A Review of THz Metamaterials

Metamaterials Role In Millimeter-Wave and THz Industries

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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:**

- Individual MM elements are much smaller than the operation wavelength.
- Their effective response is different from that of the constituent materials.

**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 $\varepsilon(\omega)$ and $\mu(\omega)$. This gives control of transmission, reflection, etc.

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1. Metamaterials  
2. THz Metamaterials  
3. The THz Regime  
4. Current Metamaterial Research  
5. Conclusions and Future Outlook
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

- 2000: Negative index material achieved experimentally in microwave regime
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Reverse Doppler Shift
The Emergence of Metamaterials

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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 \( \Rightarrow \) gives no effective response (too subwavelength)
- Many subwavelength resonators \( \Rightarrow \) Collective response gives an effective \( \mu(\omega) = \mu_1 + i\mu_2 \)
Negative Index Materials

Metallic cut wire (microstrip) creates negative $\varepsilon(\omega)$

Double split ring resonator creates negative $\mu(\omega)$

Shelby, 2001
Negative Index Materials

Composite structure with subwavelength elements

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Shelby, 2001
Super-Lensing

Negative index material lenses can theoretically refocus both the far and *near field* \( \Rightarrow \) beat diffraction limit

- Experimental demonstration: \( \varepsilon = -1 \) and \( \mu = -1 \) metamaterial resolved below the diffraction limit at \( \sim 1 \) GHz
- Limitation: material characteristics
Beyond Negative Index Materials

- Metamaterial EM Wave Absorbers (Liu, 2010)

Impedance match to free space, reflection $\rightarrow 0$
Beyond Negative Index Materials

• Metamaterial EM Wave Absorbers (Liu, 2010)

Ground plane thicker than penetration depth, transmission $\Rightarrow$ 0
Beyond Negative Index Materials

• Metamaterial EM Wave Absorbers (Liu, 2010)

Absorption = 1 – R – T \Rightarrow 1

Beyond Negative Index Materials

- Metamaterial EM Wave Absorbers (Liu, 2010)

- Multiband and broadband metamaterials
- Dynamic metamaterials: dynamically tune properties with external stimuli
MMs Across the EM Spectrum

MMs Across the EM Spectrum

VNA Systems

THz Spectroscopy

FTIR Spectroscopy

Characterization Techniques

Increasing wavelength $\lambda$

Decreasing MM size

The THz Frequency Regime

- **THz Regime**: 300 GHz – 10 THz
- **Millimeter Wave Regime**: 70 GHz – 300 GHz

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Why do we care about MMs?

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

**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

**Businessweek**
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

Example: highly applicable as an aeronautical terminal

Using metamaterials for wide-angle, all-electronic beam steering
Kymeta and the mTenna
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In 2004 the classic split ring resonator (SRR) was scaled to give a magnetic response in the THz regime.
What Makes THz MMs So Effective?

• 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

General Considerations with Dynamic THz MM Devices

Tuning Depth

Resonance frequency 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

Potential Applications

Personnel Screening with THz Imaging

Biomedical and Medical Applications

Spectroscopic Screening

THz absorption of basal cell carcinoma

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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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

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Hunt, 2013
Imaging With MM Coded Apertures
MM Device Fully Integrated Into Industry

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

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

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 MM

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 MM-SLM allows for accurate imaging in the THz regime without any moving parts and with the sensitivity of a single pixel detector.
THz Single Pixel Imager
MM Device With High Potential for Application

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Watts, 2014
THz Single Pixel Imager
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Watts, 2014
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
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. Seo¹, H. R. Park¹, S. M. Koo², D. J. Park¹, J. H. Kang³, O. K. Suwal⁴, S. S. Choi⁴, P. C. M. Planken⁵, G. S. Park¹, N. K. Park², Q. H. Park³* and D. S. Kim¹*

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. Smith¹*
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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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| 29. Potential Applications | Image courtesy of QinetiQ (https://www.qinetiq.com/Pages/default.aspx)  
| 30. – 31. THz Devices: Getting from Demand to Supply | Image courtesy of QinetiQ (https://www.qinetiq.com/Pages/default.aspx)  
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| 33. Summary of Industry-Geared.. | |
Evolv Technologies (http://evolvtechnology.com/). |
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