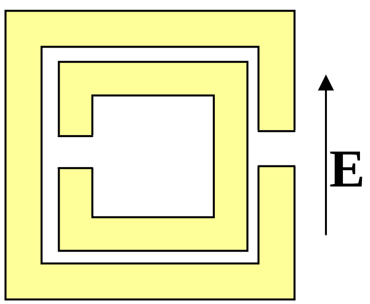


Chiral object cannot be superposed on its mirror image.

Many biomolecules are chiral, *e.g.,* sugars, aminoacids, enzymes...

Chiral molecules rotate the polarization of light.

Most metamaterial designs are sensitive to the incident polarization



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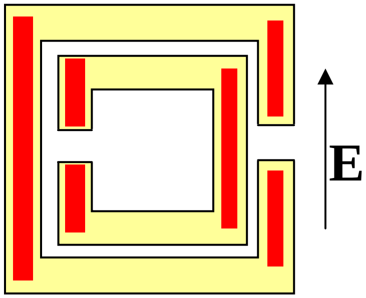

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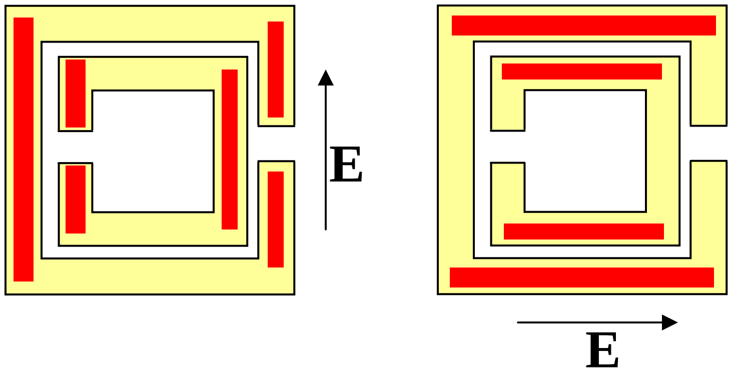
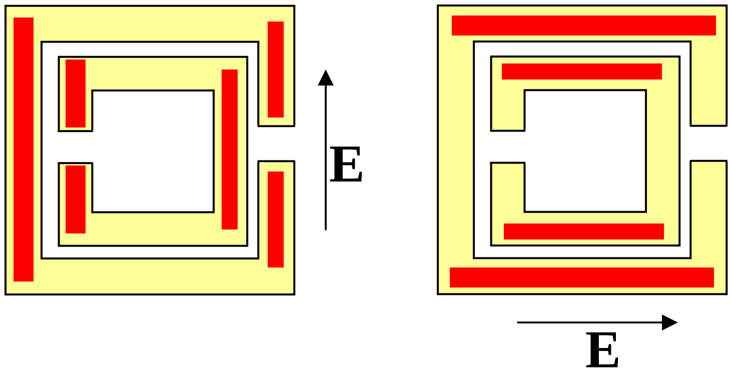


Culprit are the symmetries of the structures

Most metamaterial designs are sensitive to the incident polarization



Culprit are the symmetries of the structures

Can we design a metamaterial that is insensitive to the incident polarization?

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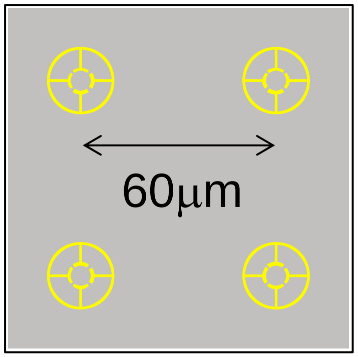
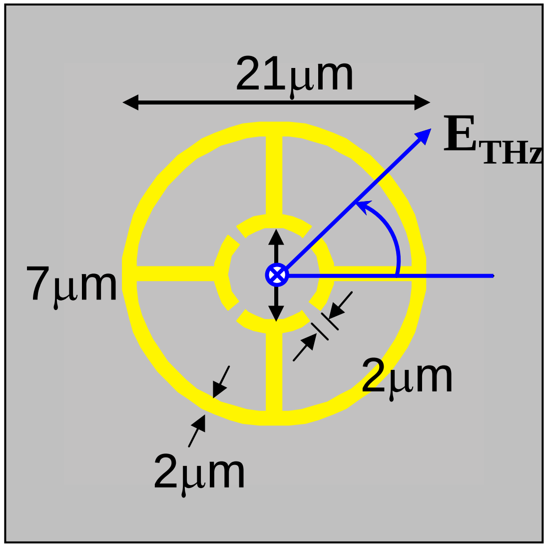
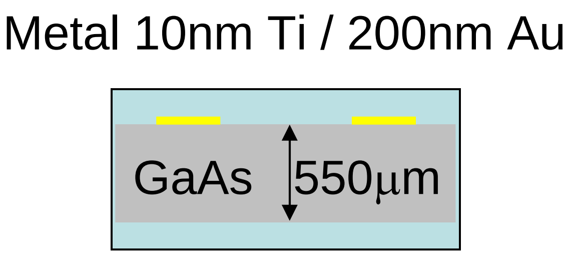
YES! With a circular split-ring resonator (CSRR)



Top view

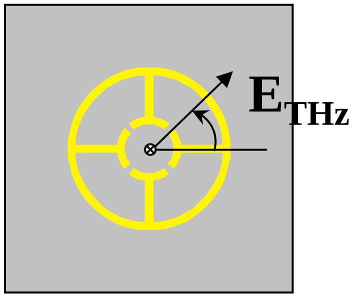


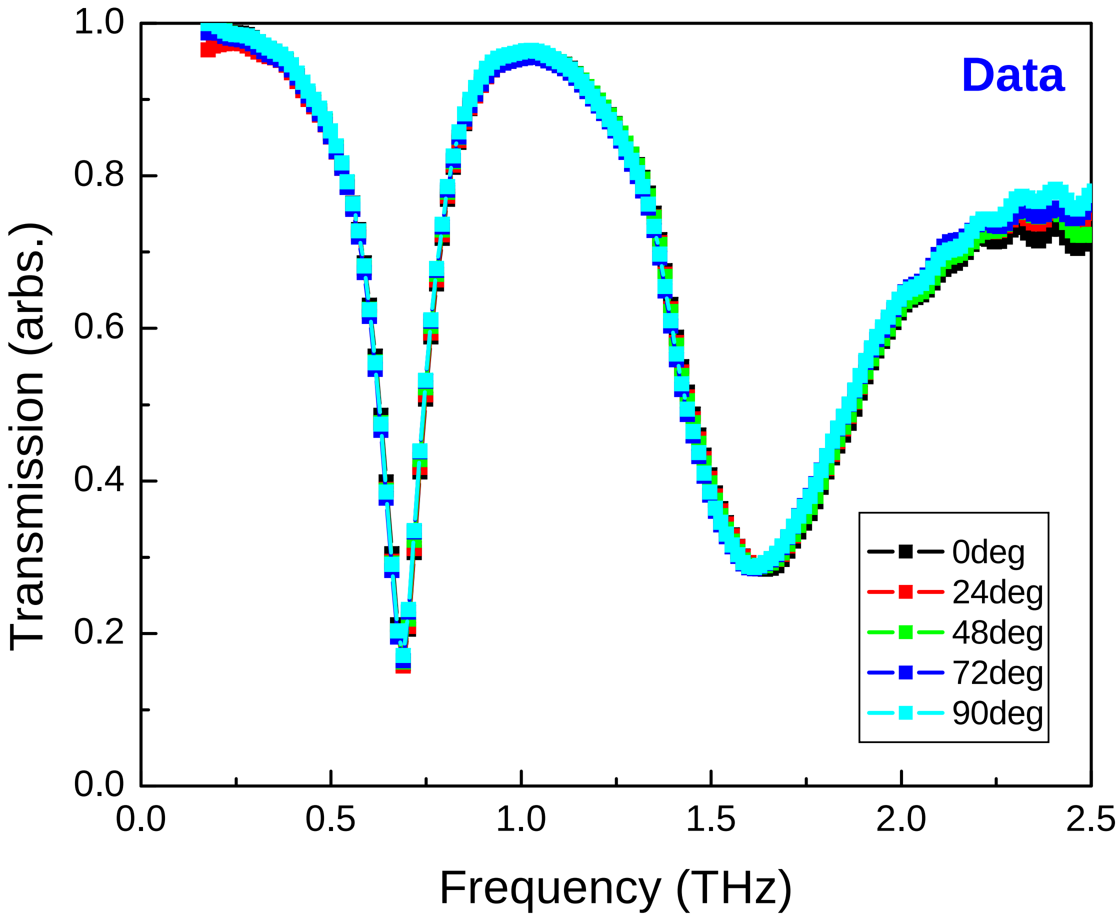


Side view

Vary the angle between the incident electric field and the horizontal axis of the circles.

CSRR metamaterial is insensitive to polarization of the incident radiation





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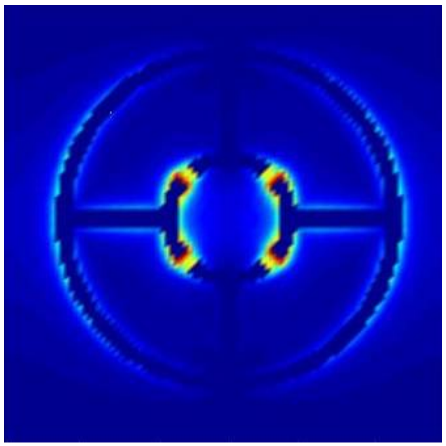
Physical origin of the resonances

E-field enhancement

|E|



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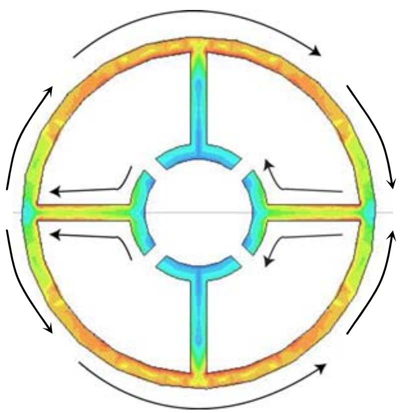
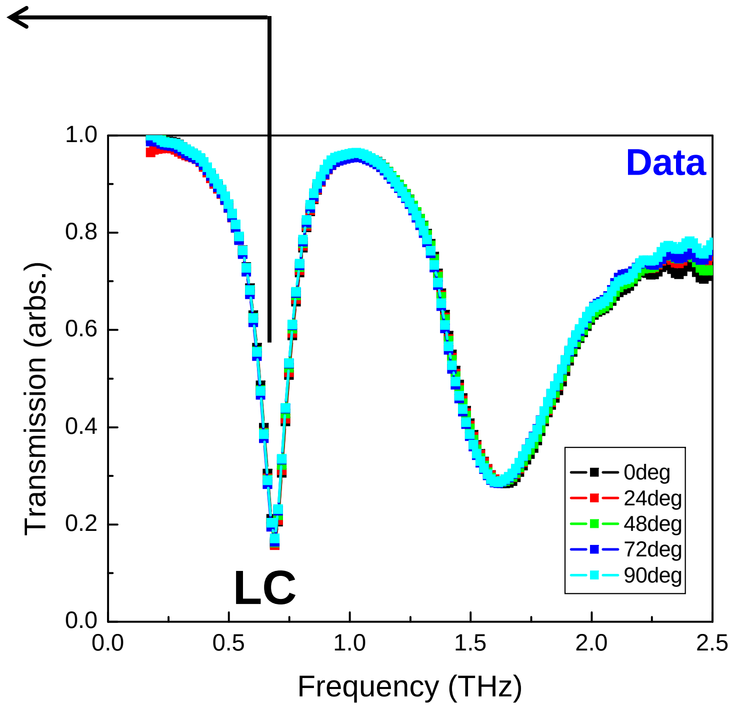


Circulating currents



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Physical origin of the resonances

E-field enhancement

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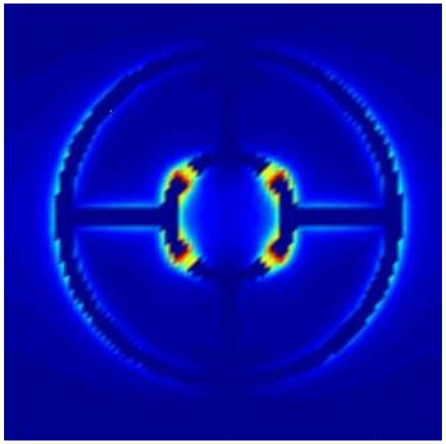

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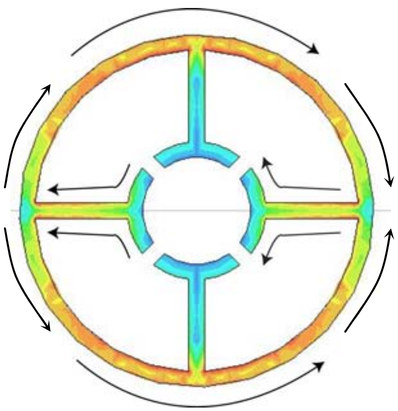
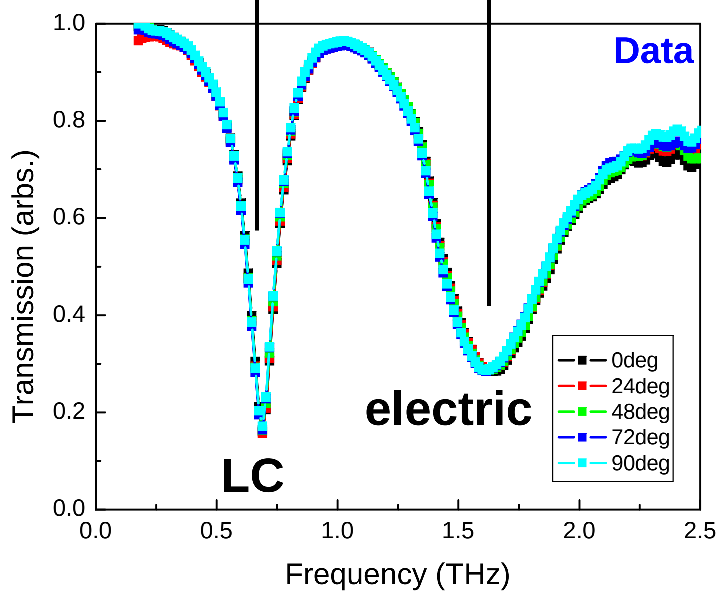
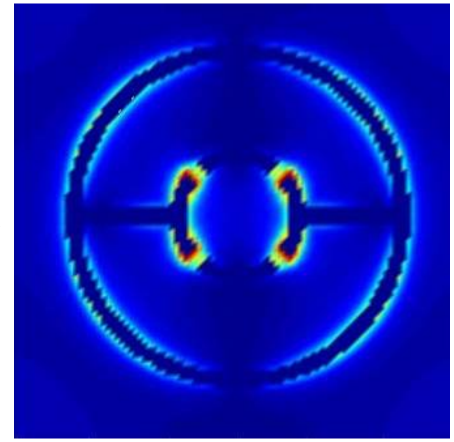


Circulating currents



E-field enhancement

|E|



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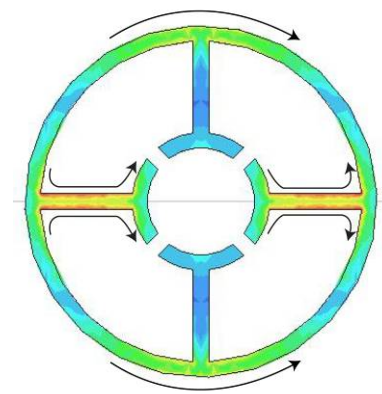

Dipole-like resonance

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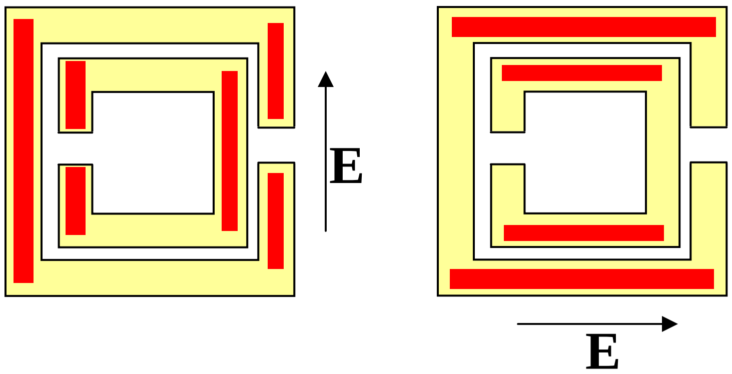
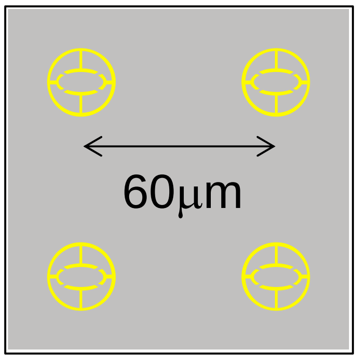
Metamaterial with circular symmetry does not respond to polarization



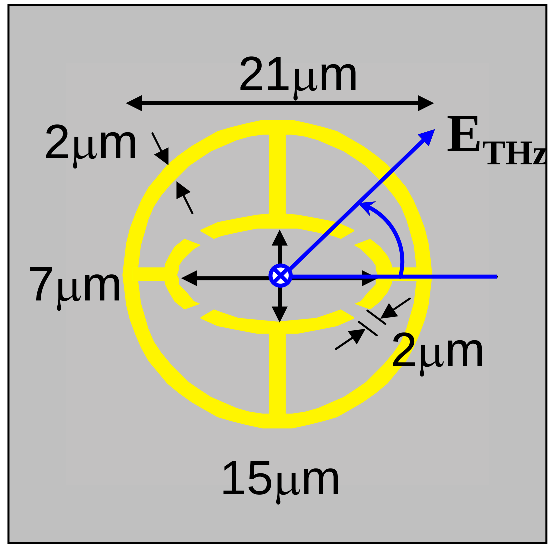
Culprit are the symmetries of the structures

➡ **Can we design a metamaterial that is sensitive to the incident polarization in a predictable manner?**

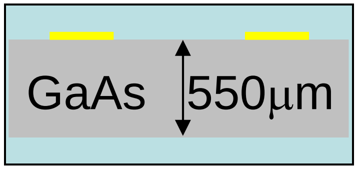
YES! By modifying the symmetry of the CSRR we obtain and elliptical split-ring resonator (ESRR)



Top view



Metal 10nm Ti / 200nm Au



Side view

Vary the angle between the incident electric field and the major axis of the ellipse.

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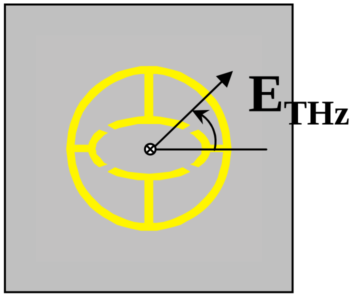
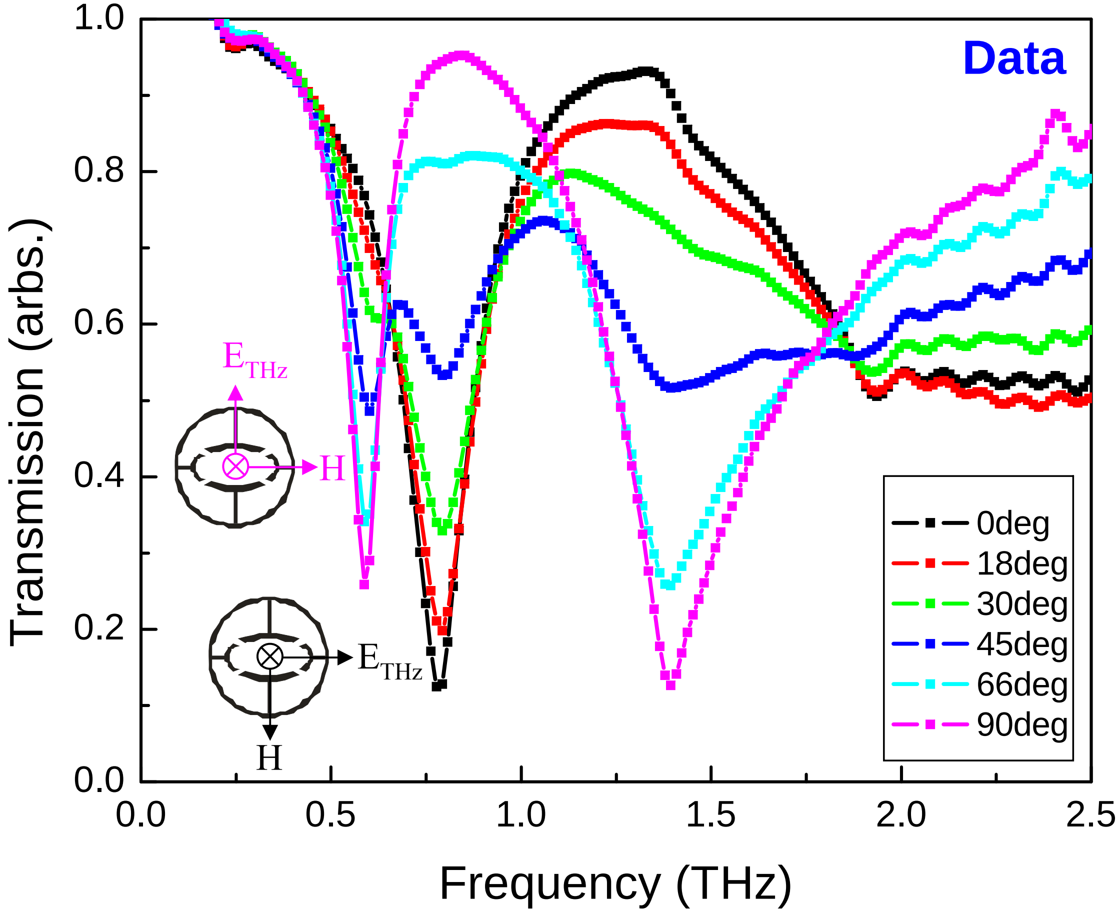
ESRR metamaterial responds to the polarization of the incident radiation





Number and amplitude of transmission minima depend on the incident polarization.

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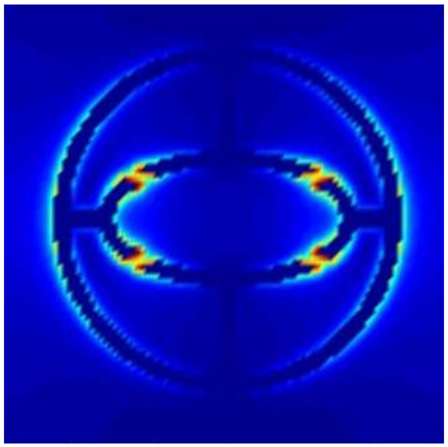
At 0°, there are strong circulating and linearly oscillating currents in both resonances

E-field enhancement

|E|



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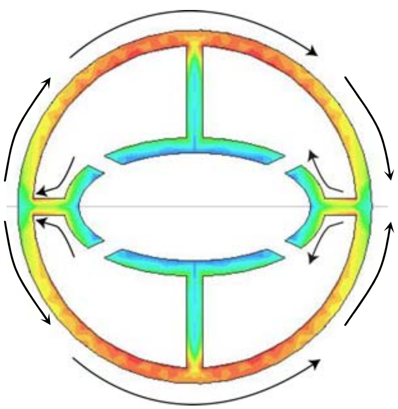
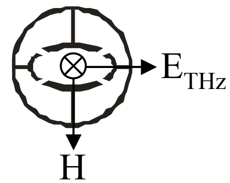
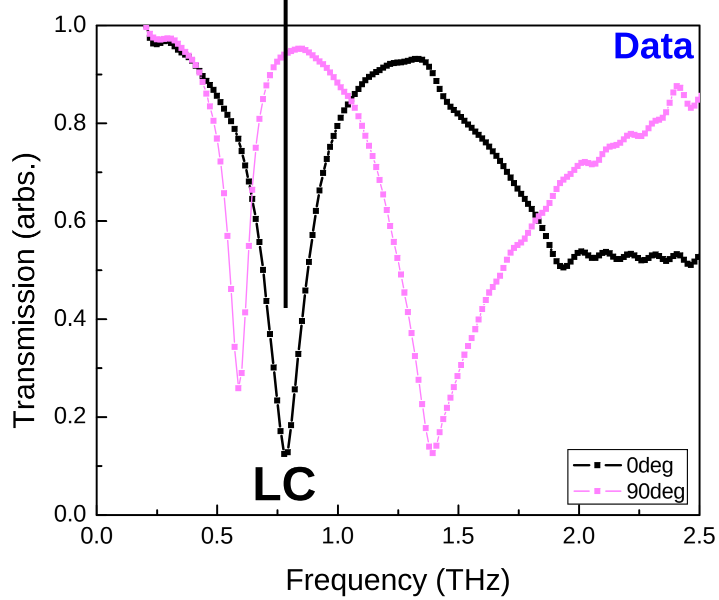
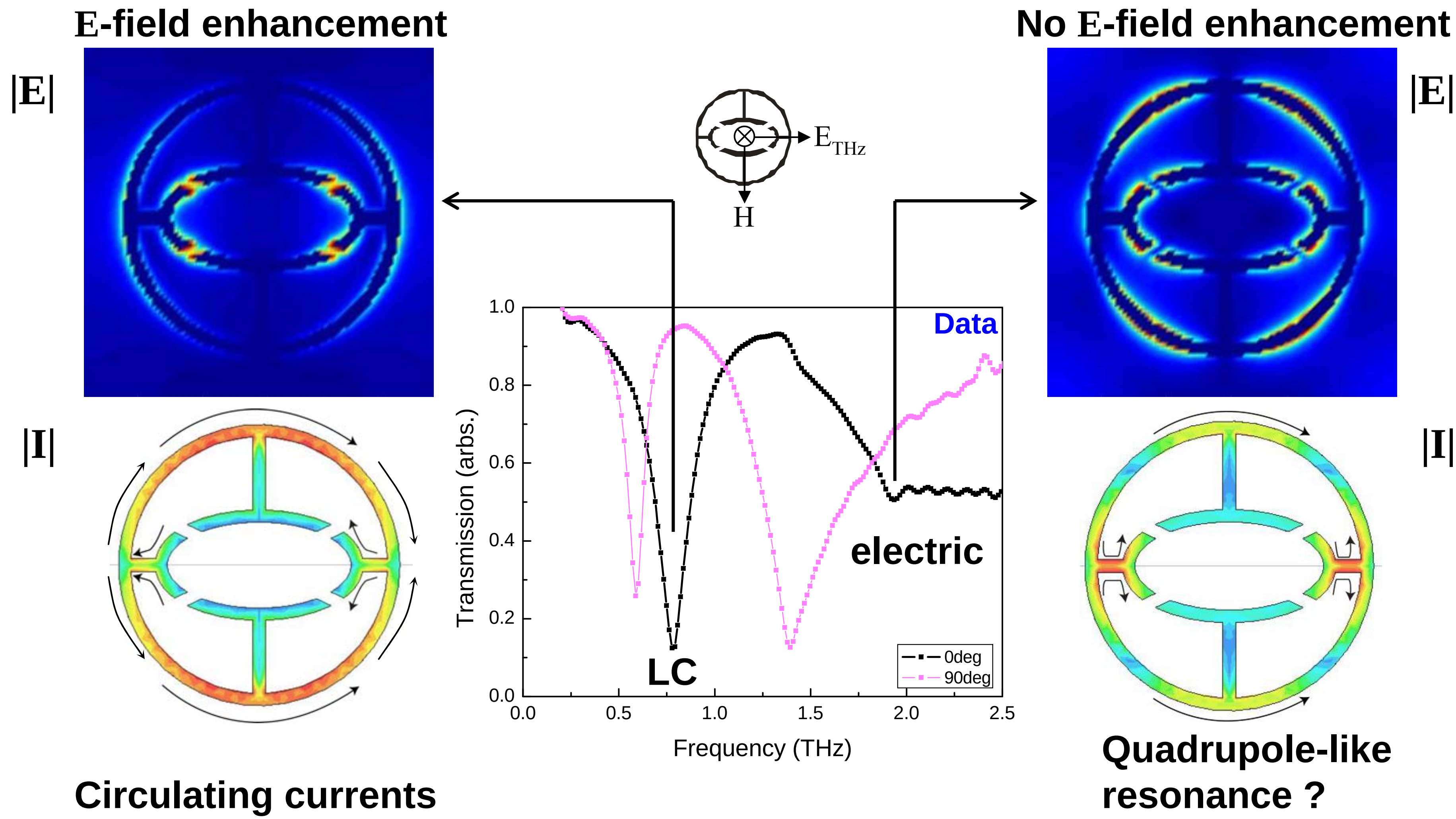






Circulating currents

At 0°, there are strong circulating and linearly oscillating currents in both resonances



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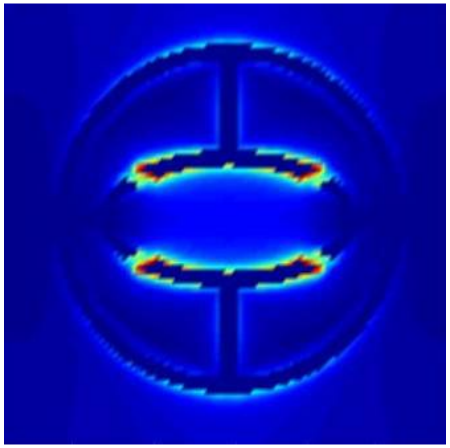
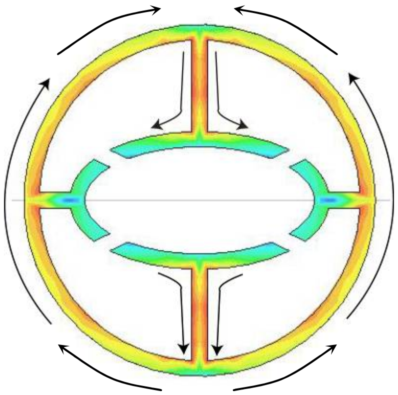
At 90°, the circulating and linearly oscillating currents are weak

Some E-field enhancement

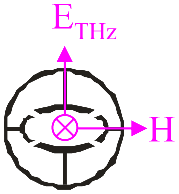
|E|

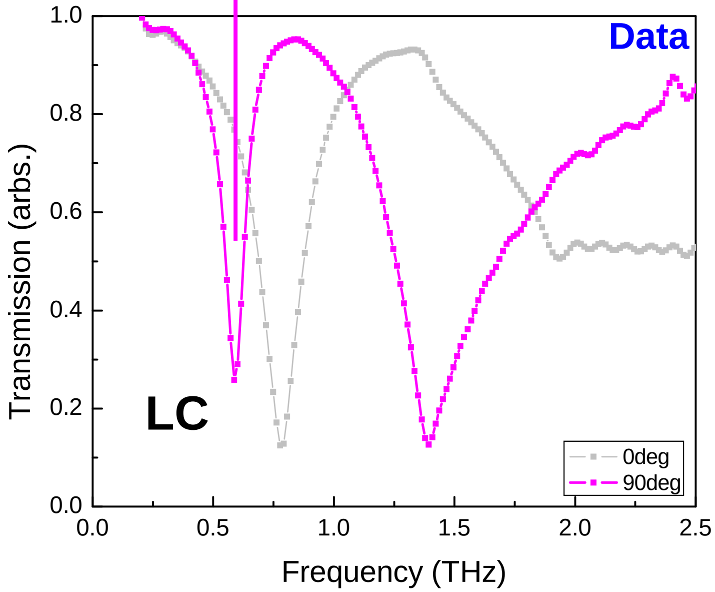


|I|



Circulating currents





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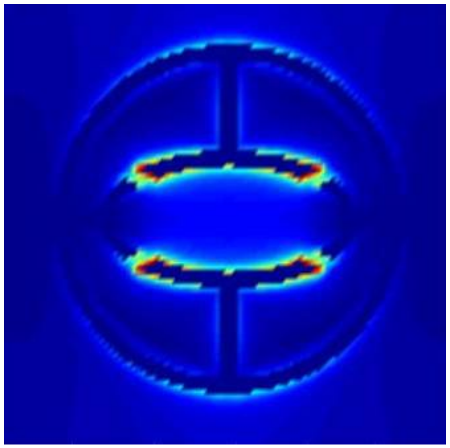
At 90°, the circulating and linearly oscillating currents are weak

Some E-field enhancement

|E|



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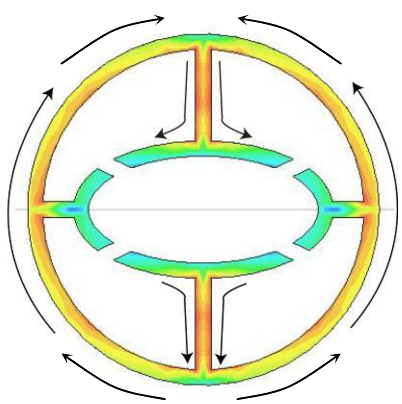
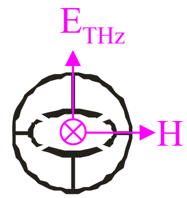
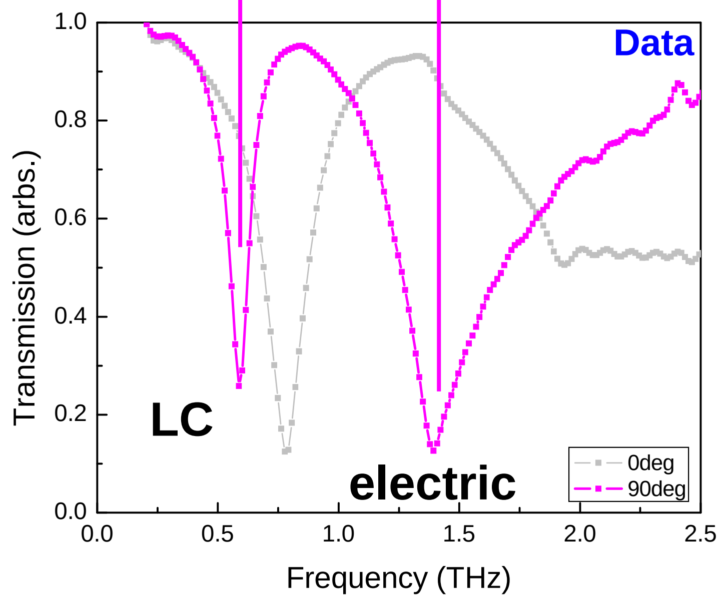


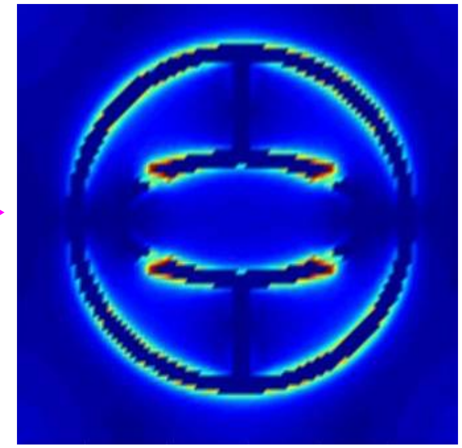
Circulating currents





Some E-field enhancement

|E|



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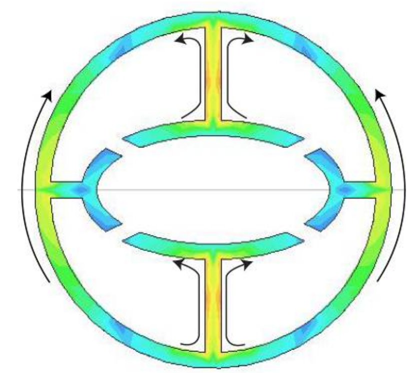

Weak dipole-like resonance

The LC resonance has the narrowest line width!

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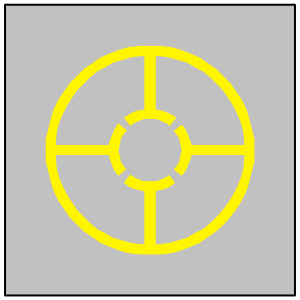
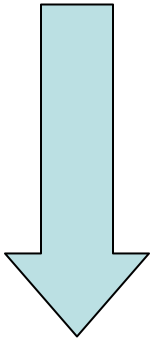
Summary for polarization sensitive and insensitive metamaterials

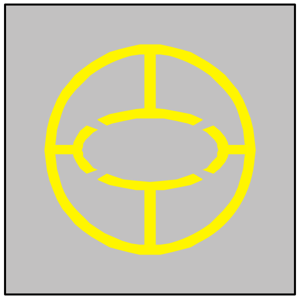
Designed, fabricated and characterized a metamaterial insensitive to the incident polarization.



Circular Split-Ring Resonator (CSRR)



By modifying the symmetry we obtained a polarization sensitive metamaterial.



Elliptical Split-Ring Resonator (ESRR)

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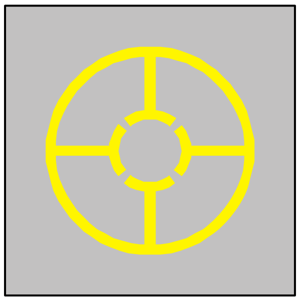
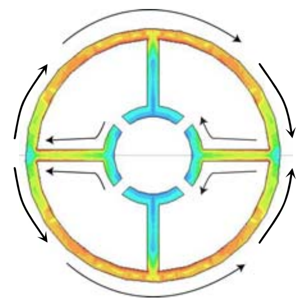
Summary for polarization sensitive and insensitive metamaterials



Designed, fabricated and characterized a metamaterial insensitive to the incident polarization.

Circular Split-Ring Resonator (CSRR)



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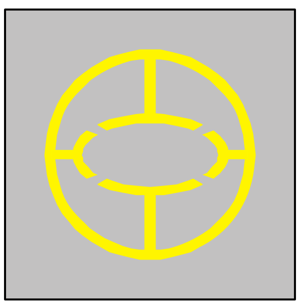
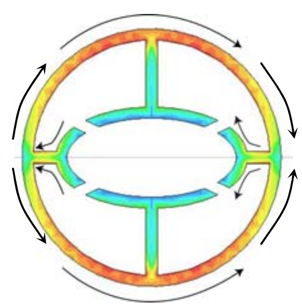


Elliptical Split-Ring Resonator (ESRR)



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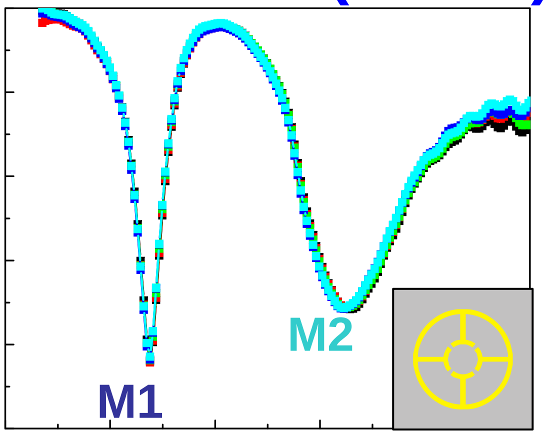
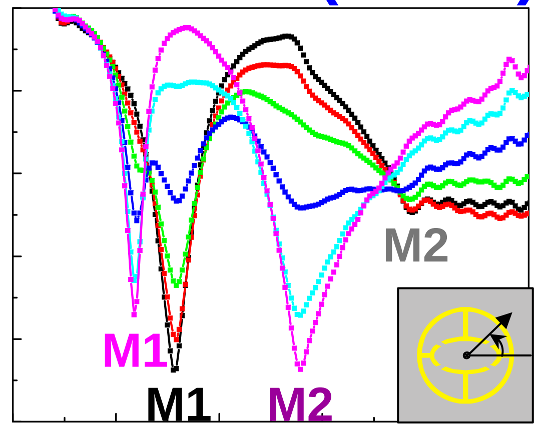
Summary for polarization sensitive and insensitive metamaterials

Circular Split-Ring Resonator (CSRR)



Elliptical Split-Ring Resonator (ESRR)



	CSRR		ESRR 0°		ESRR 90°	
	M1	M2	M1	M2	M1	M2
Enhancement of electric fields	✓	✓	✓	X	✓	✓
LC resonances	✓	X	✓	X	✓	X
Dipole-like resonance	X	✓	X	Q?	X	W

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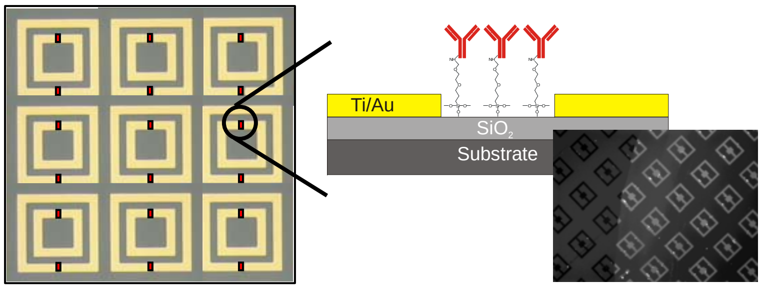
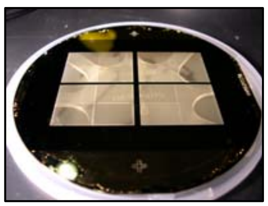
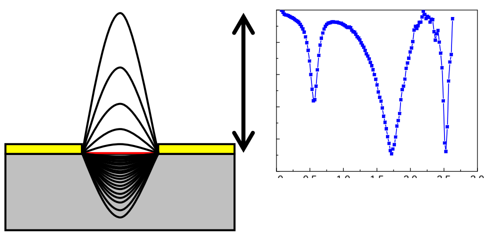
In summary, THz metamaterials enable studies of the interaction of light with biomolecules…



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

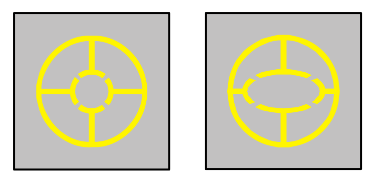




2) Implemented metamaterials on thin membranes

- **Eliminates the effect of the substrate and allows a more symmetric distribution of the electric flux**
- **Obtained narrow line widths from higher order modes which will improve the sensitivity**

3) Implemented and characterized polarization sensitive and insensitive metamaterials necessary for chirality studies in biomolecules at THz frequencies



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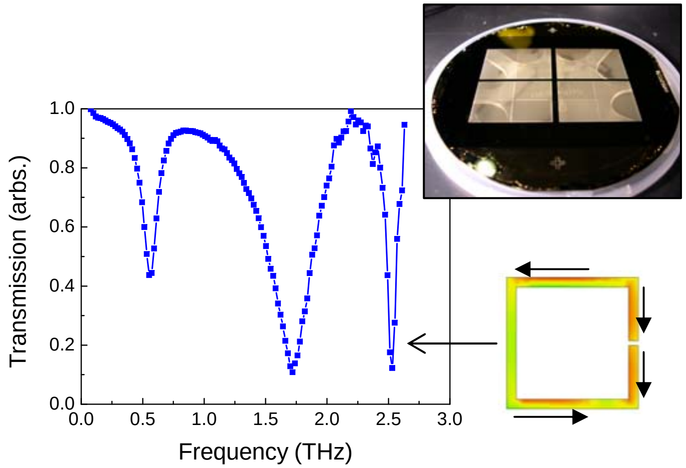
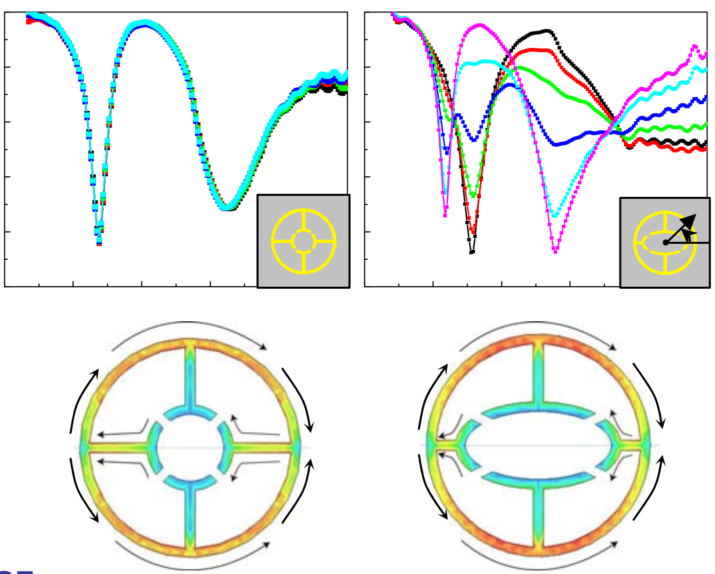
…and of the interaction of THz radiation with artificially structured materials



4) Metamaterials on thin membranes

- **Narrow line width associated with a higher order mode shows an asymmetric distribution of currents**



5) Polarization sensitive and insensitive metamaterials

- **Change in symmetry dramatically alters the response**
- **Reduced current in inner arms**

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Acknowledgements

Igal Brener (SNL)
Jeffrey Hamilton (IC Advisor)

Richard D. Averitt (BU)
Andrew Strikwerda (BU)
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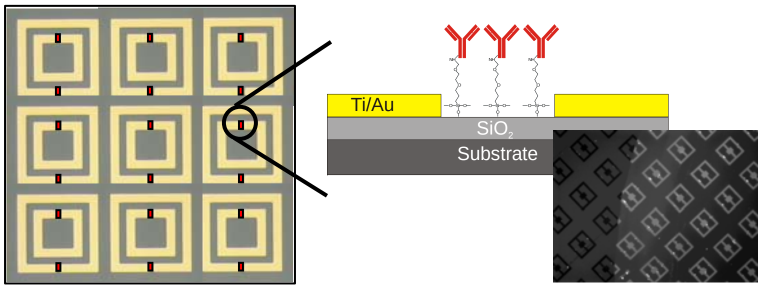
John O'Hara (LANL)
Evgenya Smirnova (LANL)

Eric A. Shaner (SNL)
Darren W. Branch (SNL)

Funding

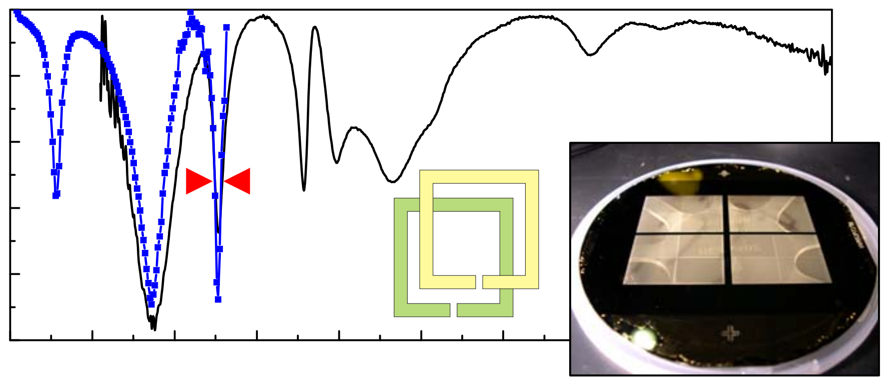
- IARPA thru the IC Postdoctoral Fellowship Program
- CINT User Program

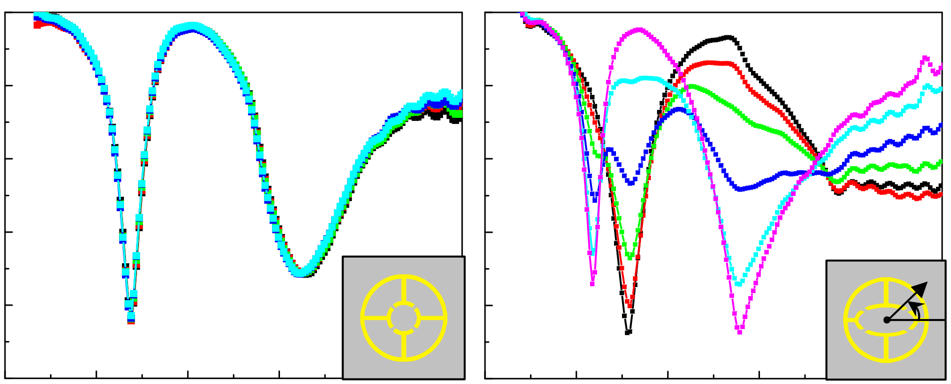
In summary, metamaterials enable studies of the interaction of light with materials



Biological sensing with metamaterials

Metamaterials on free-standing silicon nitride membranes





Polarization sensitive and insensitive metamaterials

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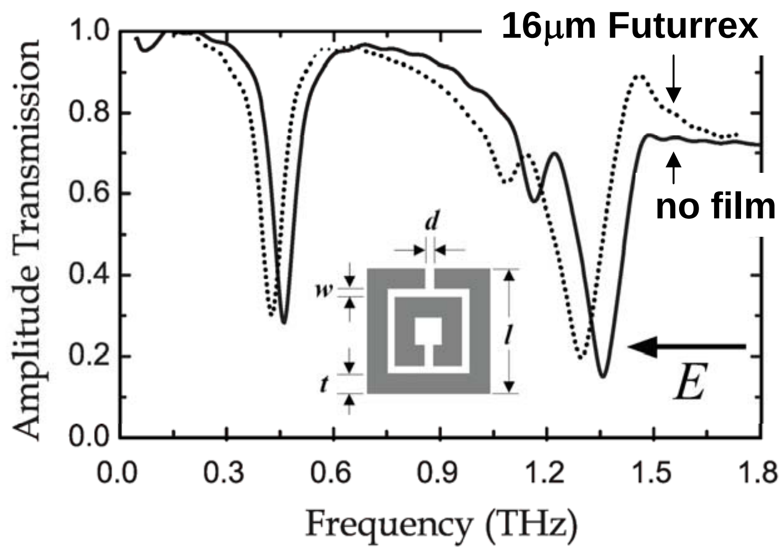
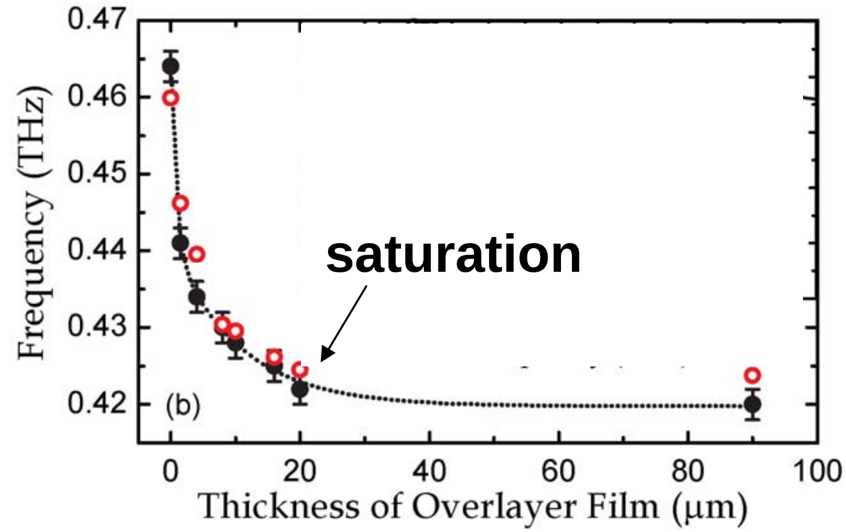
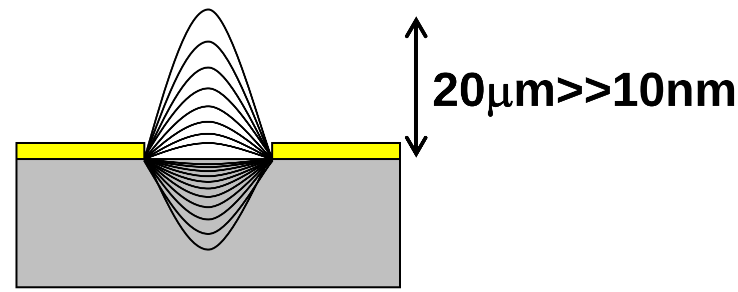
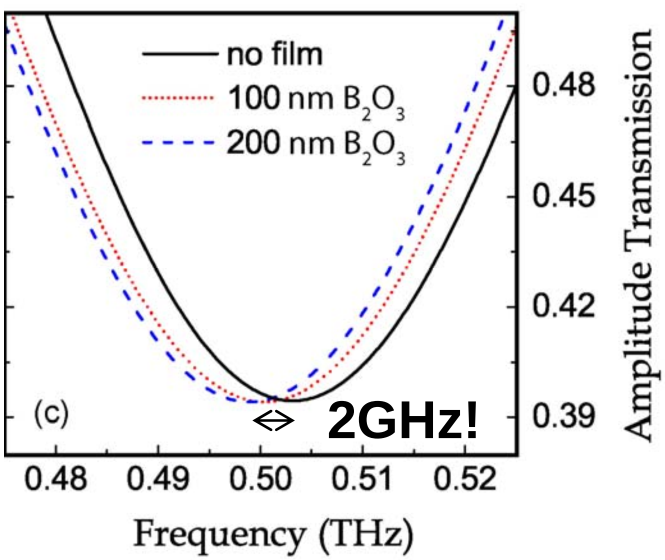
Previous studies identified some issues that need to be addressed









- Distribution of electric field.
- Line width limits sensitivity.

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

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