Microwave and Photonic Metamaterials

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Technical Intuition?
Photonic Crystals?

1887 Lord Rayleigh studies 1D periodic structures
1987 Yablonovitch and John propose Photonic Crystals
1998 Knight et al. demonstrate real optical device
              (Uni. of Bath and DTU collaboration)
Photonic Crystals: State-of-the-Art

Advanced structures for slowing light to increase material gain

Suggested theoretically by J. P. Dowling et al., JAP (1994), but never demonstrated experimentally
Photoluminescence Measurements

Spontaneous lasing due to Anderson localization:

Localisation length $\sim 4$-$6 \, \mu$m.
Q-factor $\sim 5000$

Limits amplifier gain

Metamaterials

1967  Vaselago predicts materials with negative $\varepsilon$ and $\mu$

1999  Pendry proposes split ring structures with negative $\mu$
        and founds the modern field of metamaterials

2000  Smith et al. demonstrate functional metamaterials

-2014 Explosion of research in metamaterials,
        however, most experimental demonstrations at microwaves
Challenges

- Broadband operation without distortions
- 3D omnidirectional operation
- Functional devices at visible wavelengths
Avoiding Metals For The Optical Range?

Massive photonics industry at visible and near-infrared wavelengths

Metals are the bottleneck of performance in many classes of optical metamaterials:

• High losses, large magnitude of permittivity, lack of tunability of optical properties
• Challenges associated with nanofabrication and integration

Metal-free plasmonic metamaterial:

• Hyperbolic metamaterials
• Semiconductor-based (dilute metals)
• Boltaseva et al., Purdue and DTU, 2012
• Al:ZnO/ZnO metamaterial
• Negative refraction @ 1.8-2.4 μm (for incident angles of 40 degrees)
• Enhanced light-matter interactions due to large photonic density-of-states
“Meta-Atoms”

Nanoparticles as “meta-atoms”:
Bridging the gap between outer and inner photoelectric effects

Microscopic: Interface effect  
Macroscopic: Bulk-material effect

Photoelectric metamaterials with intricate nanoantennas: 
New perspectives in sensing, photo-electro-chemistry, etc.

Electrochemistry  Chirality sensing  Optical rectennas
Plasmonic Metamaterial Effect

- Conventional plasmonics is an electromagnetic problem; free electron motion is restricted by the nanoparticle
- Conventional metamaterials are also considered as an electromagnetic problem
- Photoelectric effect is a quantum problem
- If we relax the restriction of electrons to stay inside a nanoparticle and include photoelectric effects: New photoconductive metamaterial structures, where metamaterials are now introduced merging classic and quantum effects
Directional Photocurrent

Resulting values of effective photogalvanic tensor exceeds bulk-media values by orders of magnitude!
Optical Fibers

- Hollow core fibers with large core dimensions, millimeter level
- Proposed @ DTU; Yan & Mortensen, Optics Express, 2009
- Not yet realized, but **disruptive possibilities** in:
  - Materials processing, Telecommunications and Defense applications

- New advanced production technologies @ Uni. Sydney, Nature Communications, 2013
Optical Fibers

- Miniaturized optoelectronics
- Highly sensitive sensors

Colorful Plastic Using Plasmonics Metasurfaces

Clausen et al., Nano Lett. 14, 4499 (2014)
Metasurfaces In Reflectarray Antennas

Metasurface based on sub-wavelength dual split-ring loop resonators.

Unlike natural materials, this surface maintains the sense of circular polarization upon reflection!

Element pattern may be modulated to synthesise a specified radiation pattern for a satellite communication antenna with European coverage.


In close cooperation with Cobham Satcom and Ticra.
Sub-wavelength Resonant Scatterers And Antennas

Superdirective magnetic dipole array – designed for DTU-ESA Spherical Near-Field Antenna Test Facility

Measurement results:
D = 9.2dB
G = 7dB

**Sub-wavelength Resonant Scatterers And Antennas**

Spherical split-ring antenna on ground plane

Other DTU sub-wavelength antennas

- **Multiarm spherical helix antenna**
  
  \( k\alpha \approx 0.254 \)
  
  \( R_0 = 50\Omega \)

- **Spherical SRR antenna**
  
  \( k\alpha \approx 0.131 \)
  
  \( R_0 = 50\Omega \)

- **Spherical split-ring antenna**
  
  \( k\alpha \approx 0.184 \)
  
  \( R_0 = 50\Omega \)

- **Spherical meander antenna**
  
  \( k\alpha \approx 0.266 \)
  
  \( R_0 = 72\Omega \)

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Sub-Wavelength Resonant Scatterers And Antennas

3D printing technology is employed to realize complicated wire antenna structures

Spherical helix antenna

Spherical zigzag antenna

\(ka=0.4\)

Looking Towards The Future – Applications

- Lenses for high-gain antennas
- Shielding of sensitive medical devices from disruption by MRI scanners
- Cloaks to route cellphone signals around obstacles
- Light concentrators for solar cells

Inspiration for disruptive applications outside electromagnetics:
- Shielding structures from earthquakes
- Improving ultrasonic sensors
- Shielding from noise
Sonic Applications: Cloaking

2014, Steven Cummer et al.
Acoustic invisibility cloak
Duke University
Sonic Applications: Broadband Noise Absorption

Exp. Theory

(a) (b)

Frequency (kHz)

Incident Angle $\theta$ ($^\circ$)

Christensen et al., Scientific Reports 4, 4674 (2014)
Your task is not to foresee the future, but to enable it.

Antoine de Saint-Exupéry