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## Metamaterials Role In Millimeter-Wave and THz Industries

Claire Watts

Boston College, Chestnut Hill, MA, USA

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# How are metamaterials enabling new products in the THz and Millimeter-Wave Industries?

THz radiation has many applications and creates a need for products

Can MMs inspire new technology?

Metamaterials offer means to translate existing RF and IR technologies into the THz Gap

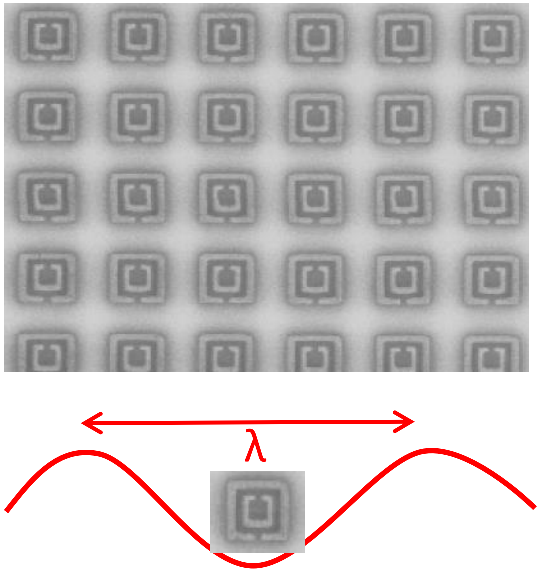
# Presentation Outline

1. Metamaterials: concepts and history
2. THz Metamaterials
3. The THz Regime: promising yet problematic
4. Current metamaterial research that can inspire industry products
5. Conclusions and future outlook

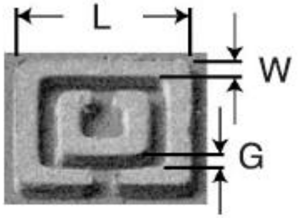
# Metamaterials

Electromagnetic Metamaterial (MM): designer electromagnetic materials comprised of subwavelength elements whose properties can be tuned through their geometry

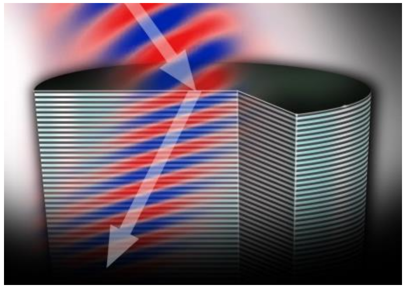
**Subwavelength:**




**Controlled by Geometry:**
The characteristics of metamaterials are determined by their material characteristics and geometry – not their chemistry




**Designer EM Materials:**
Through the geometry, the user has control of ε(ω) and μ(ω). This gives control of transmission, reflection, etc.

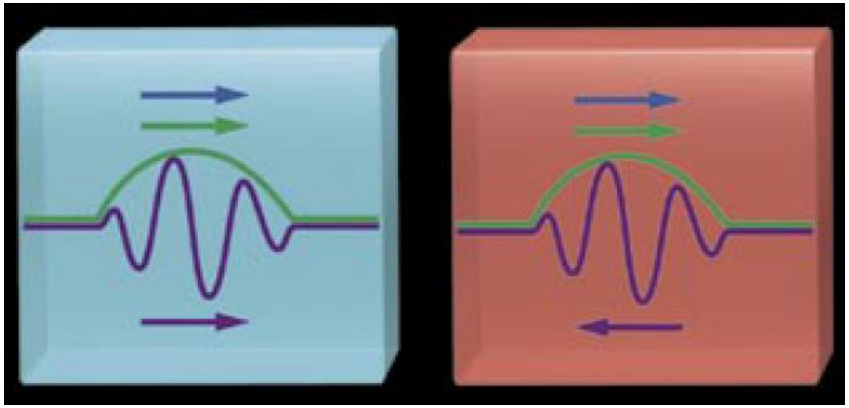


# The Emergence of Metamaterials

- 1940's: Bell Laboratories makes strides in artificial dielectrics
- 1999: John Pendry's artificial magnetism opens up possibility for negative index of refraction (NIR)

- $n = \sqrt{\varepsilon(\omega) \cdot \mu(\omega)}$
- negative $\varepsilon(\omega)$ and $\mu(\omega)$ leads to $n < 0$
- Veselago predicted some consequences of NIR in 1968

**Opposite Phase and Group Velocity**



- 2000: Negative index material achieved experimentally in microwave regime

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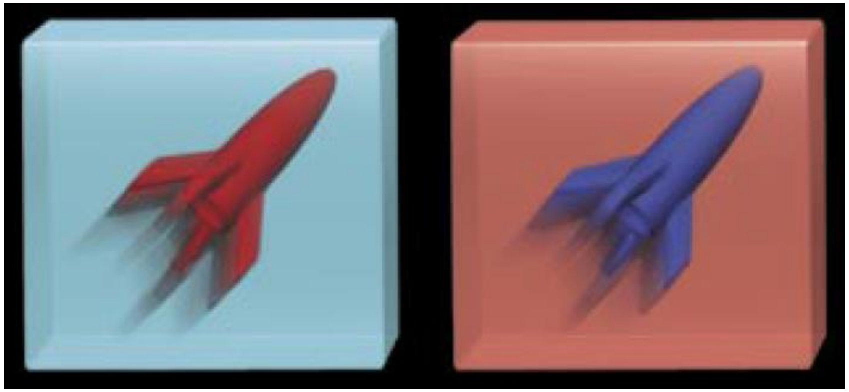
**Reverse Doppler Shift**



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# The Emergence of Metamaterials

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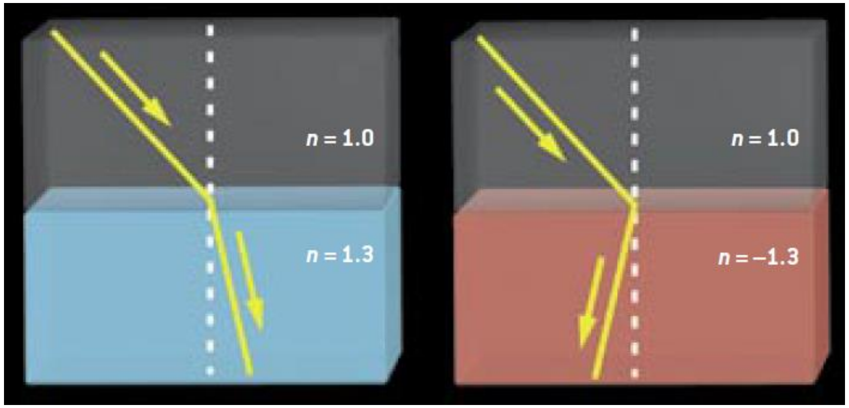
**Snell's Law Reversed**




- 2000: Negative index material achieved experimentally in microwave regime

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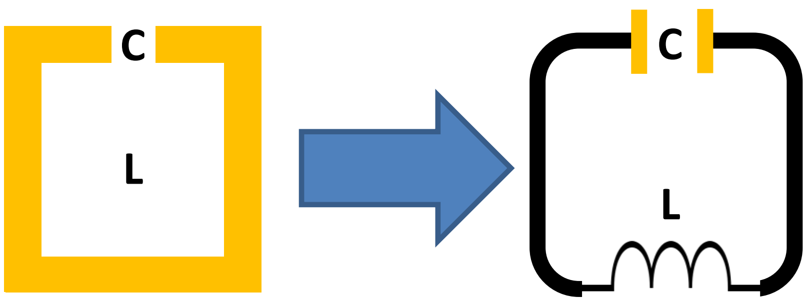
# MMs as an Effective Medium

## LC Resonator Analogy



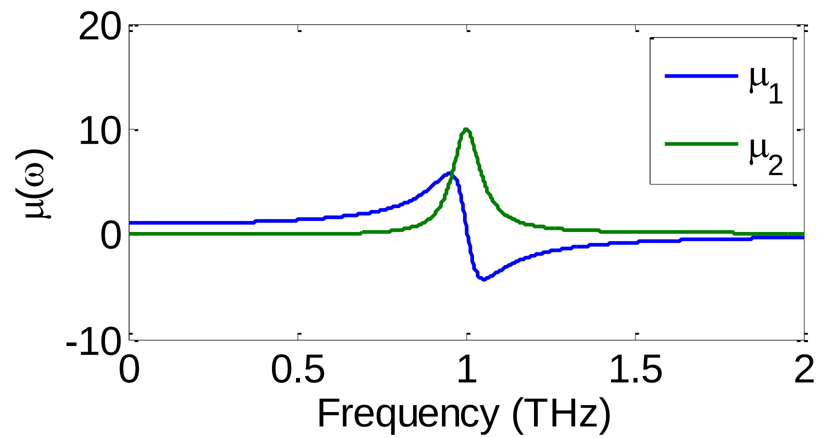

- Similar to an LC circuit, SRR will have a resonance condition

$$\omega_0 \sim \frac{1}{\sqrt{LC}}$$

- Effective capacitance and inductance determined by geometry and material properties

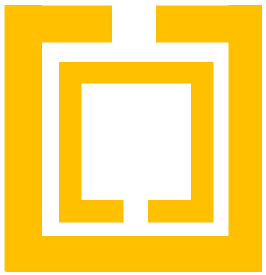
## Effective Optical Constant

- Single resonator → gives no effective response (too subwavelength)
- Many subwavelength resonators → Collective response gives an effective $\mu(\omega) = \mu_1 + i\mu_2$

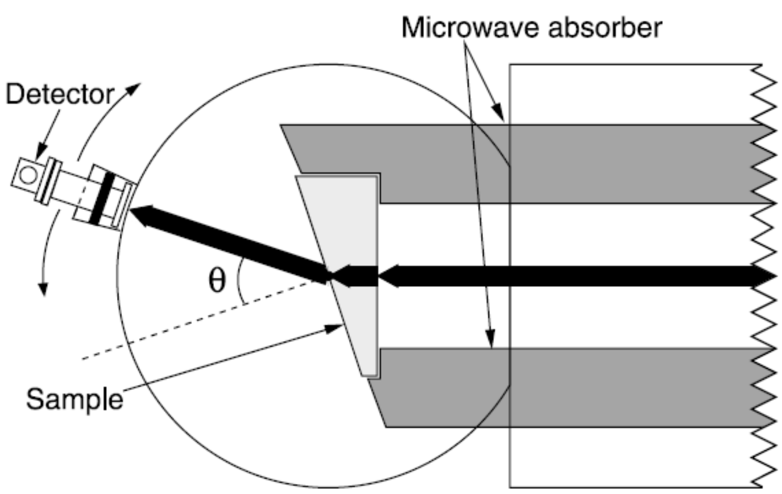


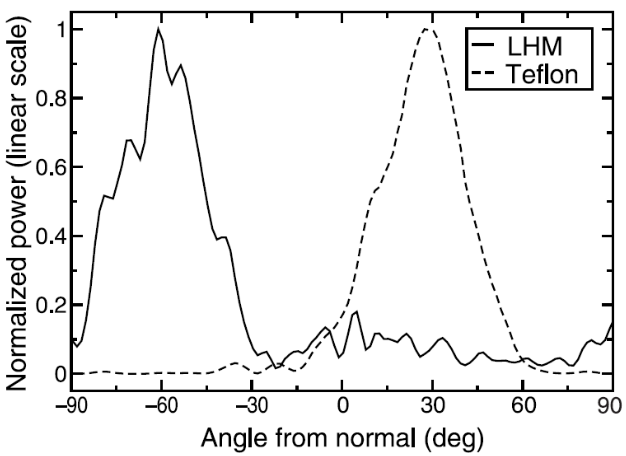
# Negative Index Materials

Metallic cut wire (microstrip) creates negative ε(ω)



Double split ring resonator creates negative μ(ω)




Shelby, 2001

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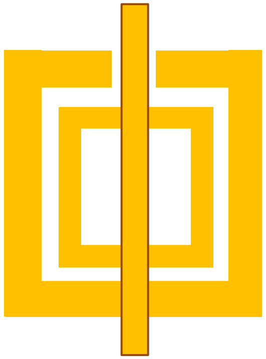
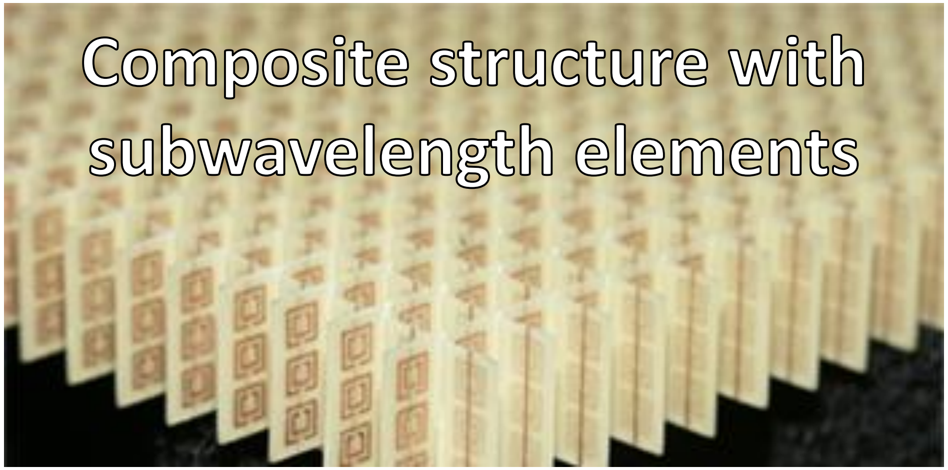
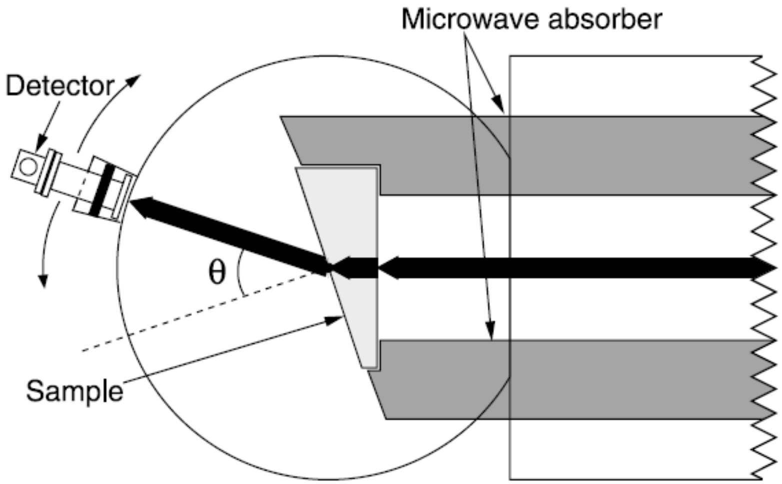
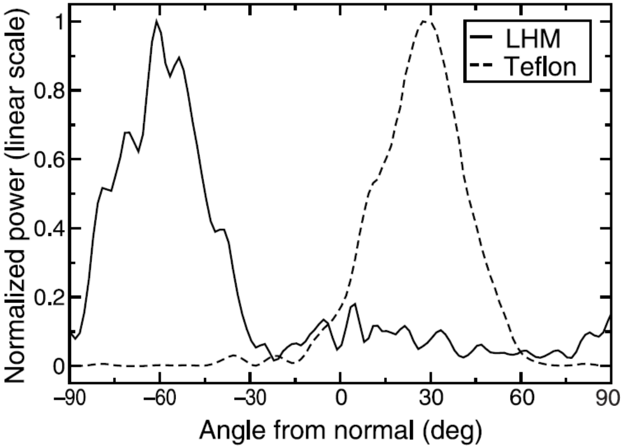
# Negative Index Materials



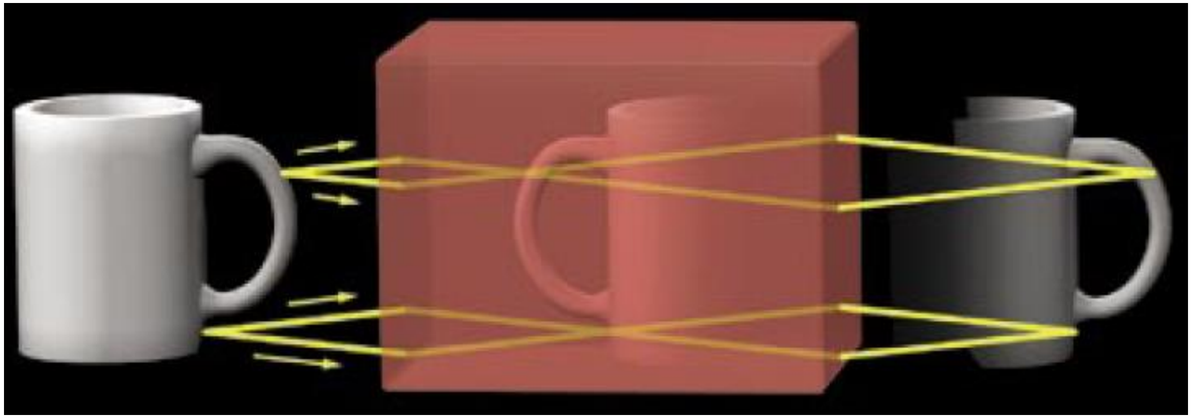


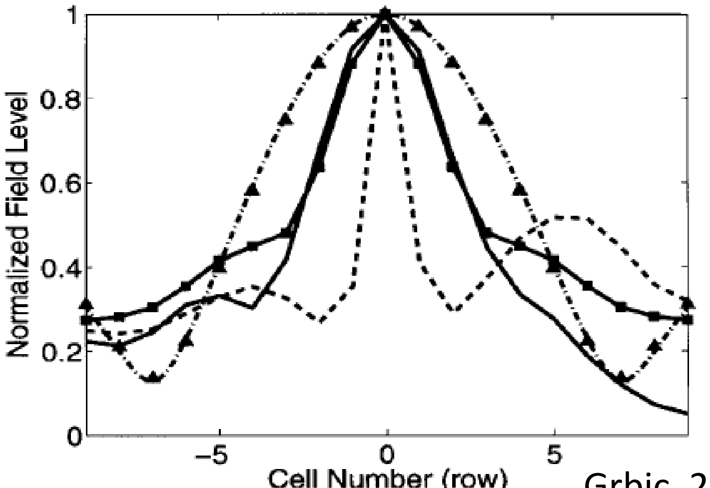

Shelby, 2001

# Super-Lensing



Negative index material lenses can theoretically refocus both the far and *near field* ➔ beat diffraction limit

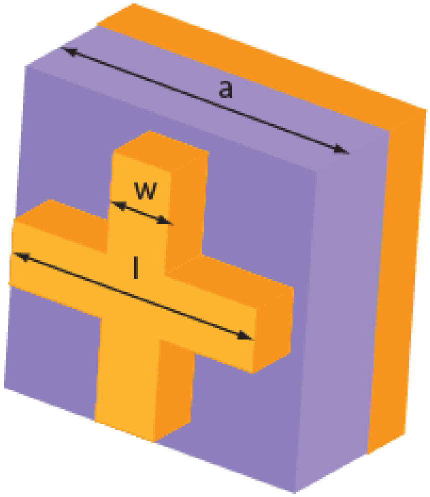
- Experimental demonstration: ε = -1 and μ = -1 metamaterial resolved below the diffraction limit at ~1 GHz
- Limitation: material characteristics

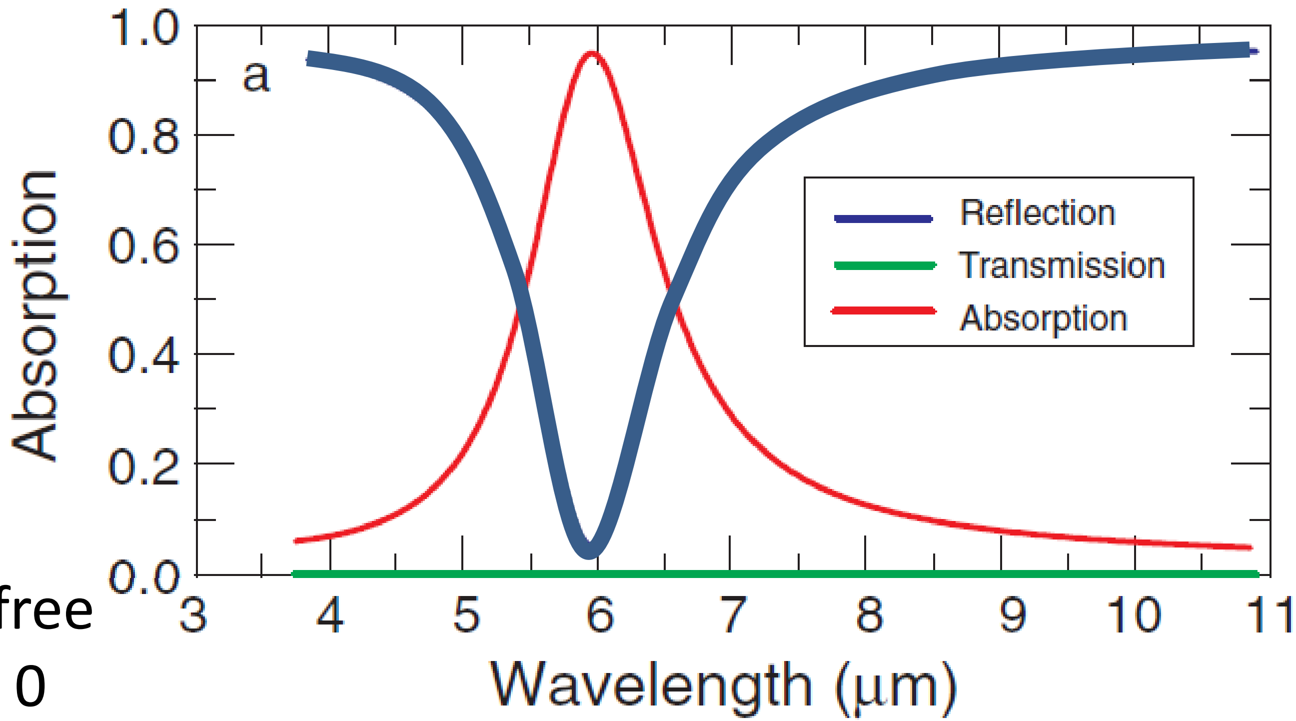



Grbic, 2004

# Beyond Negative Index Materials

- Metamaterial EM Wave Absorbers (Liu, 2010)




Impedance match to free space, reflection → 0

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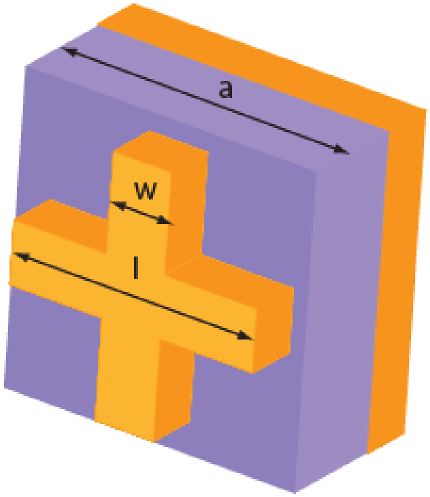


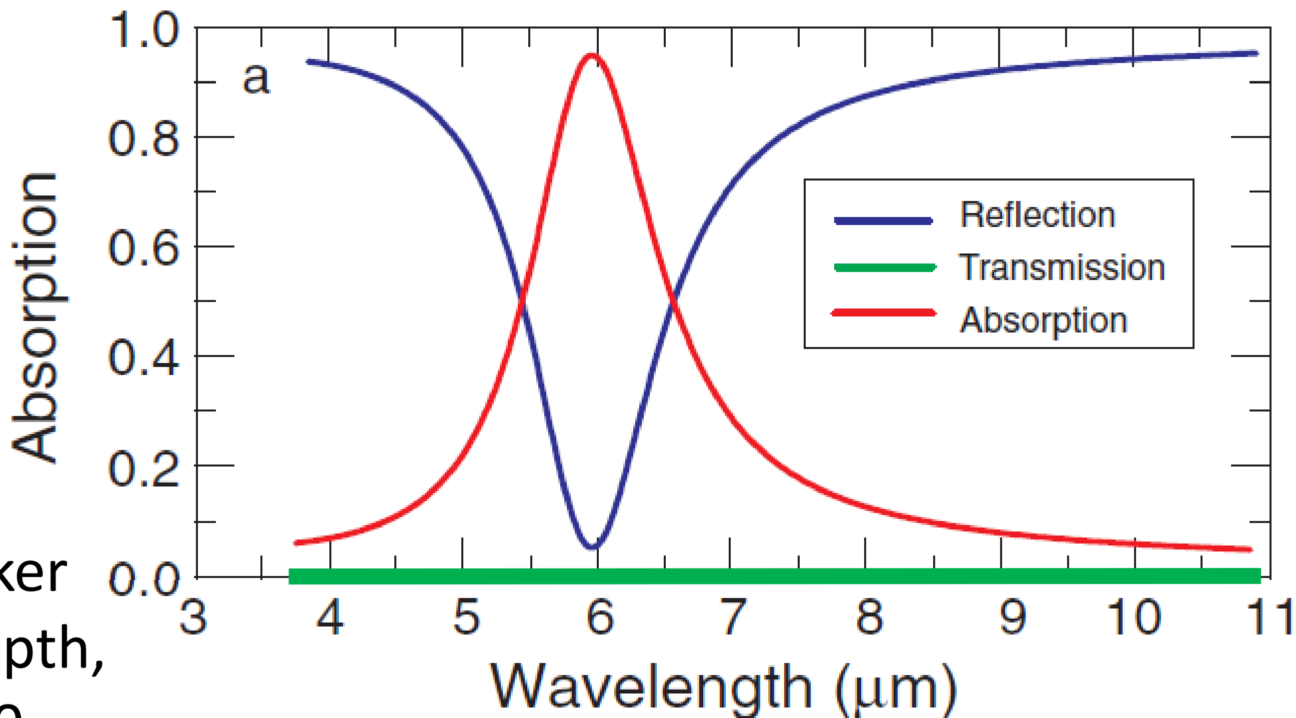


Ground plane thicker than penetration depth, transmission ➔ 0

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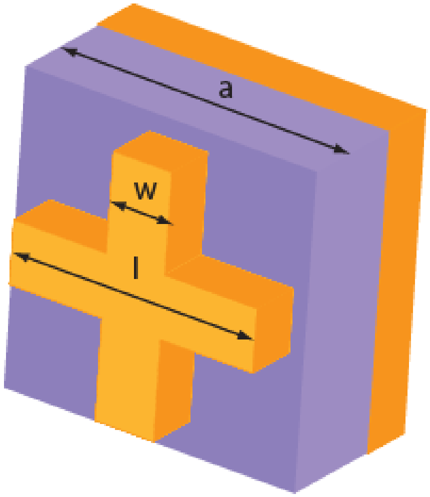


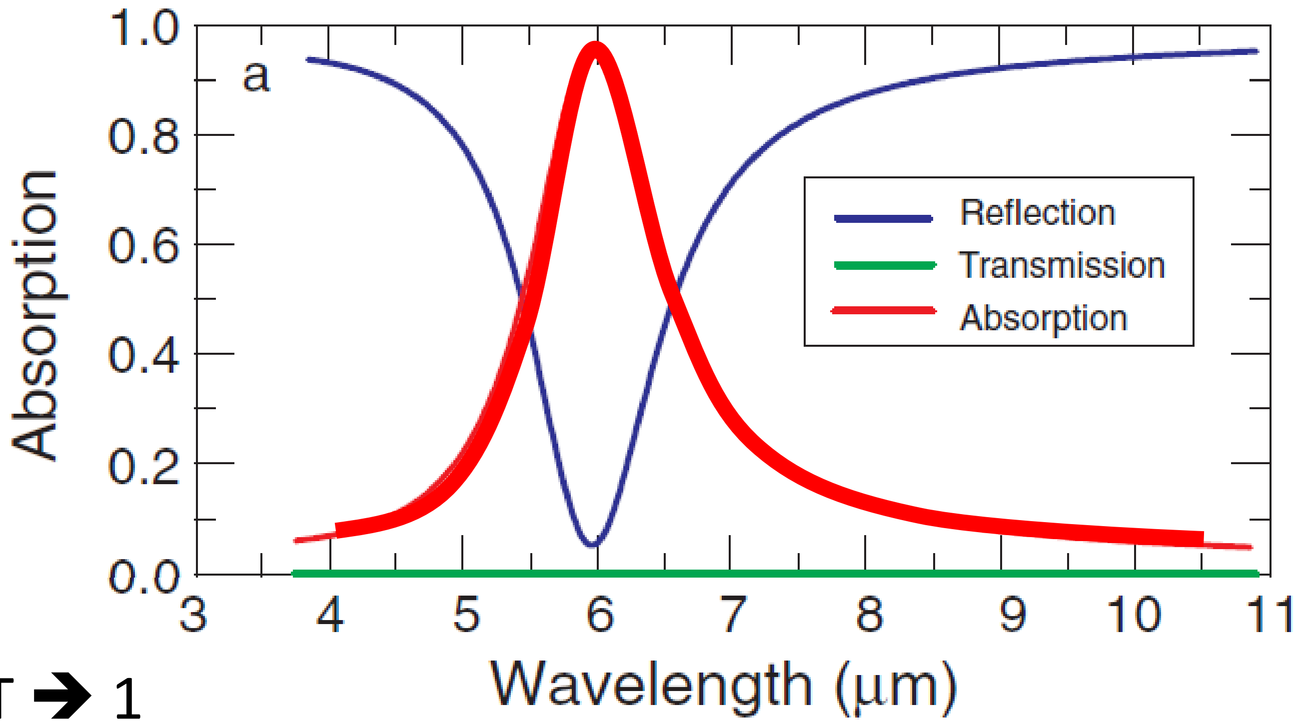


Absorption = 1 – R – T ➔ 1

# Beyond Negative Index Materials

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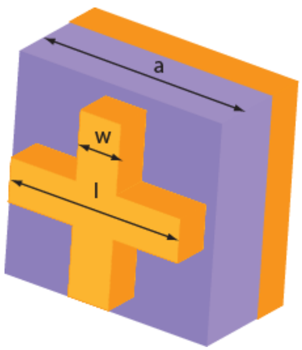


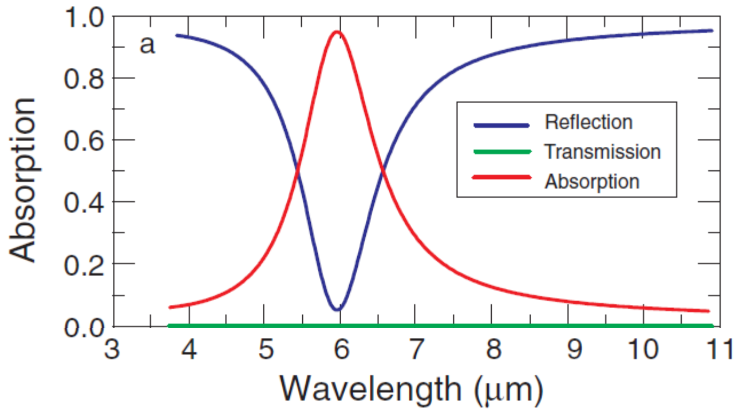


- Multiband and broadband metamaterials
- Dynamic metamaterials: dynamically tune properties with external stimuli

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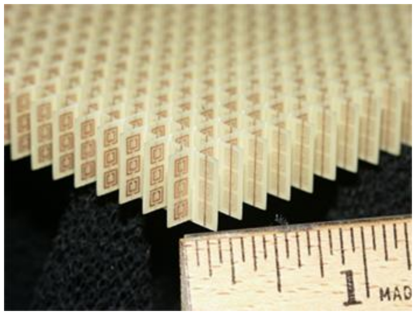
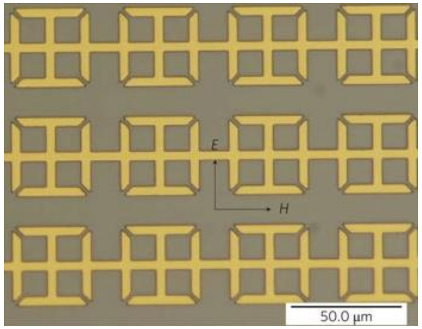
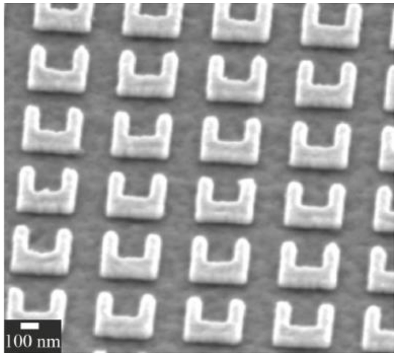
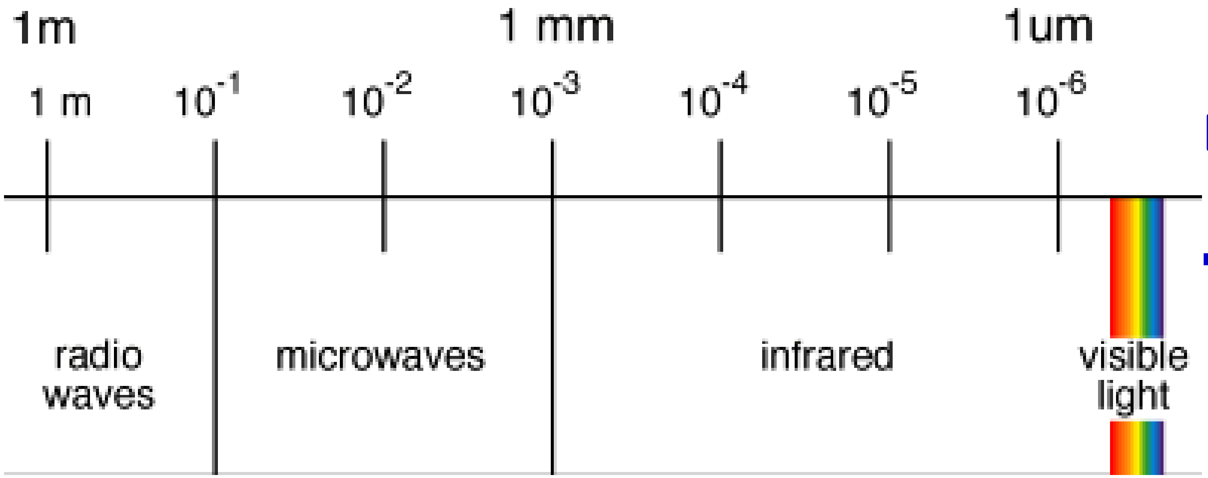
# MMs Across the EM Spectrum

**Fabrication Techniques**

| PCB techniques | Photolithography | E-Beam Lithography |
|---|---|---|
|  |  |  |



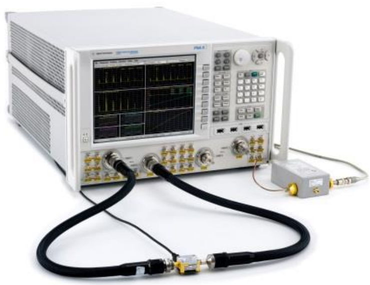

**Increasing wavelength λ** ←

**Decreasing MM size** →

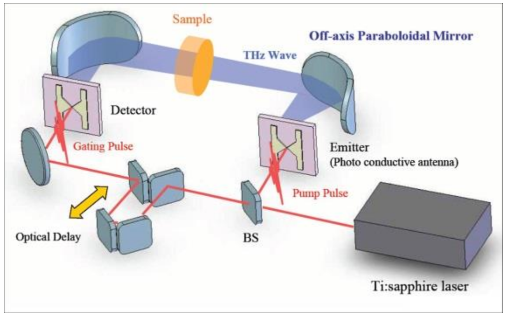
# MMs Across the EM Spectrum

**Characterization Techniques**

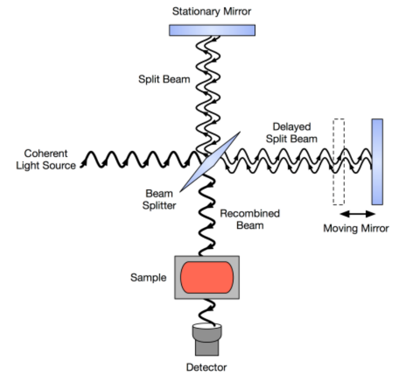
VNA Systems



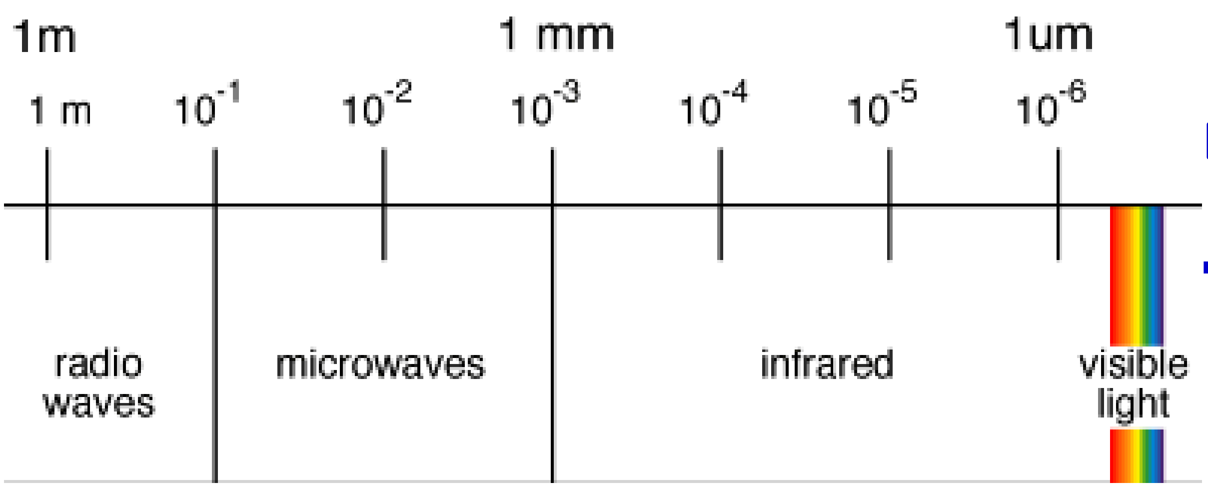
THz Spectroscopy




FTIR Spectroscopy




**Increasing wavelength λ**




**Decreasing MM size**

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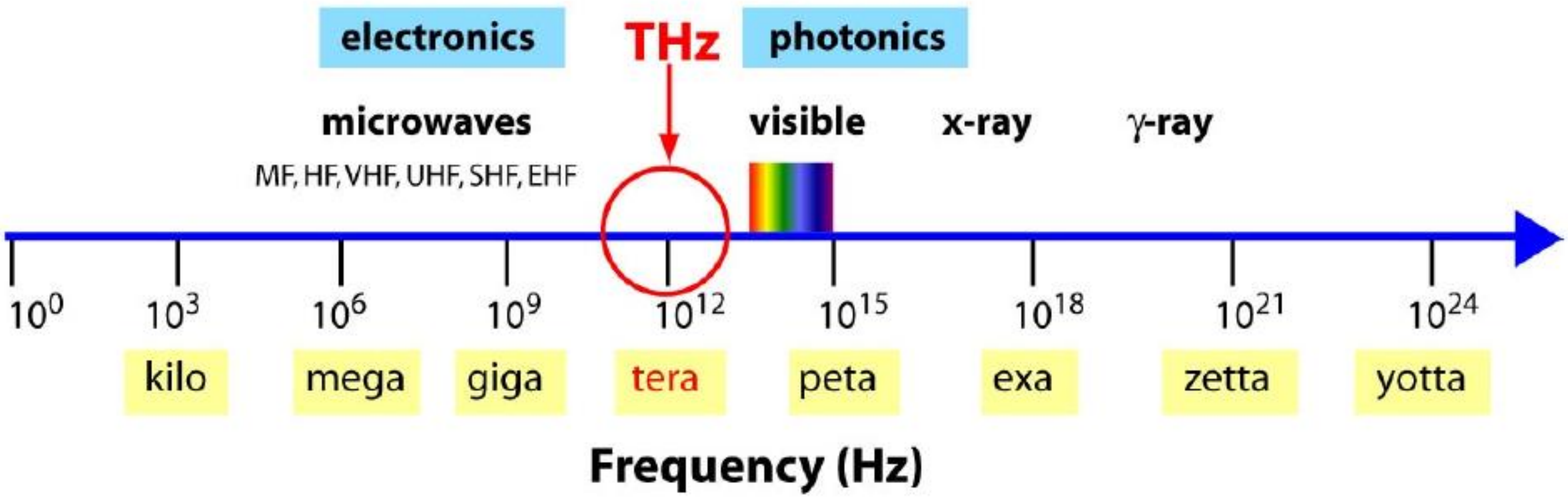
# The THz Frequency Regime




**Millimeter Wave Regime**
70 GHz – 300 GHz

**THz Regime**
300 GHz – 10 THz

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# Why do we care about MMs?

Science AAAS

**Experimental Verification of a Negative Index of Refraction**
R. A. Shelby *et al.*
*Science* **292**, 77 (2001);
DOI: 10.1126/science.1058847

Science AAAS

**Metamaterial Electromagnetic Cloak at Microwave Frequencies**
D. Schurig *et al.*
*Science* **314**, 977 (2006);
DOI: 10.1126/science.1133628

The New York Times

**Light Fantastic: Flirting With Invisibility**

Bloomberg

Bam! Science Inspired by Superheroes

**BloombergBusinessweek**
**Technology**

Innovator

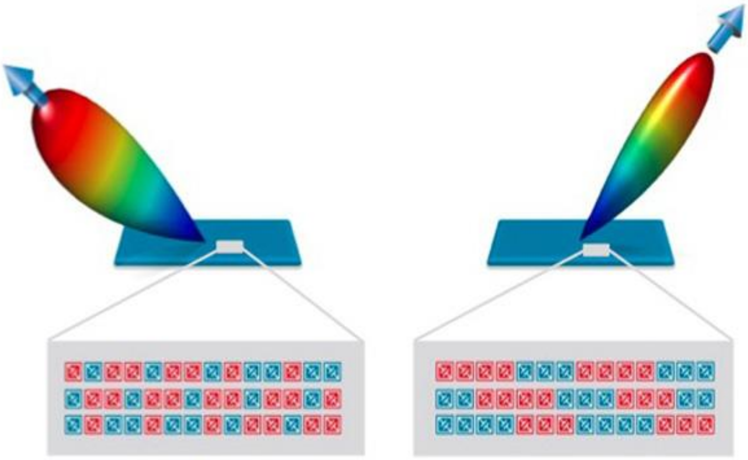
**Nathan Kundtz's MTenna May Replace the Satellite Dish**

The New York Times

Antenna Company Raises $12 Million From Bill Gates and Lux Capital

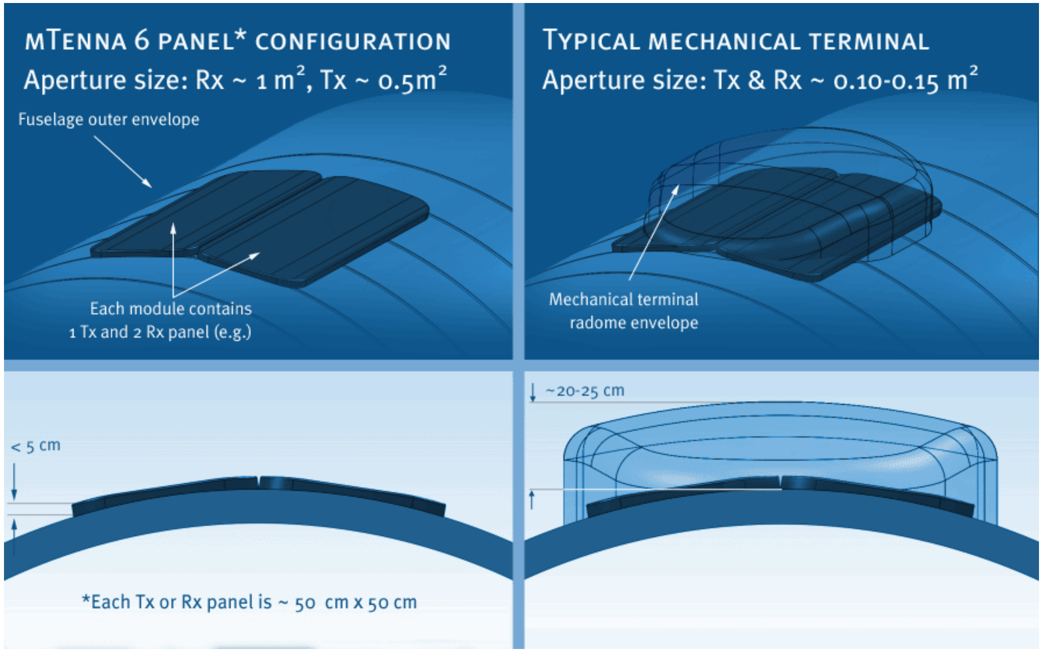
The start-up uses a lightweight material called metamaterials to produce antennas intended to improve satellite connections used for broadband Internet.

# Kymeta and the mTenna

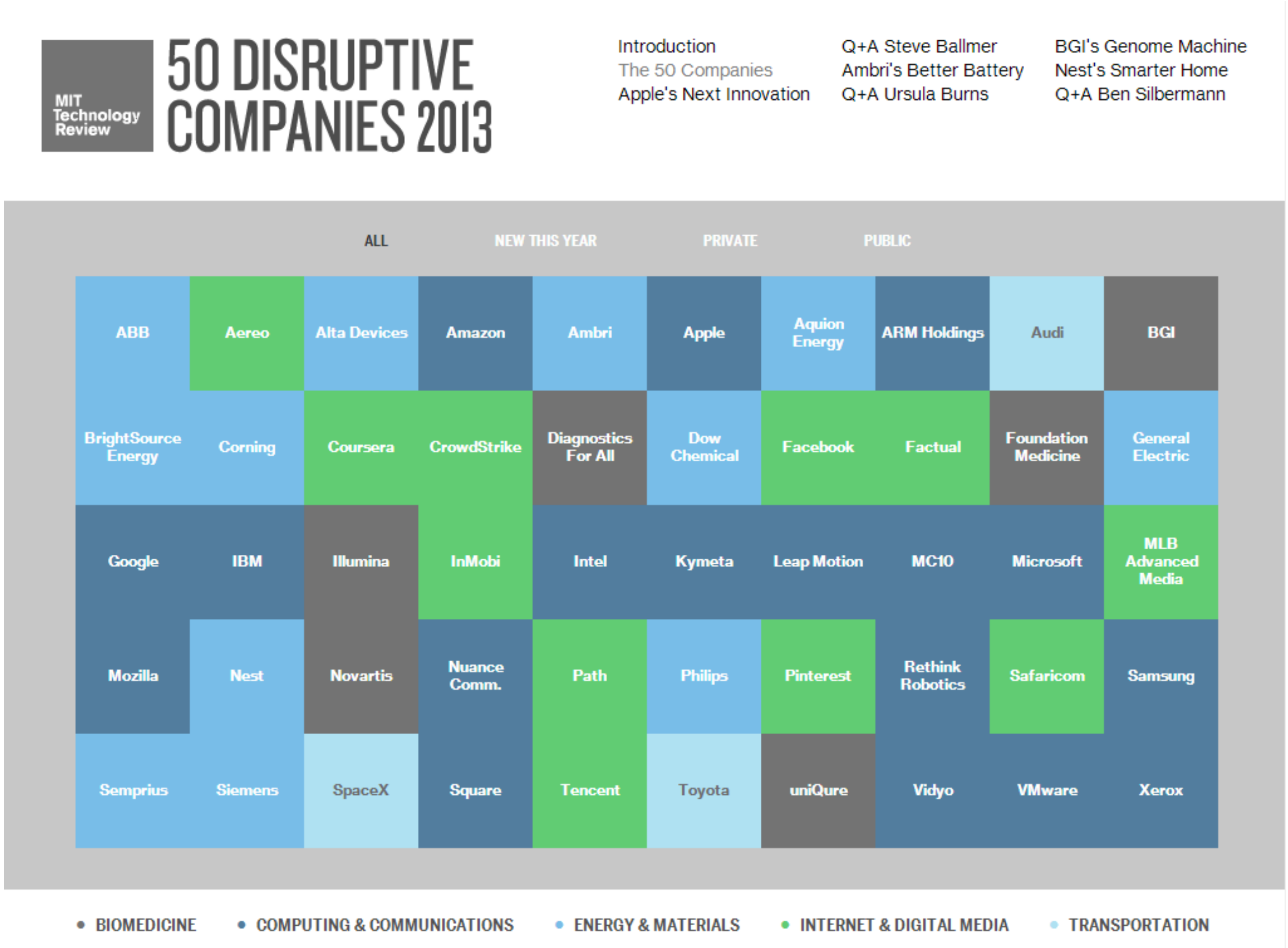


Using metamaterials for wide-angle, all-electronic beam steering

Example: highly applicable as an aeronautical terminal



# Kymeta and the mTenna



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1. Metamaterials: concepts and history
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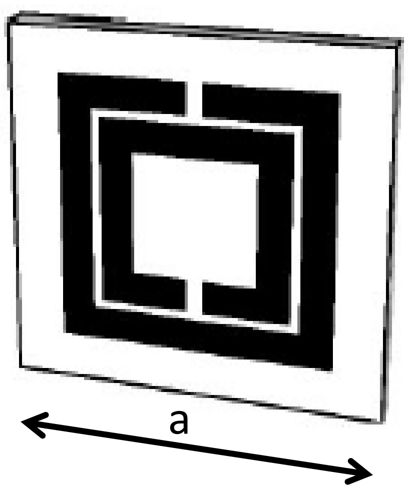
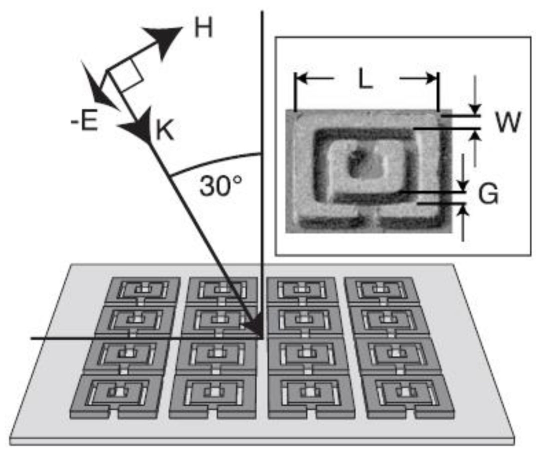
# Introduction of the THz Metamaterial

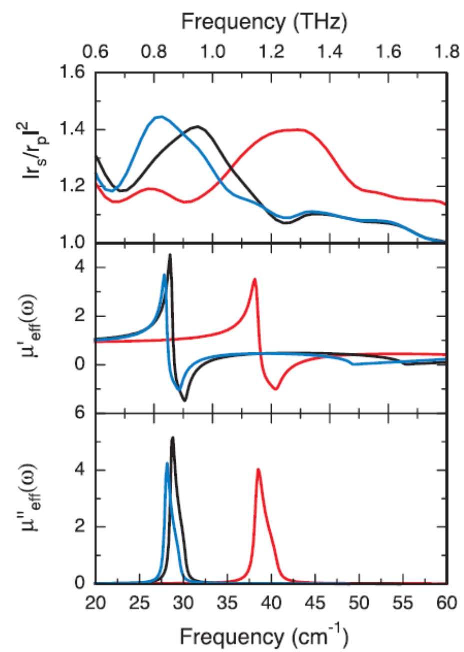
In 2004 the classic split ring resonator (SRR) was scaled to give a magnetic response in the THz regime




Microwave MM:
**a = 8 mm**



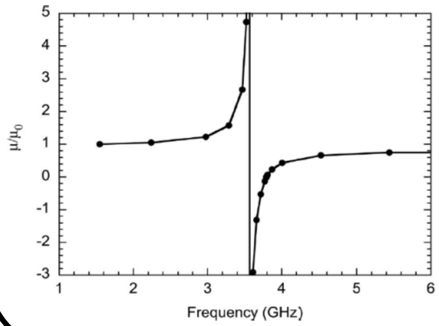

Terahertz MM:
**a = 36 μm**

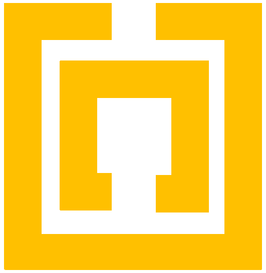



Yen, 2004

# What Makes THz MMs So Effective?

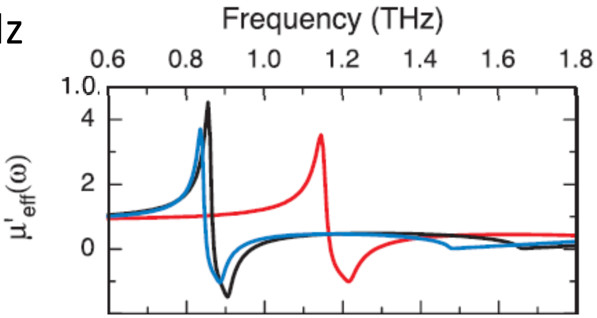
## Established RF MMs



## THz MMs

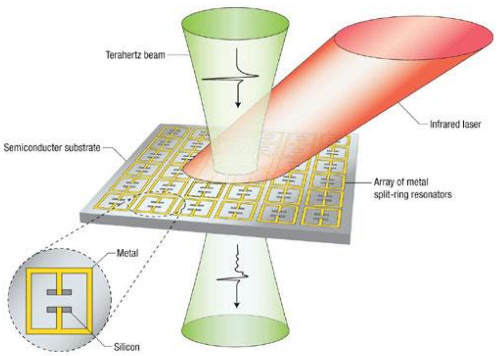
Sub-λ in THz regime



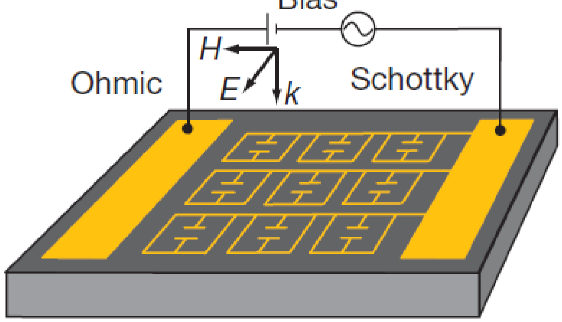

- The geometry can be scaled and give a similar response at higher frequencies
- Most natural materials have weak electromagnetic responses and generally cannot be made scalable

# Dynamic THz Metamaterials

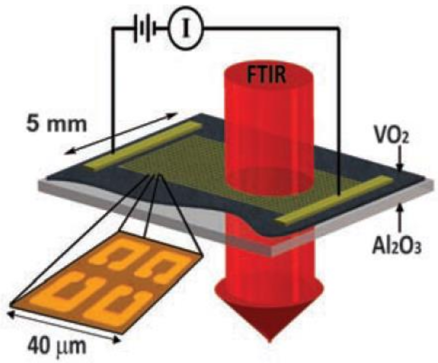
## Photodoping



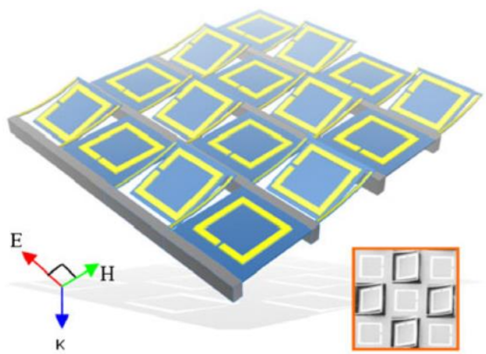

## Electronic Control




## Phase Change

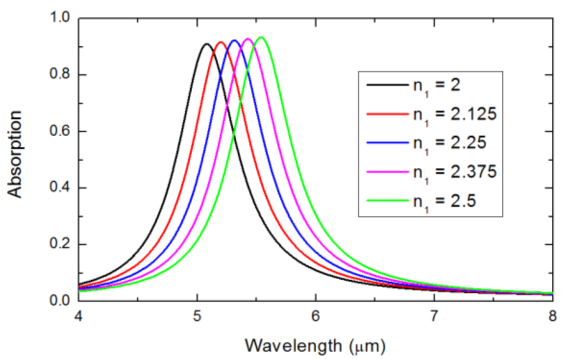



## MEMS

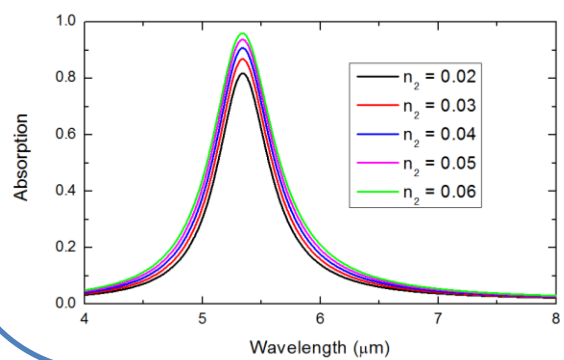


# General Considerations with Dynamic THz MM Devices

## Tuning Depth



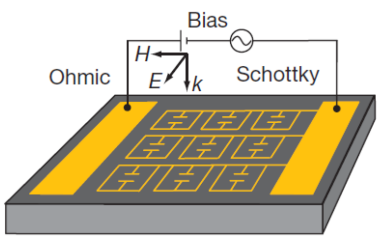

Resonance frequency tuning

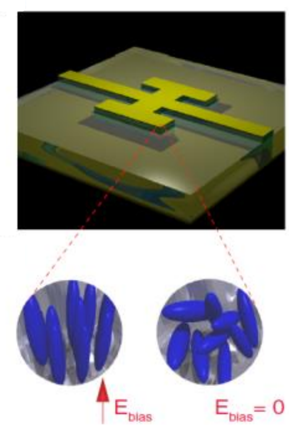



Resonance amplitude tuning

## Modulation Speed

Semiconductor-based devices: very fast (up to MHz speeds)




Liquid crystal devices: slower (operate best at kHz speeds)

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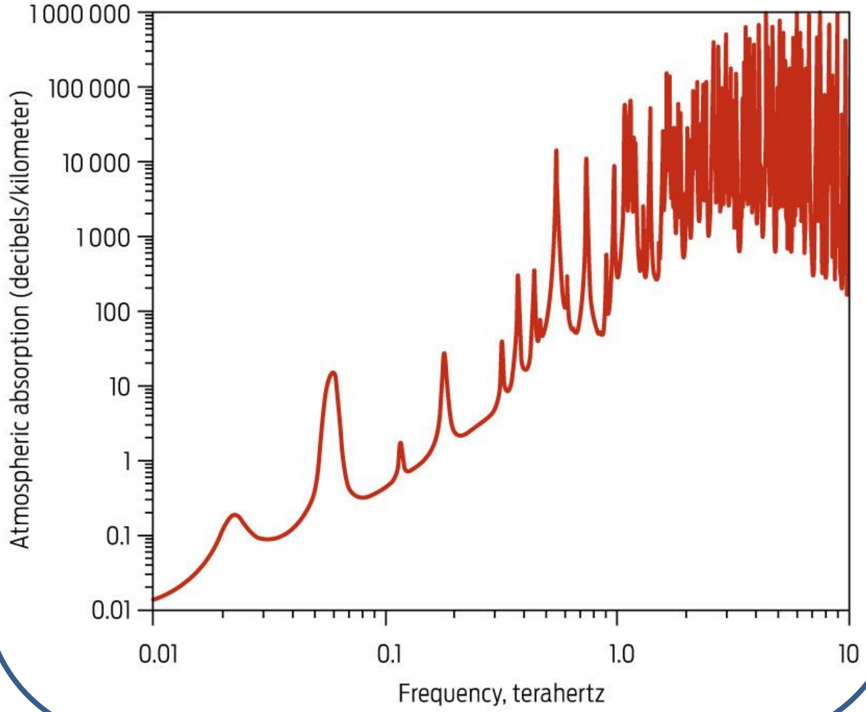
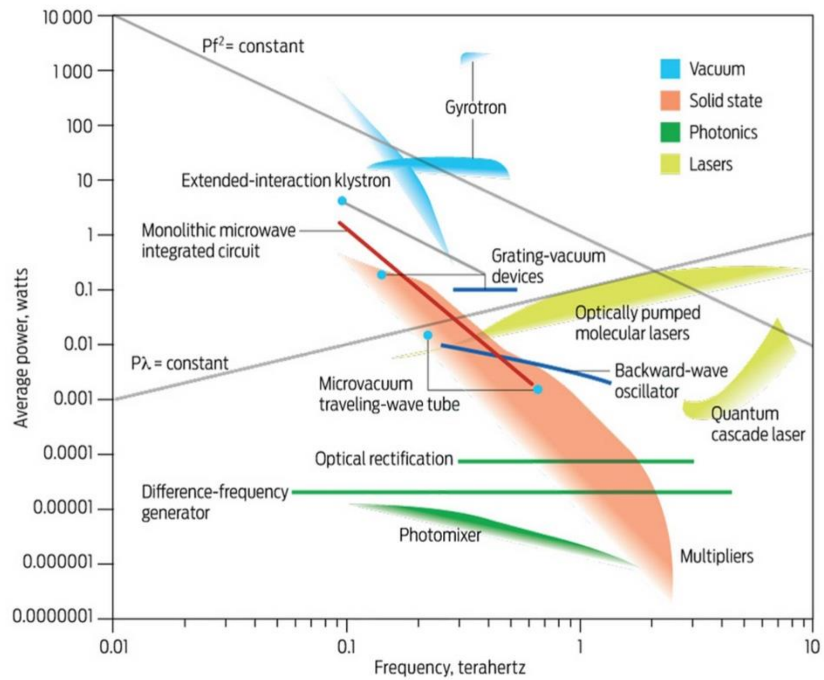
# Difficulties of the THz Gap

## Signal attenuation in atmosphere




## General Lack of High-Powered Sources



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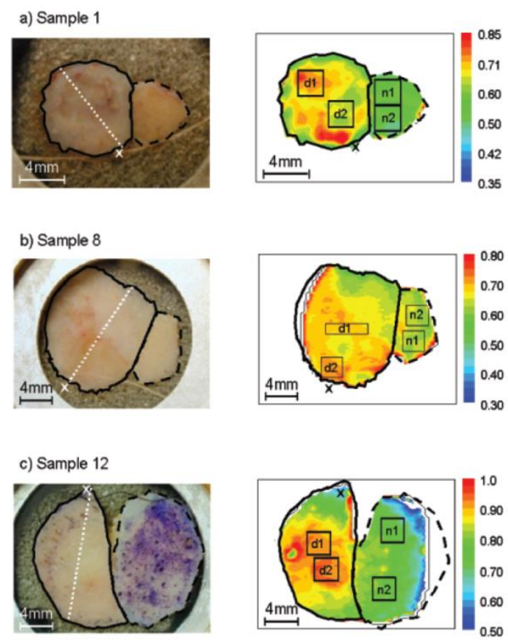
# Potential Applications

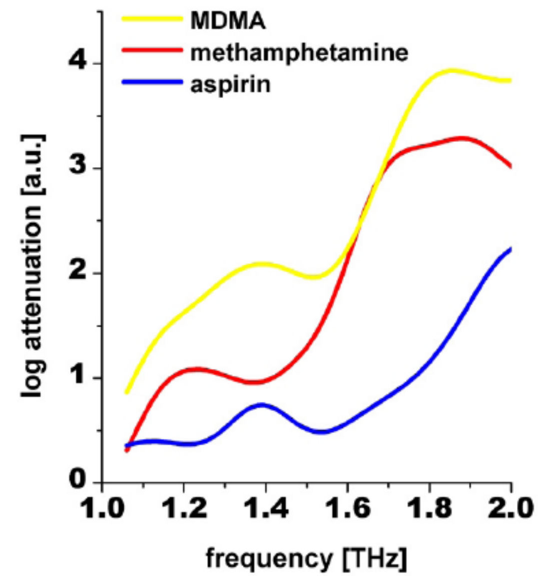
## Personnel Screening with THz Imaging

## Biomedical and Medical Applications




THz absorption of basal cell carcinoma

## Spectroscopic Screening



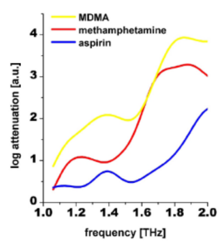

Visually identical substances have different THz responses

# THz Devices: Getting From Demand to Supply

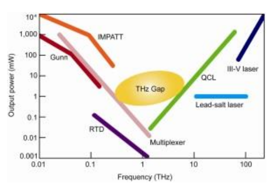
## Demand

**Security Screening**

**Spectroscopic Screening**




**THz Systems**




## Supply

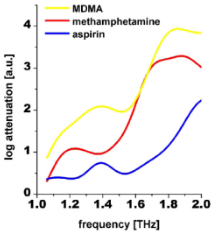
**Natural materials have difficulty supplying these devices → Metamaterials can do this!**

# THz Devices: Getting From Demand to Supply

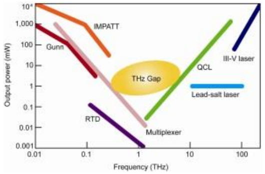
## Demand

**Security Screening**

**Spectroscopic Screening**




**THz Systems**




## Supply

**THz Metamaterial Imaging Components and Systems**

**THz Biospectroscopy Metamaterials**

**THz Metamaterial Filters and Modulators**

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# Presentation Outline

1. Metamaterials: Concepts and History
2. THz Metamaterials
3. The THz Regime: Promising yet Problematic
4. Current metamaterial research that can inspire industry products
5. Conclusions and future outlook

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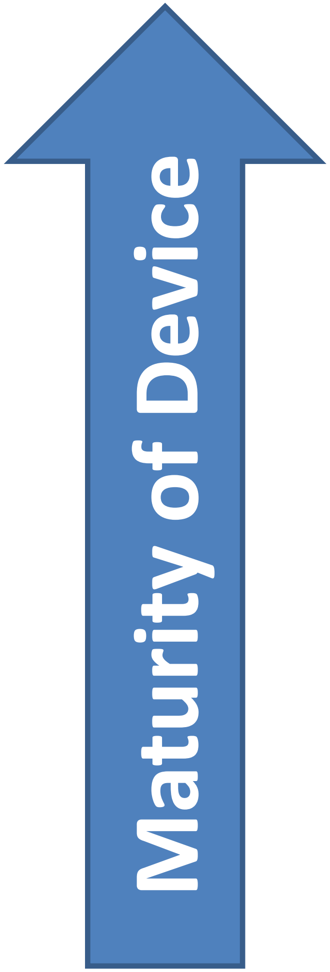
# Summary of Industry-Geared THz Metamaterial Research




**Evolv Technologies**
Based on metamaterial imaging technology developed at Duke University

Biospectroscopy with THz metamaterials

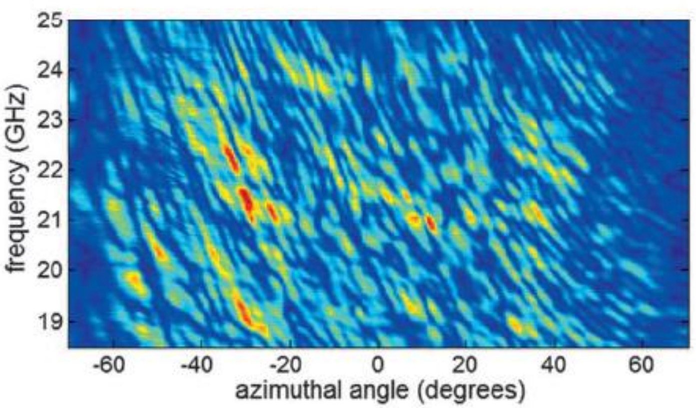
Single pixel THz imaging using an active THz metamaterial spatial light modulator

Dynamically tunable THz and millimeter wave filters and resonators

# Imaging With MM Coded Apertures

## MM Device Fully Integrated Into Industry

- 1D leaky waveguide couples energy into characteristic far field modes
- Modes determined through parameters of resonant metamaterials

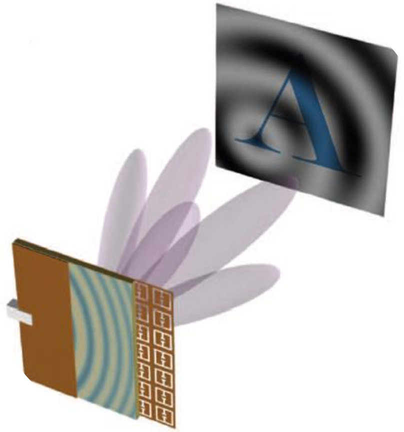


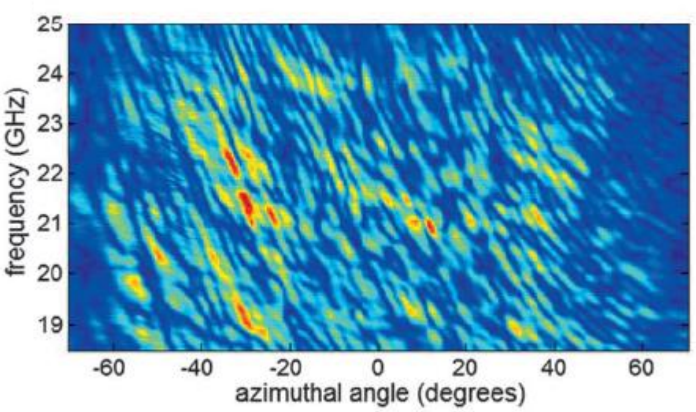

- Frequency is used to index far-field modes
- Scene is illuminated and back-scattered radiation is incident on the metamaterial
- Spectral measurement is used to reconstruct the scene

Hunt, 2013

# Imaging With MM Coded Apertures

## MM Device Fully Integrated Into Industry






- Frequency is used to index far-field modes
- Scene is illuminated and back-scattered radiation is incident on the metamaterial
- Spectral measurement is used to reconstruct the scene

Hunt, 2013

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# Imaging With MM Coded Apertures

## MM Device Fully Integrated Into Industry

Bill Gates, General Catalyst back Boston startup Evolv in $11.8M round

BOSTON BUSINESS JOURNAL

GeekWire

**Intellectual Ventures spinout Evolv gets $11.8M from Bill Gates and others, aims to transform security scanning**

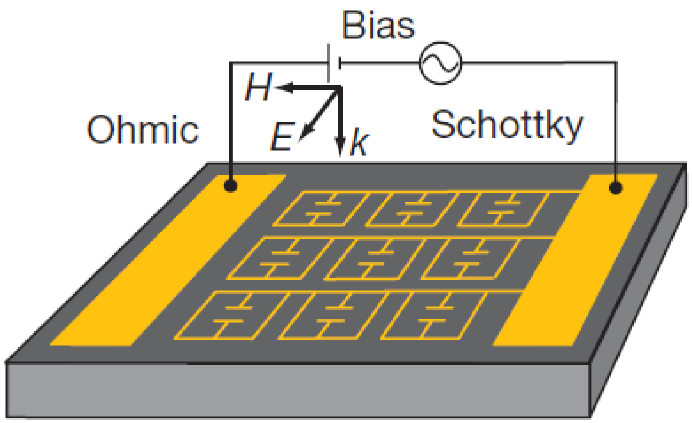
**Application to the THz and millimeter wave regimes?**

- **Demand: need for imaging systems in this regime**
- **Scalability of metamaterials**

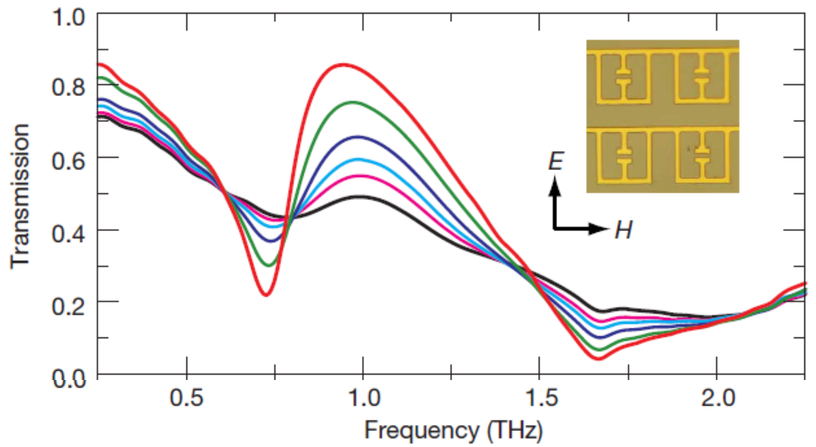
# Biosensing with THz MMs

## MM Device on the Verge of Industrial Application

**Dynamically tune metamaterial properties**




**Detect change in EM response**



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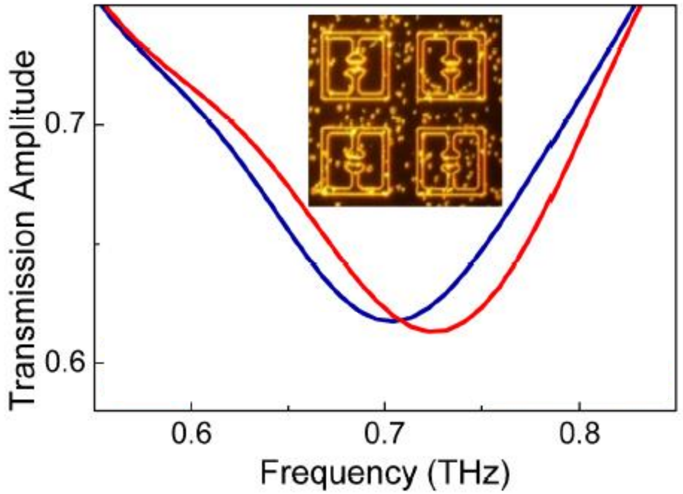
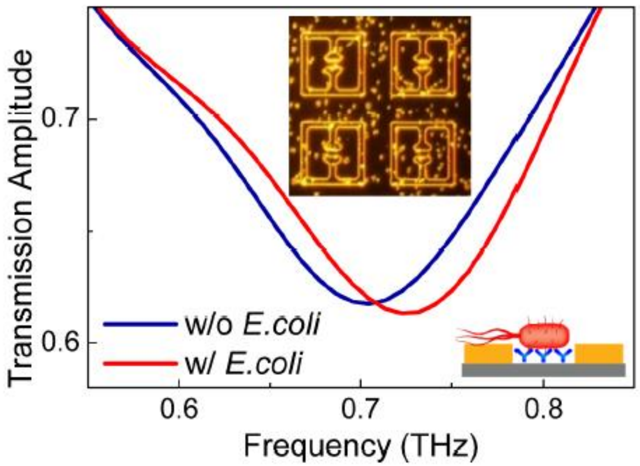
# Biosensing with THz MMs

## MM Device on the Verge of Industrial Application

**Detect change in EM response**



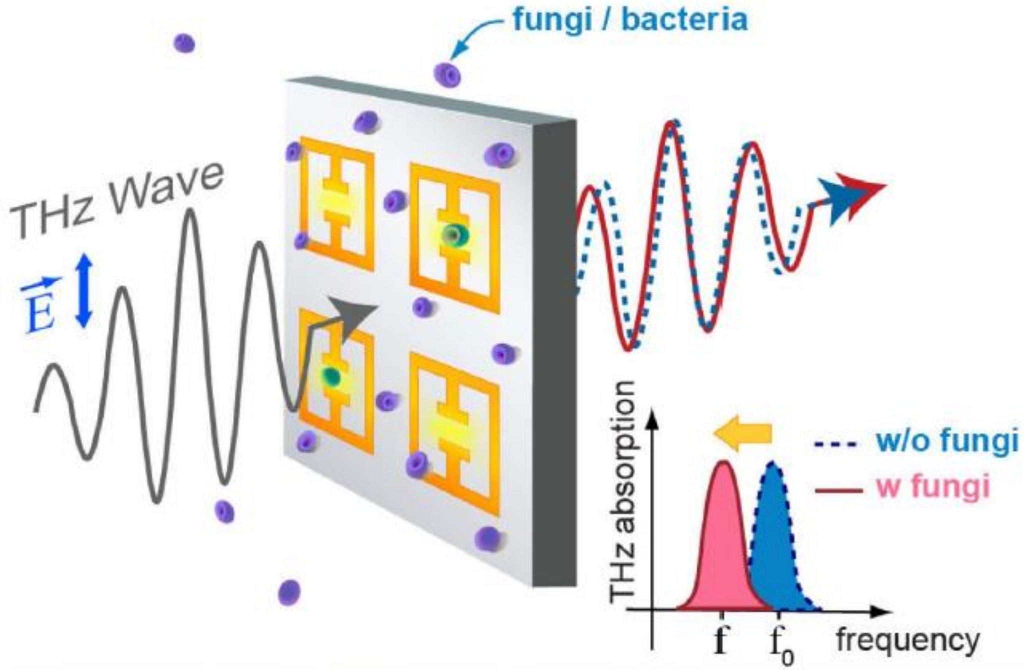

**Infer information about metamaterial properties**




**Tune or Be Tuned**

# Biosensing with THz MMs

## MM Device on the Verge of Industrial Application




**THz metamaterials as biosensors**

- Highly sensitive
- High-speed, on-site detection
- Tunable to specific needs

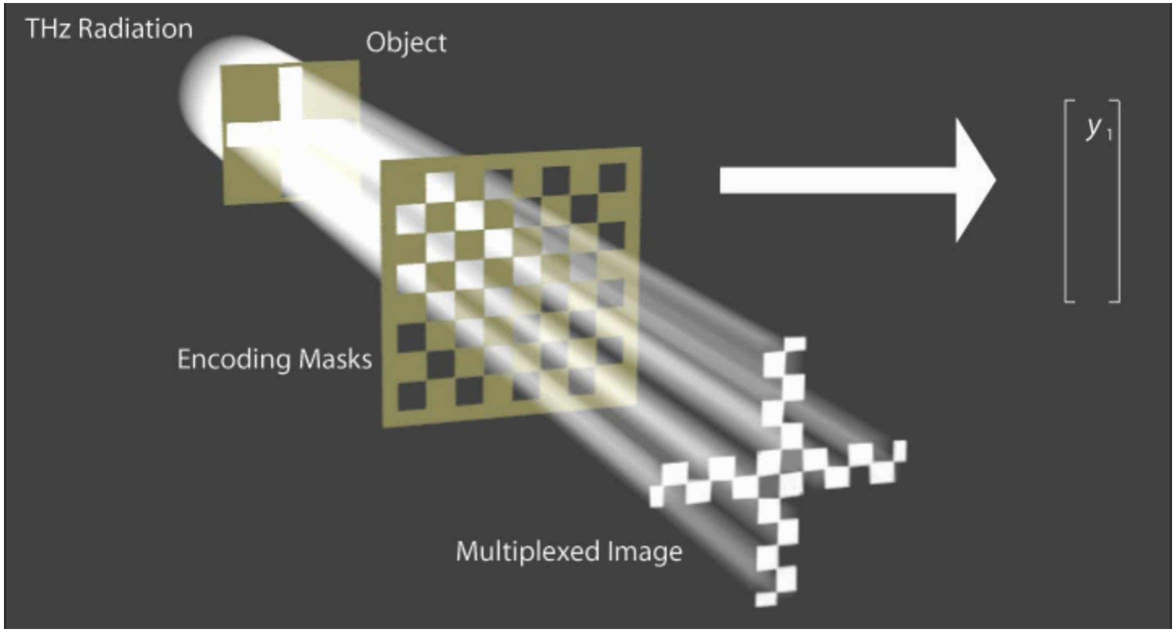
Park, 2014

# THz Single Pixel Imager

## MM Device With High Potential for Application

Single pixel imaging in THz regime:

- Single pixel detectors more sensitive than detector arrays
- Using an active mask negates the need for any mechanical motion



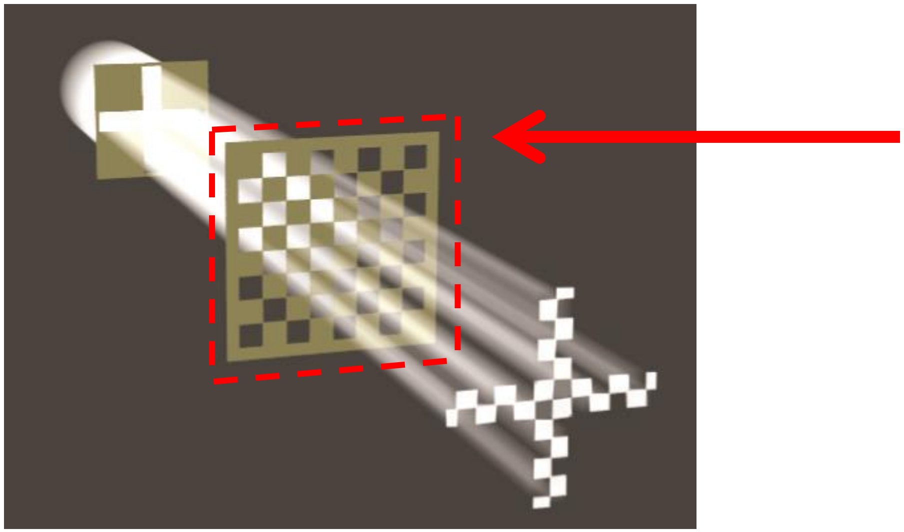

**Problem:** lack of viable natural materials for THz spatial light modulator

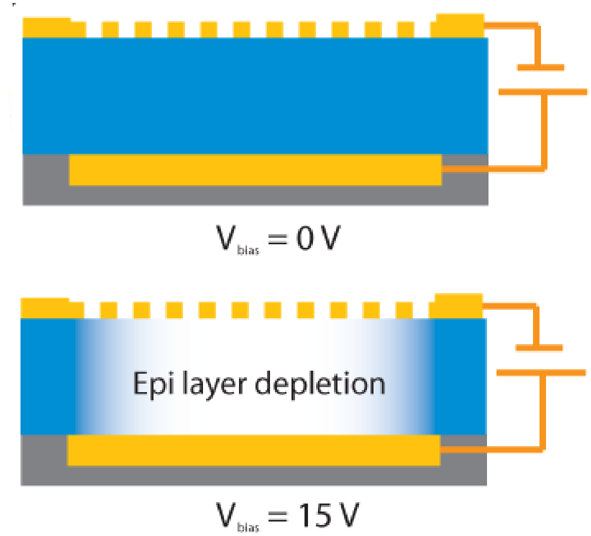
**Solution:** THz MMs

Watts, 2014

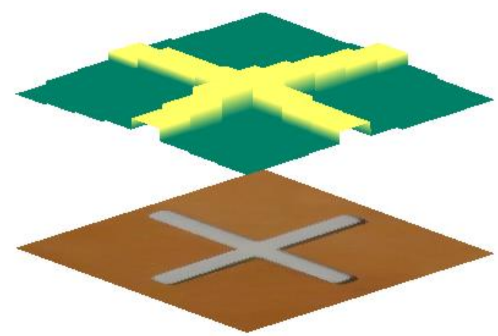
# THz Single Pixel Imager

## MM Device With High Potential for Application





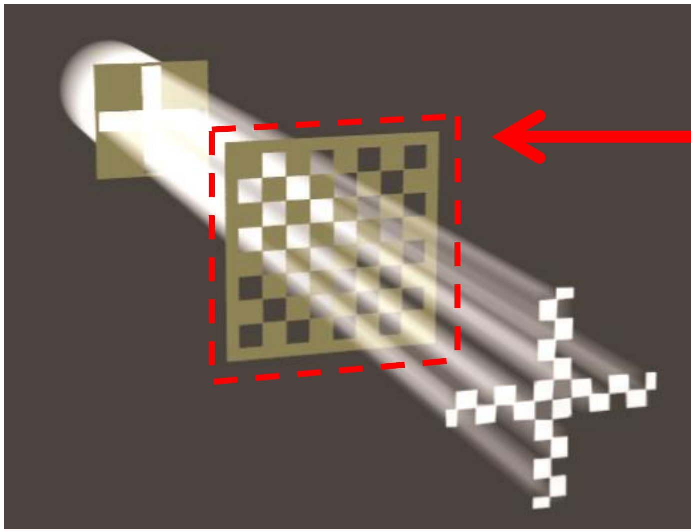

THz MM-SLM allows for accurate imaging in the THz regime without any moving parts and with the sensitivity of a single pixel detector

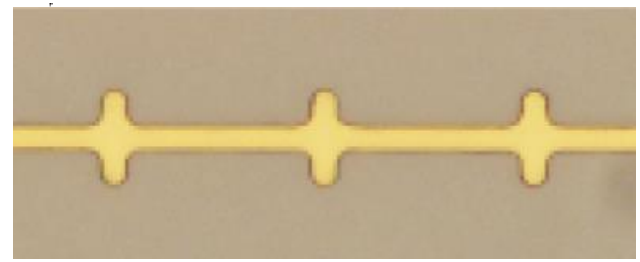


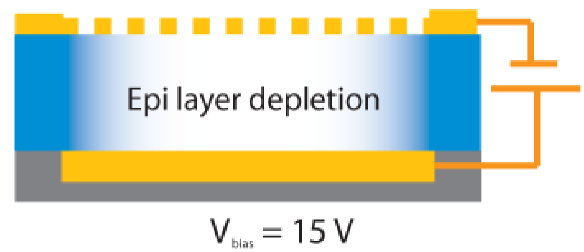
Watts, 2014

# THz Single Pixel Imager

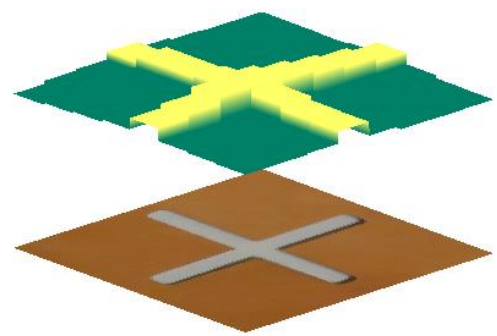
## MM Device With High Potential for Application







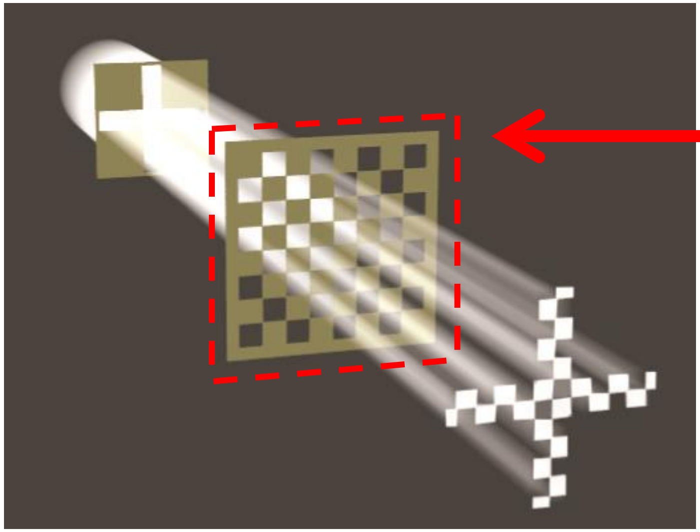

THz MM-SLM allows for accurate imaging in the THz regime without any moving parts and with the sensitivity of a single pixel detector

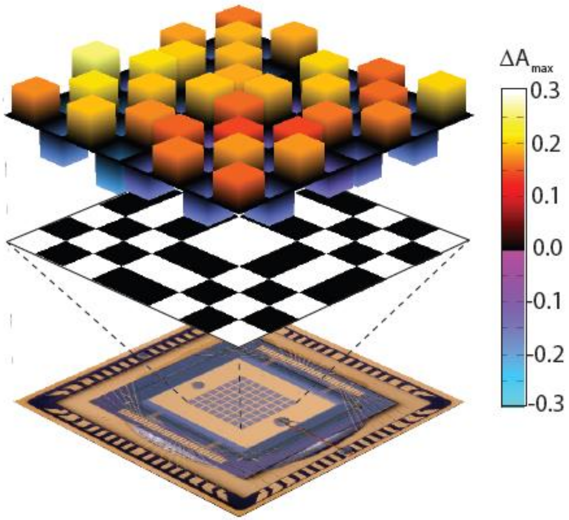


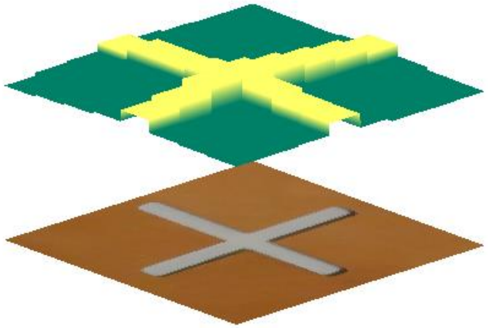
Watts, 2014

# THz Single Pixel Imager

## MM Device With High Potential for Application





THz MM-SLM allows for accurate imaging in the THz regime without any moving parts and with the sensitivity of a single pixel detector

Watts, 2014

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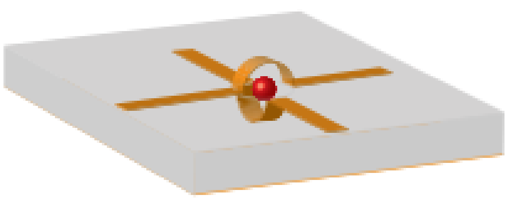
# Tunable Metamaterial Filters

## Existing MM device that could be used to solve a problem in the THz regime

- Microwave and RF systems ➔ components are very mature at low frequencies

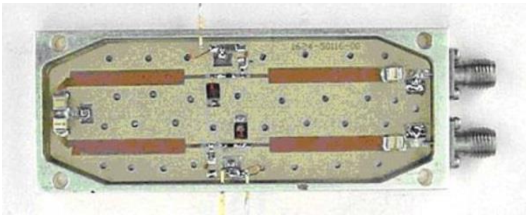
**Current devices don't scale to the THz gap**

**YIG Filters**



- Operates up to 90 GHz
- High frequency ➔ components too small

**Varactor Diodes**

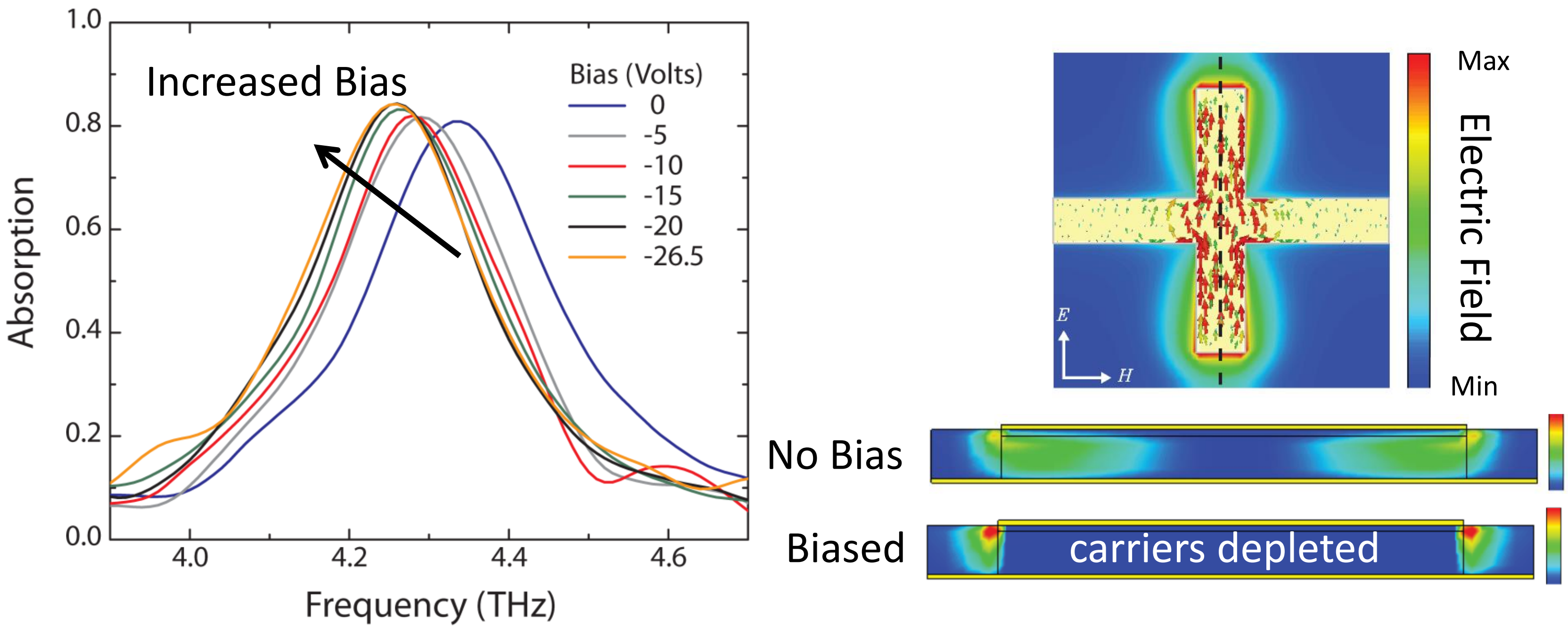


- Operates up to 50 GHz
- High frequency ➔ parasitic capacitance

# Tunable Metamaterial Filters

## Existing MM device that could be used to solve a problem in the THz regime

**Can we use dynamic metamaterial filters to solve this problem?**




Shrekenhamer, 2013

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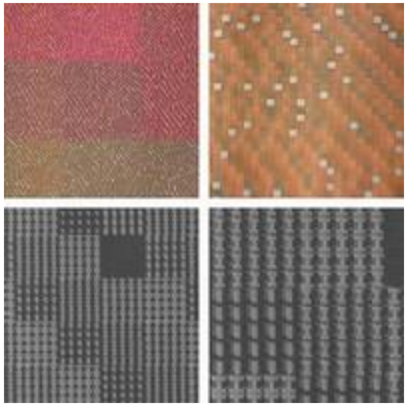
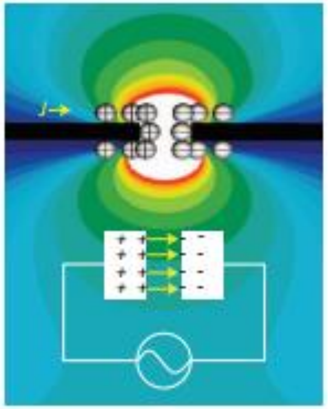
# More Metamaterial Devices

## Infrared metamaterial phase holograms

Stéphane Larouche, Yu-Ju Tsai, Talmage Tyler, Nan M. Jokerst & David R. Smith



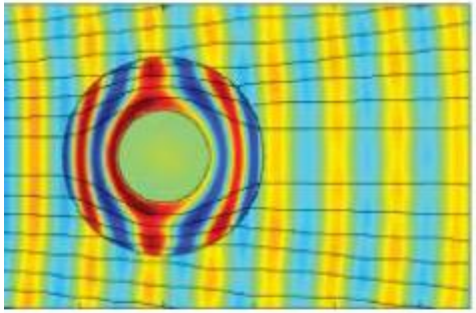


## Terahertz field enhancement by a metallic nano slit operating beyond the skin-depth limit

M. A. Seo[1], H. R. Park[1], S. M. Koo[2], D. J. Park[1], J. H. Kang[3], O. K. Suwal[4], S. S. Choi[4], P. C. M. Planken[5], G. S. Park[1], N. K. Park[2], Q. H. Park[3]* and D. S. Kim[1]*

## Metamaterial Electromagnetic Cloak at Microwave Frequencies

D. Schurig,[1] J. J. Mock,[1] B. J. Justice,[1] S. A. Cummer,[1] J. B. Pendry,[2] A. F. Starr,[3] D. R. Smith[1]*



# Presentation Outline

1. Metamaterials: concepts and history
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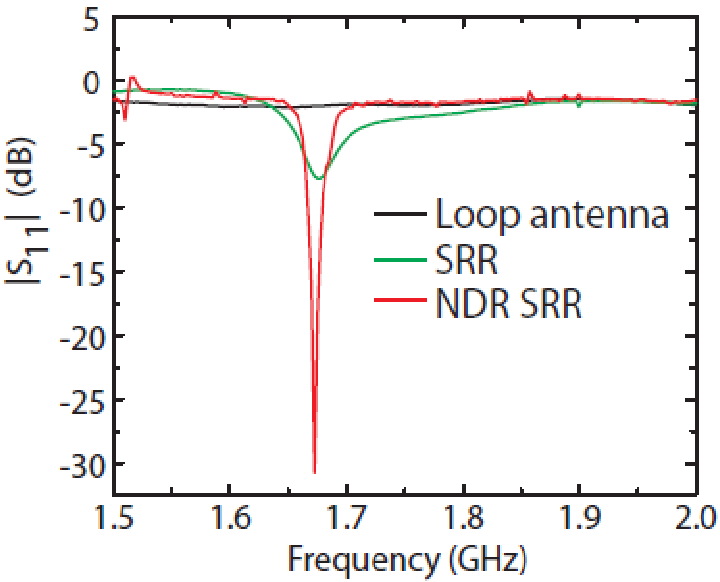
# Final Questions

## Are MMs the answer to all our problems in the THz and millimeter wave regime?

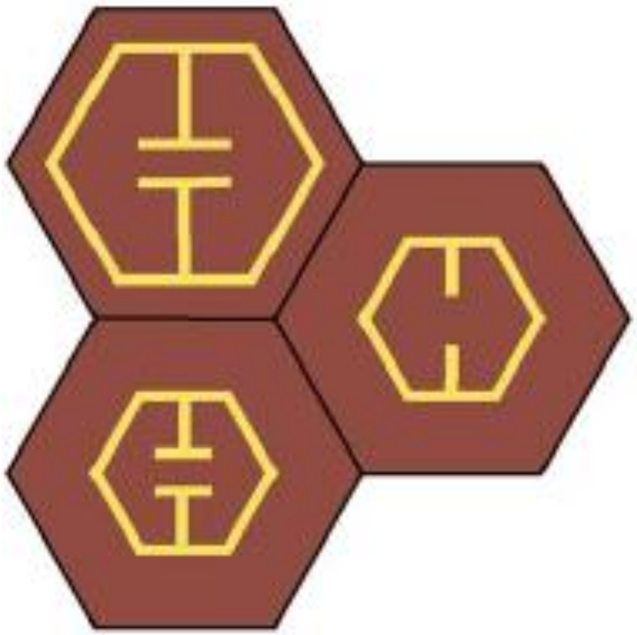
### Material Loss

- Material losses can become high, specifically as we move to higher frequencies
- Solutions ➔
  - Alternative materials
  - Introduction of gain medium
  - Electrical loss compensation (i.e. embedded transistors – Xu, 2012)



# Final Questions

## Are MMs the answer to all our problems in the THz and millimeter wave regime?

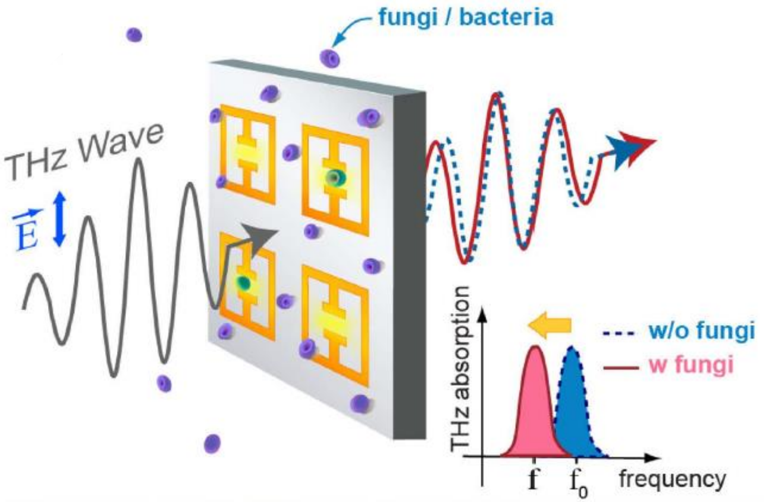


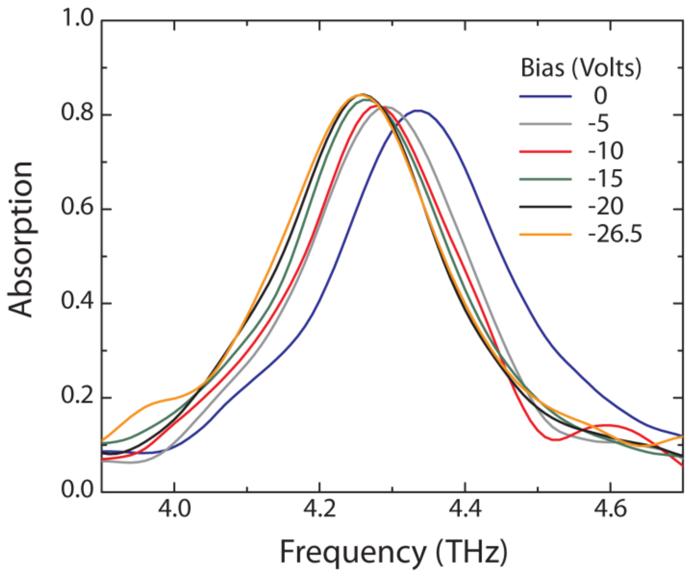
### Bandwidth

- Traditional metamaterials are typically narrow-band
- Solutions ➔
    - Different types of unit cells (Bingham, 2008)
    - Higher order modes
    - Tunable metamaterials

# Final Questions

**How can we use metamaterials to fulfil existing needs?**




Scalability

Inspiring New Technology

# Final Questions

How can we better connect basic research to product development in industry?

3rd TeraHertz: New opportunities for industry
Materials measurements and applications towards THz frequencies

**What is the future role of metamaterials in industry?**

# Thank you!

*All referenced works are included at the end of the presentation

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| Slide | Reference |
|---|---|
| 1. Title | |
| 2. Big topic | |
| 3. Outline | |
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