http://www.mit.edu/~fadel/courses/MAS.s60/index.html

MAS.S60

How to Wirelessly Sense Almost Anything

Lecture 10:
Smart Surfaces & Metamaterials

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This Week in Wireless Sensing

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Nokia to lead KOMSENS-6G, integrating sensing into the communications system

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Press Release

- Nokia is named the overall lead for KOMSENS-6G, a German national-funded 6G technology project.
- KOMSENS-6G targets to expand the scope of wireless networks by integrating sensing capabilities.
- Unlike previous generations, in the 6G era the mobile network itself could act as a sensor, creating synergies that can be used to localize non-connected objects while at the same time optimizing data transmission.

15 November 2022

https://www.nokia.com/about-us/news/releases/2022/11/15/nokia-to-lead-komsens-6g-integrating-sensing-into-the-communications-system/

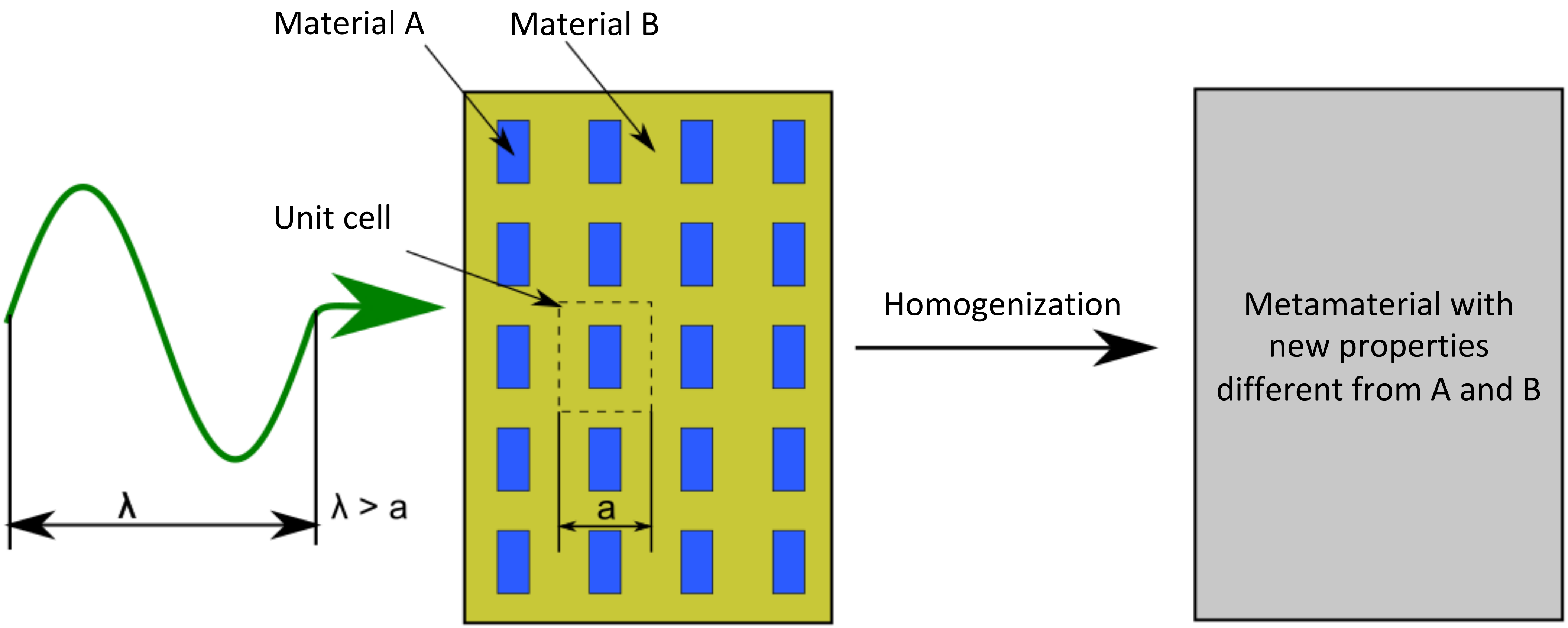
Objectives of Today's Lecture

Learn the fundamentals of **smart surfaces and metamaterials** applications, and implications on **wireless sensing.**

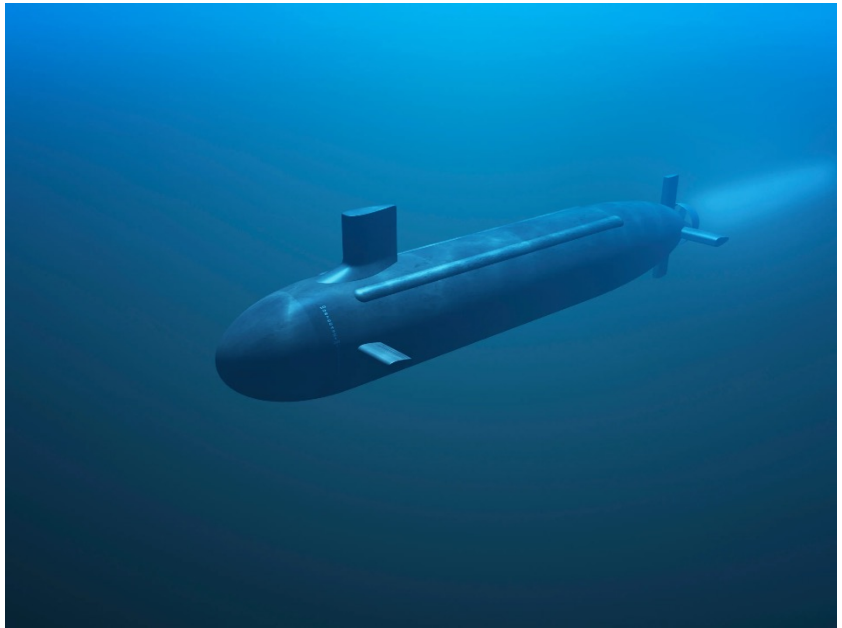
1. What are metamaterials? And how can we make one?
2. What are reconfigurable smart surfaces? How are they related to metamaterials?
3. What can we build using smart surfaces and metamaterials?
4. How can we use smart surfaces and metamaterials in wireless sensing?

What are metamaterials?

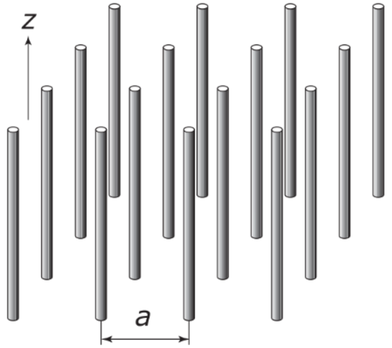
Metamaterials are effectively homogeneous subwavelength engineered structures with unusual properties unavailable in natural materials.



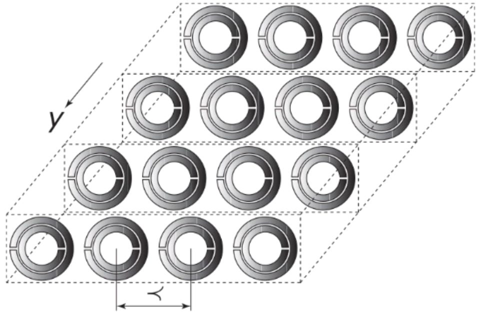
Metamaterials technology



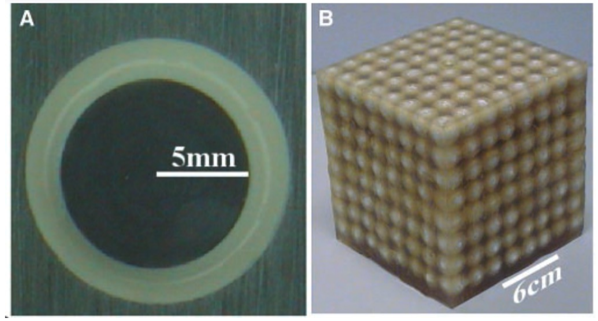
First electromagnetic and acoustic metamaterials



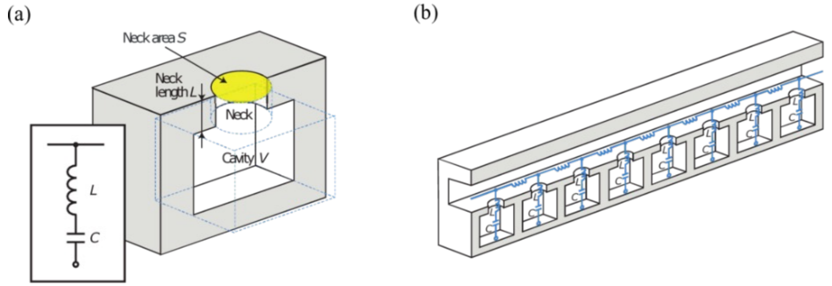
Metamaterial with negative ϵ at 8.2 GHz [Pendry et al. 1998]



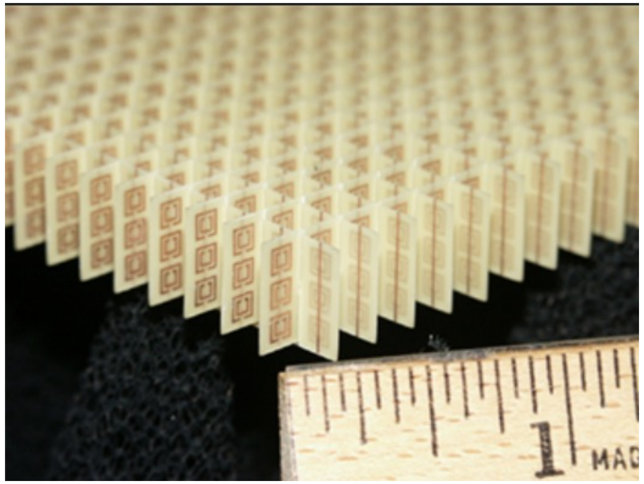
Metamaterial with negative μ at 13.5 GHz [Pendry et al. 1998]



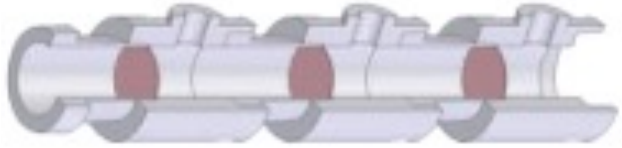
Lead in silicone metamaterial had a negative ρ at 400 Hz [Liu et al. 2000]



Helmholtz metamaterial had a negative B at 30 kHz [Fang et al. 2006]



Metamaterial with a negative refractive index (n) for microwaves at 10.5 GHz [Smith et al. 2000]



Slot-membrane waveguide had a negative n at 342 Hz [Lee et al. 2010]

How can material properties affect wave propagation?

- Wave propagation in a homogeneous medium is governed by the wave equation:

Electromagnetic waves

$$\nabla^2 E + \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$$

$$c = \pm\frac{1}{\sqrt{\mu\epsilon}}$$

Acoustic waves

$$\nabla^2 p + \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

$$c = \pm\sqrt{\frac{B}{\rho}}$$

- The solution of the wave equation is:

$$E(d,t) \ = Ae^{j(\omega t - kd)}$$

- k is the propagation constant/ wavenumber

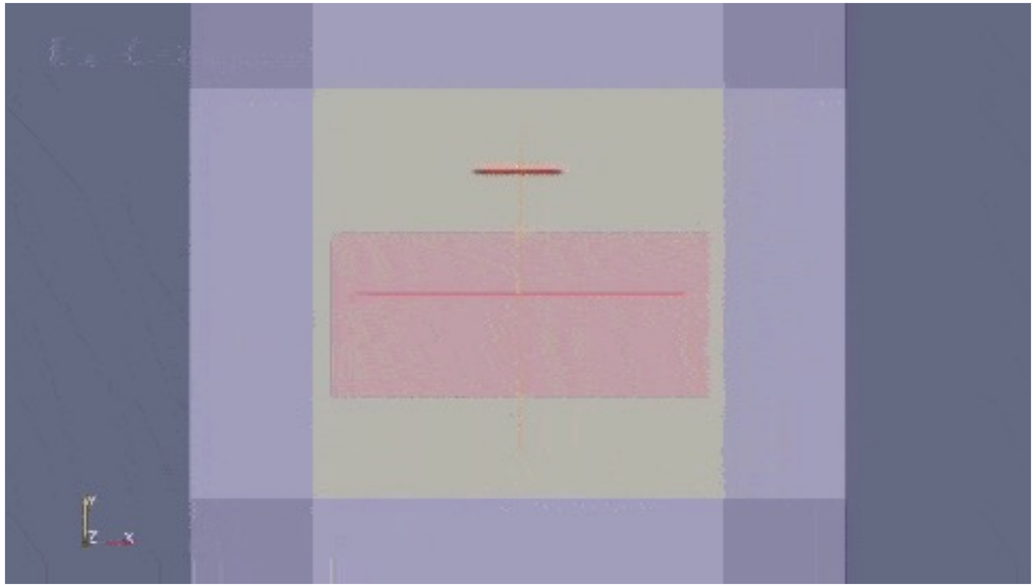
$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

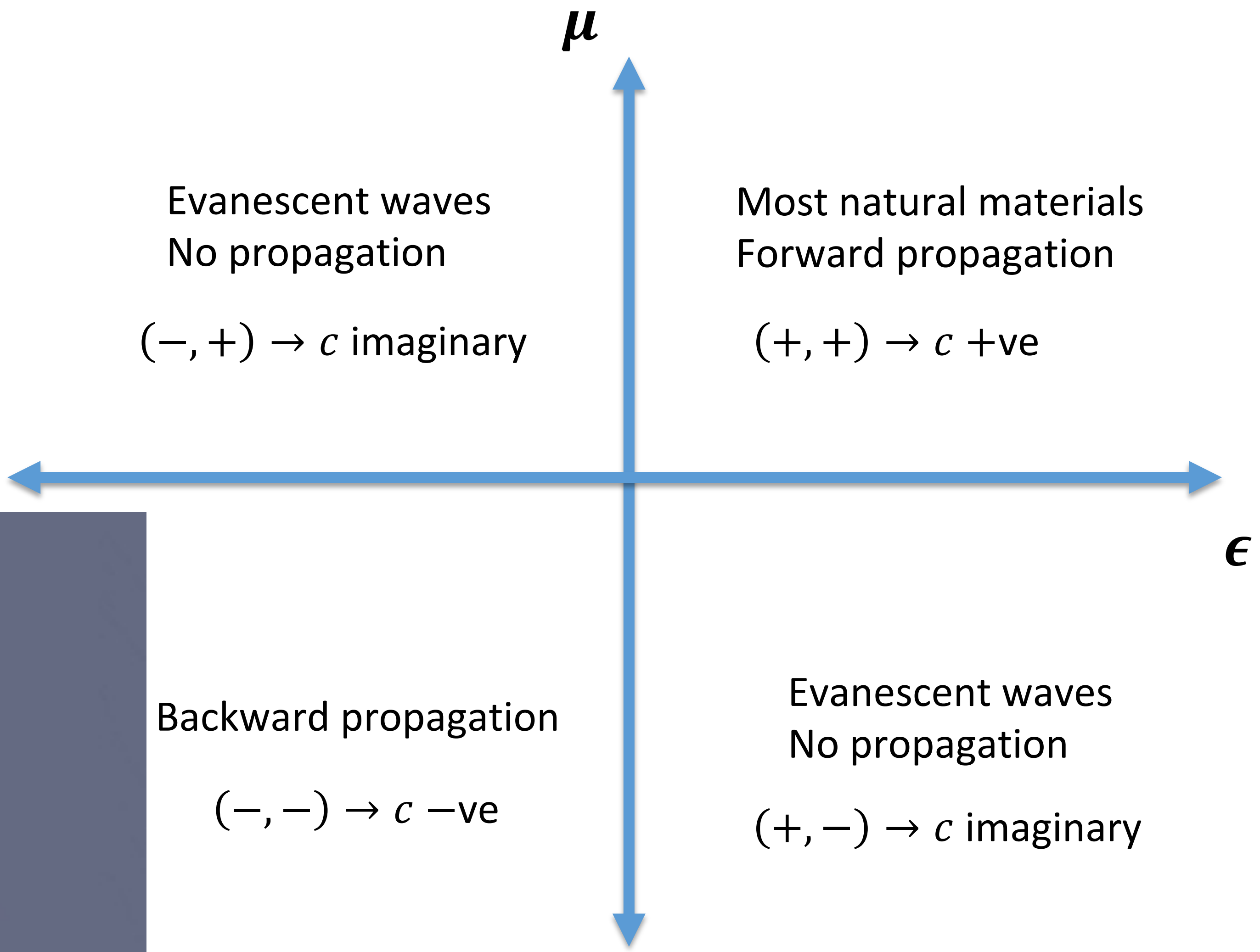
What does it mean to have negative properties?

$$E = Ae^{j(\omega t - \frac{\omega}{c} d)}$$

- Propagation depends on c

$$c = \pm \frac{1}{\sqrt{\mu \epsilon}}$$

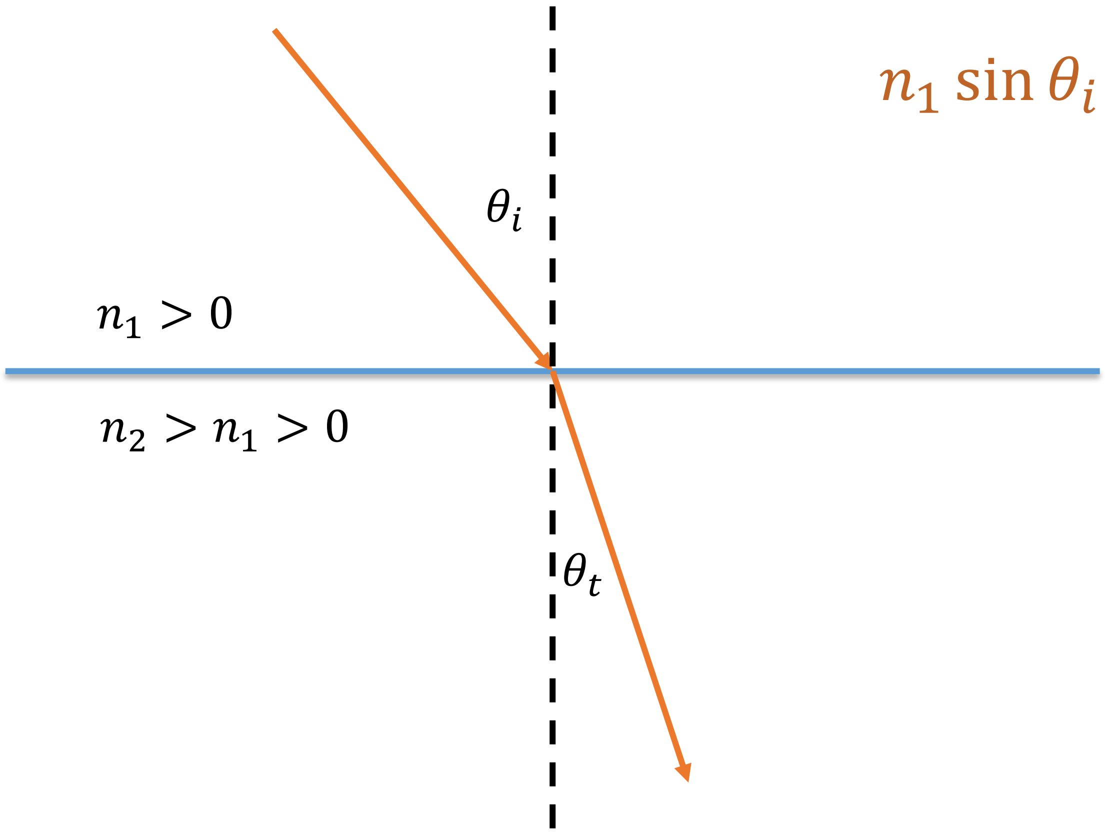




Snell's Law

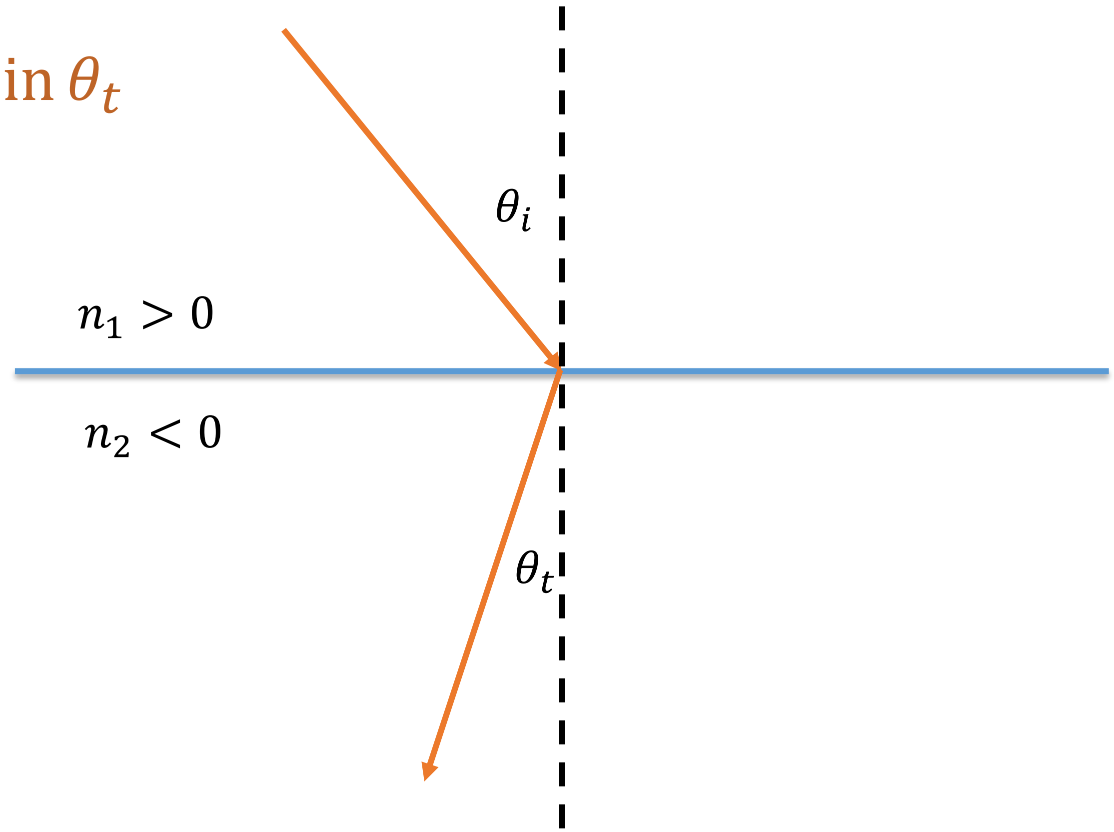
- The refractive index is: $n = \frac{c_o}{c}$
- A wave refracts (bends) when there is a change in the refractive index.

Positive refraction



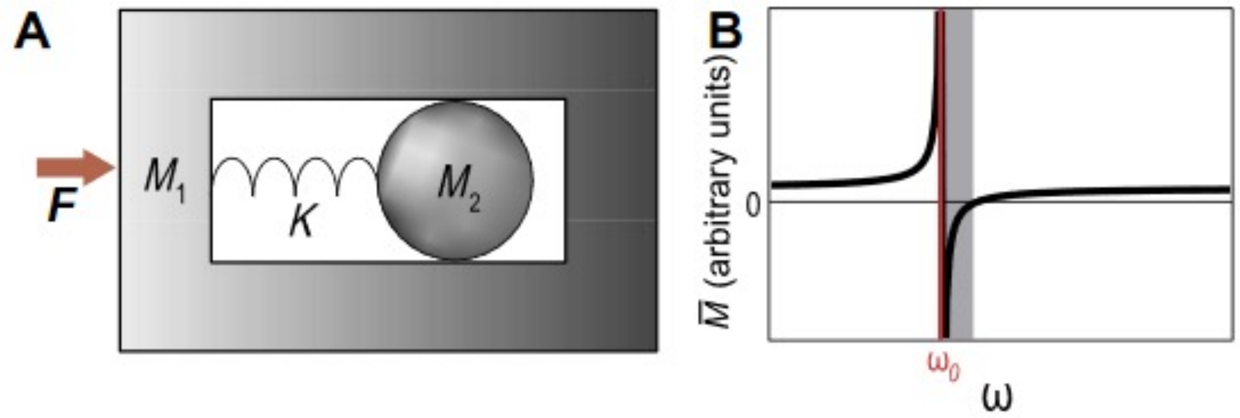
$$n_1 \sin\theta_i = n_2 \sin\theta_t$$

Negative refraction



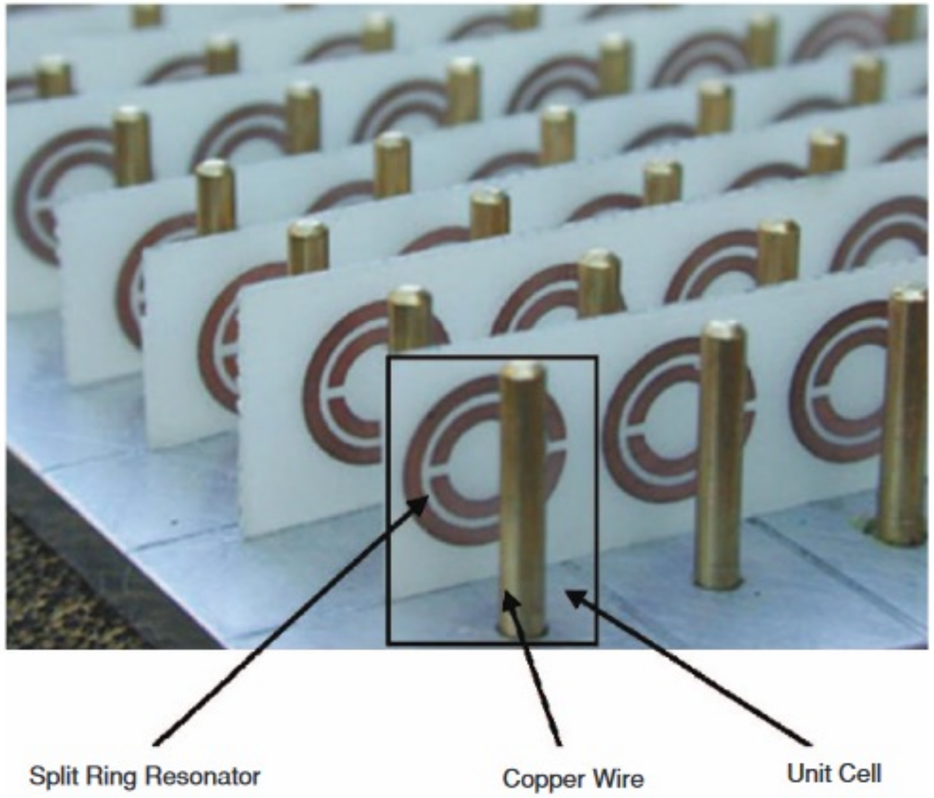
How can we make metamaterials?

1. Local resonance: include resonators in the unit cell design



Acoustic

[Ma and Sheng 2018]

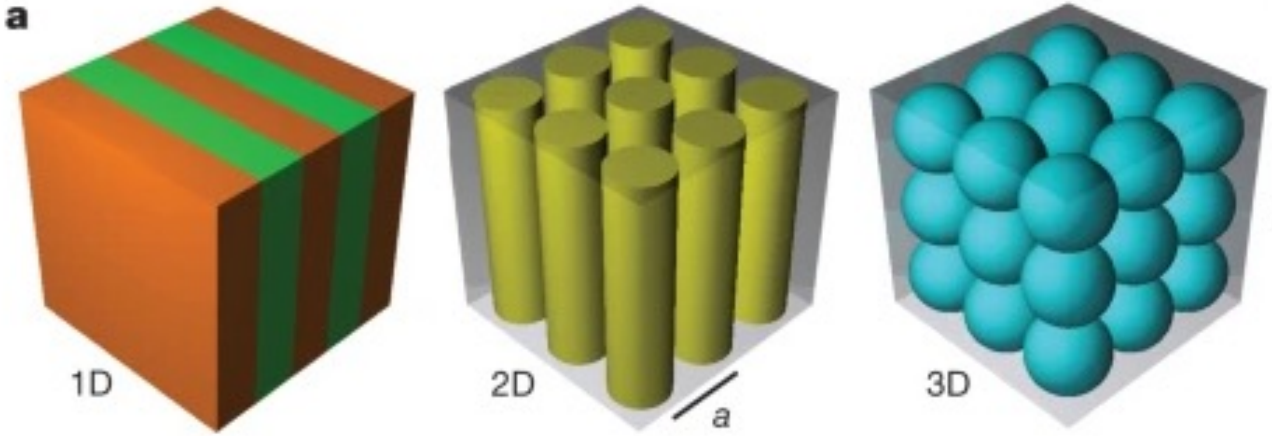


Electromagnetic

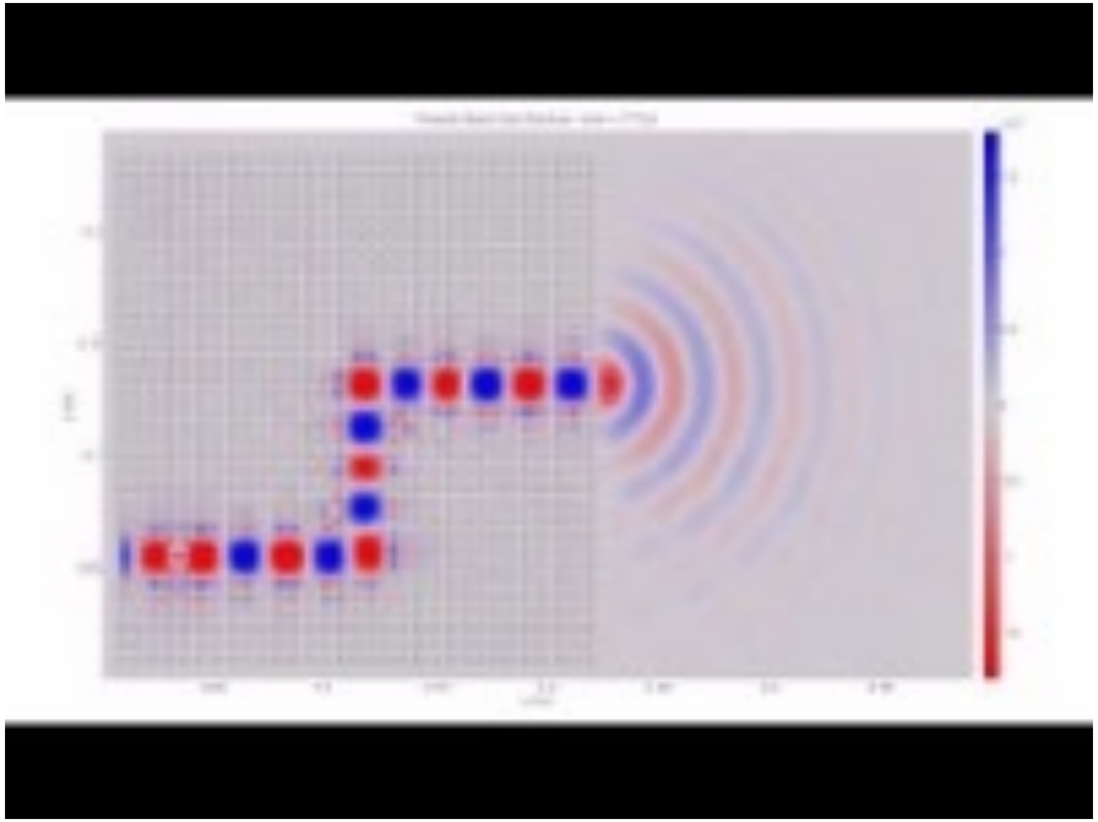
[Smith et al. 2000]

How can we make metamaterials?

2. Photonic/phononic crystals: use two materials with contrasting impedance (periodicity and multiple scattering effects lead to new properties)

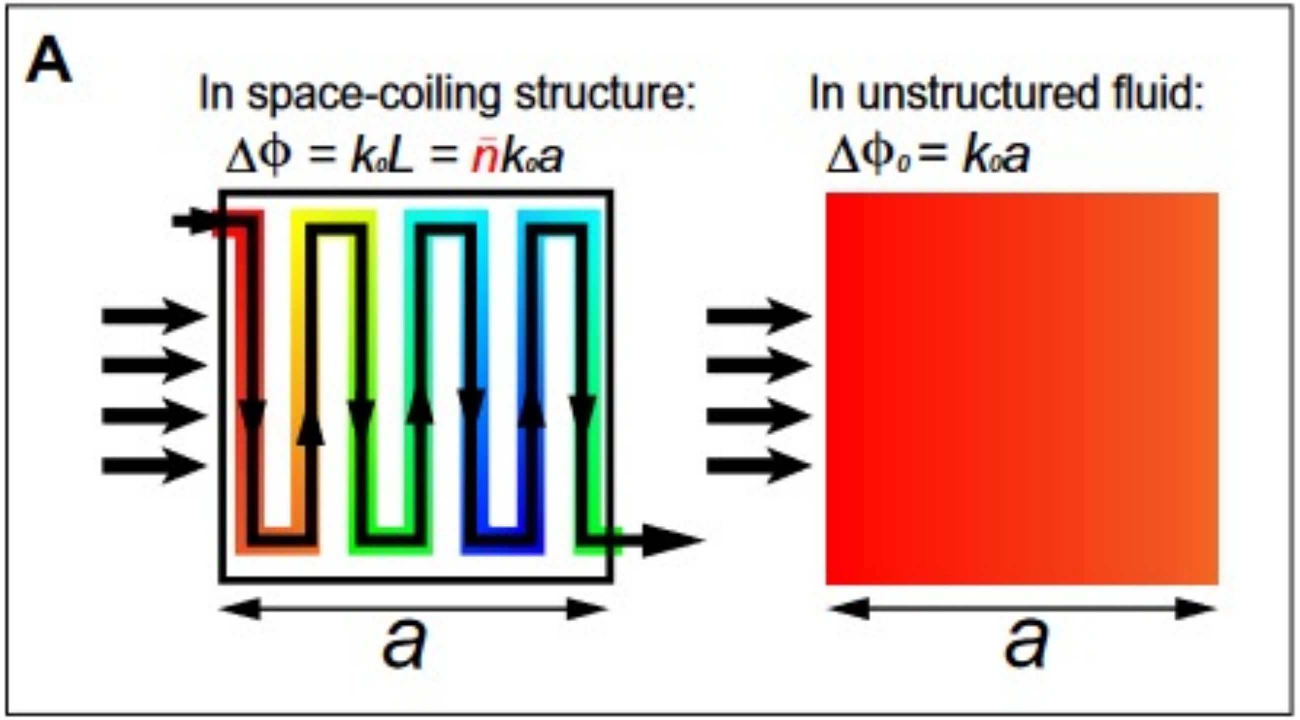


[Maldovan 2013]

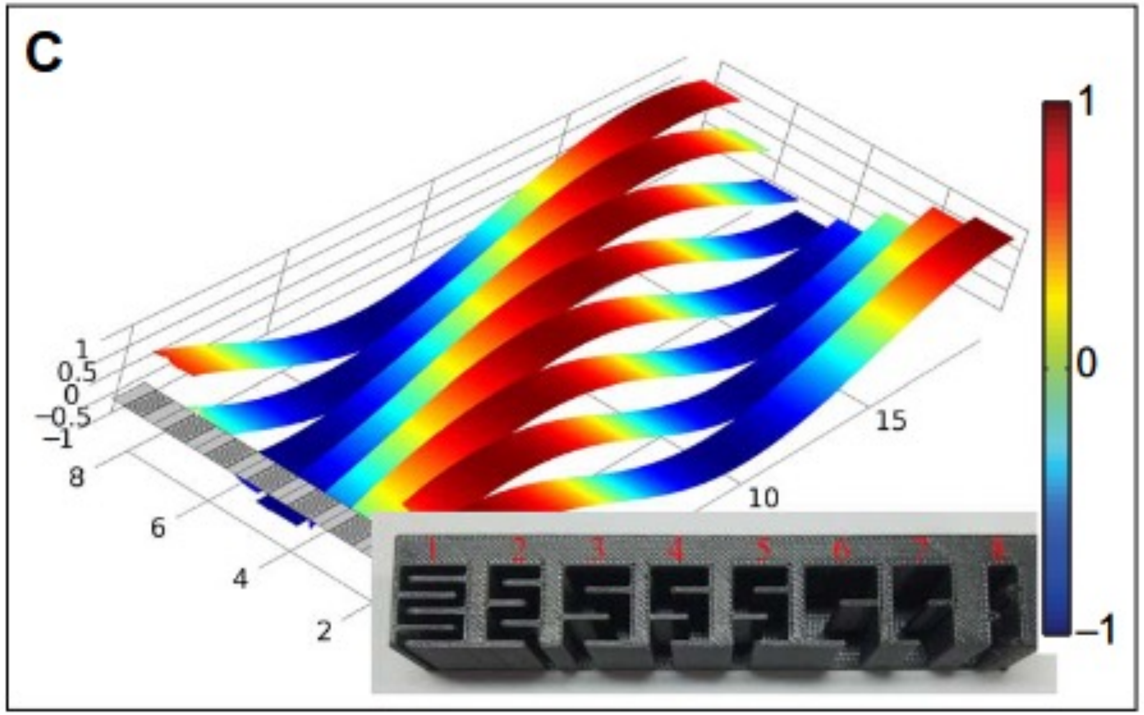


How can we make metamaterials?

3. Space coiling: Force the wave to move in a labyrinth waveguide



[Ma and Sheng 2013]

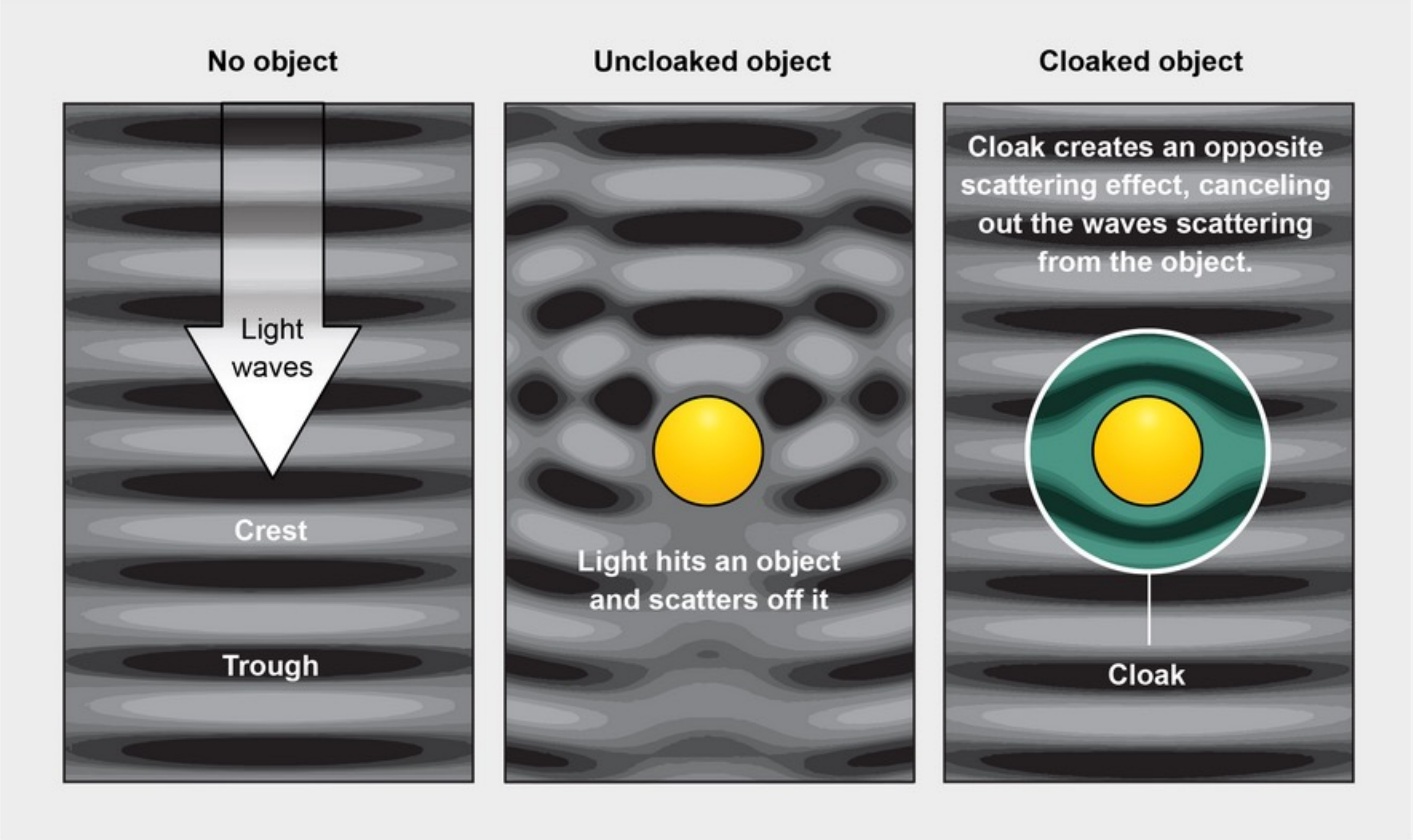


[Li et al. 2013]

What can we make using metamaterials?

Invisibility Cloaks

- We can use coordinate transformations to shape the refractive index and bend the waves around the object.
- The transformations require negative properties at some locations for perfect cloaking.

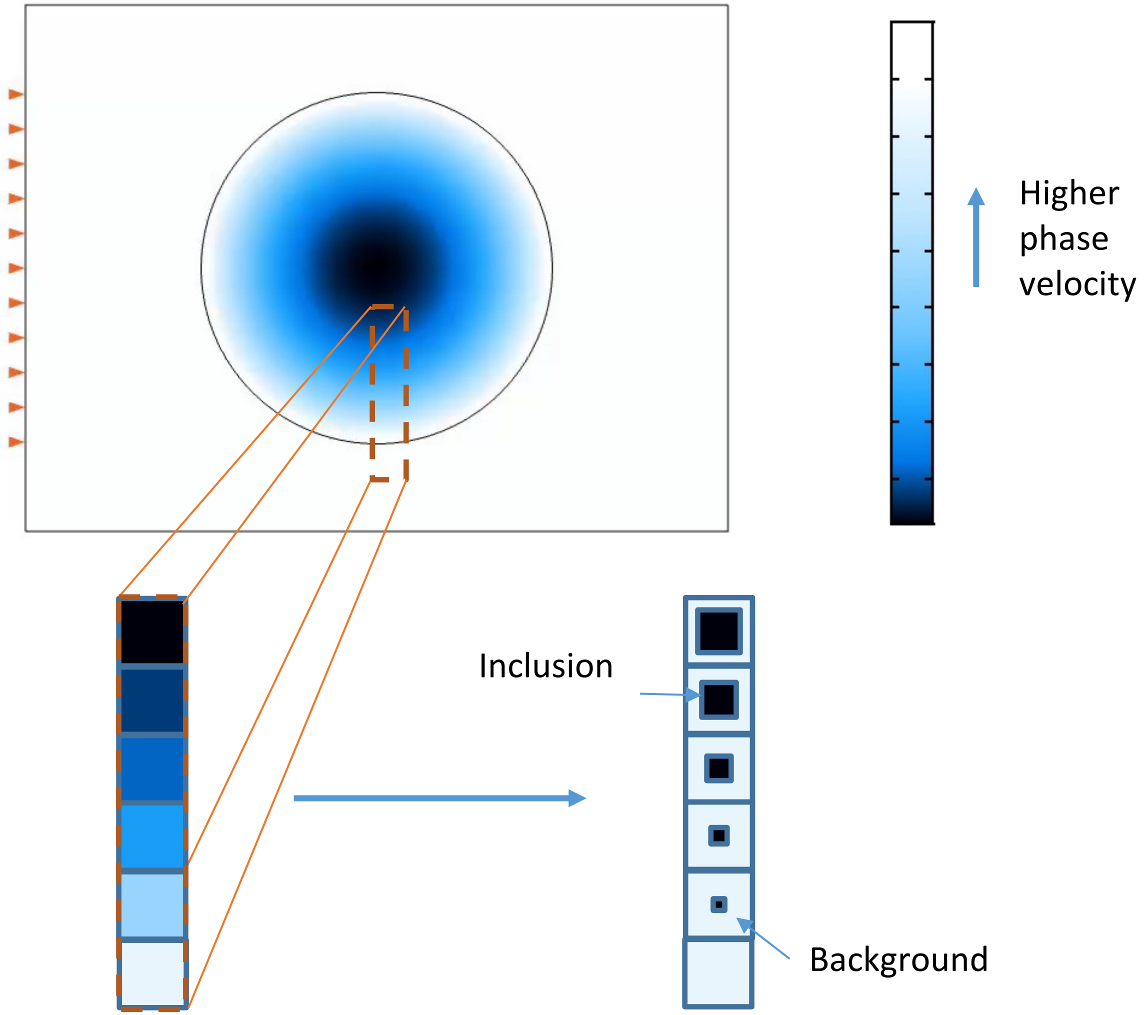


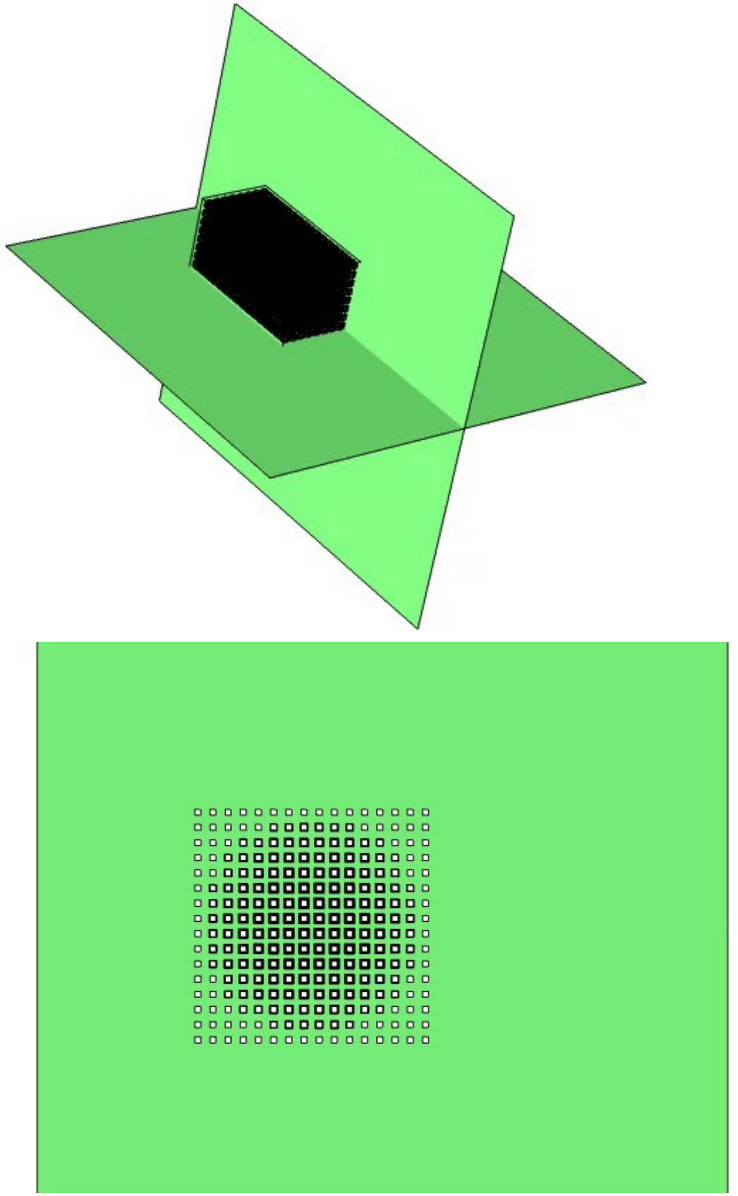
Credit: Jen Christiansen

https://www.scientificamerican.com/article/engineered-metamaterials-can-trick-light-and-sound-into-mind-bending-behavior/

What can we make using metamaterials?

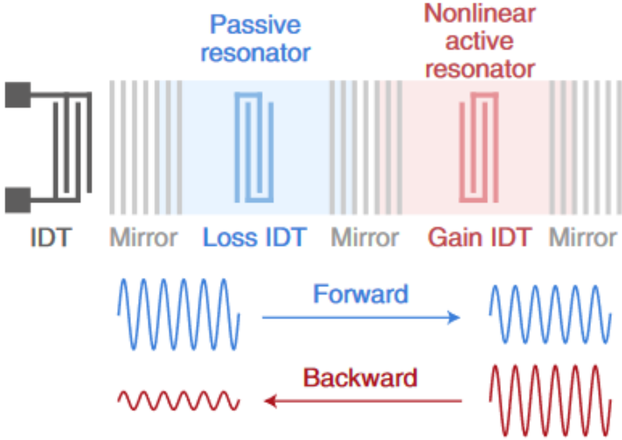
Lenses





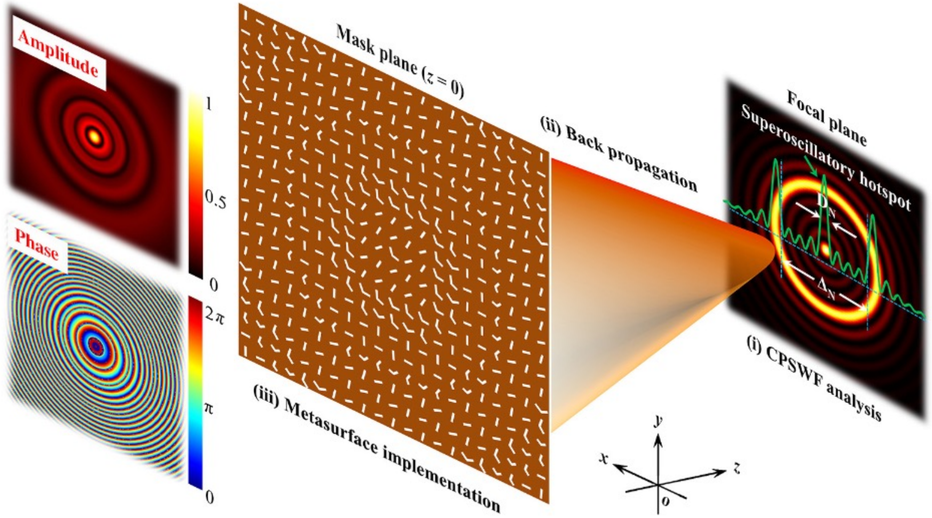
What can we make using metamaterials?

Non-reciprocal transmission domains to realize acoustic diodes



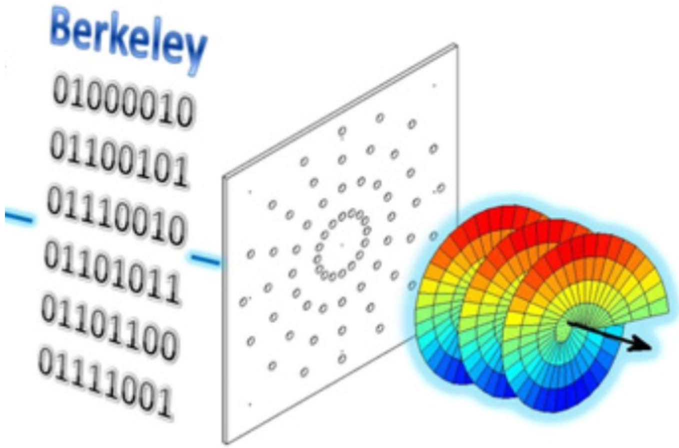
[Shau et al. 2020]

Superlenses to break the diffraction limit in imaging



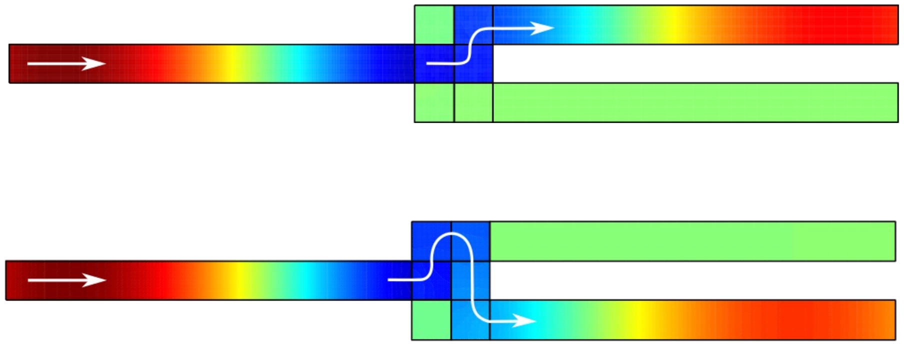
[Yuan et al. 2019]

Polarization control and realizing acoustic spin for underwater communications



[Shi et al. 2017]

Realizing active and reconfigurable waveguides



[Allam et al. 2016]

What are smart reconfigurable surfaces?

- Metasurfaces are metamaterials designed to form a thin surface to **reflect** or **refract/defract** incident waves.
- Metasurfaces are easier to design than metamaterials by tailoring the phase of the transmitted/reflected wave $\phi = nkd$.
- Smart reconfigurable surfaces are metasurfaces with programmable "reconfigurable" unit cells.

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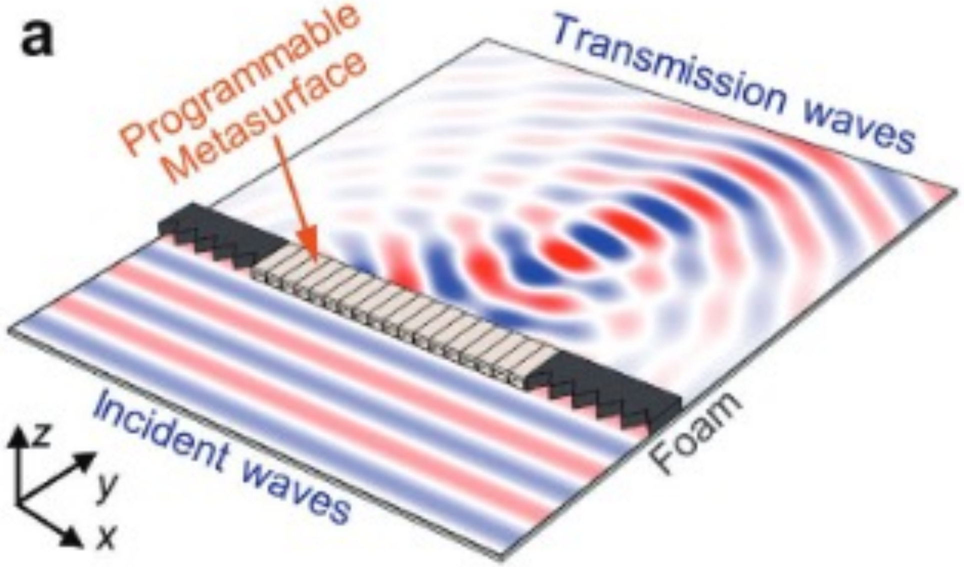
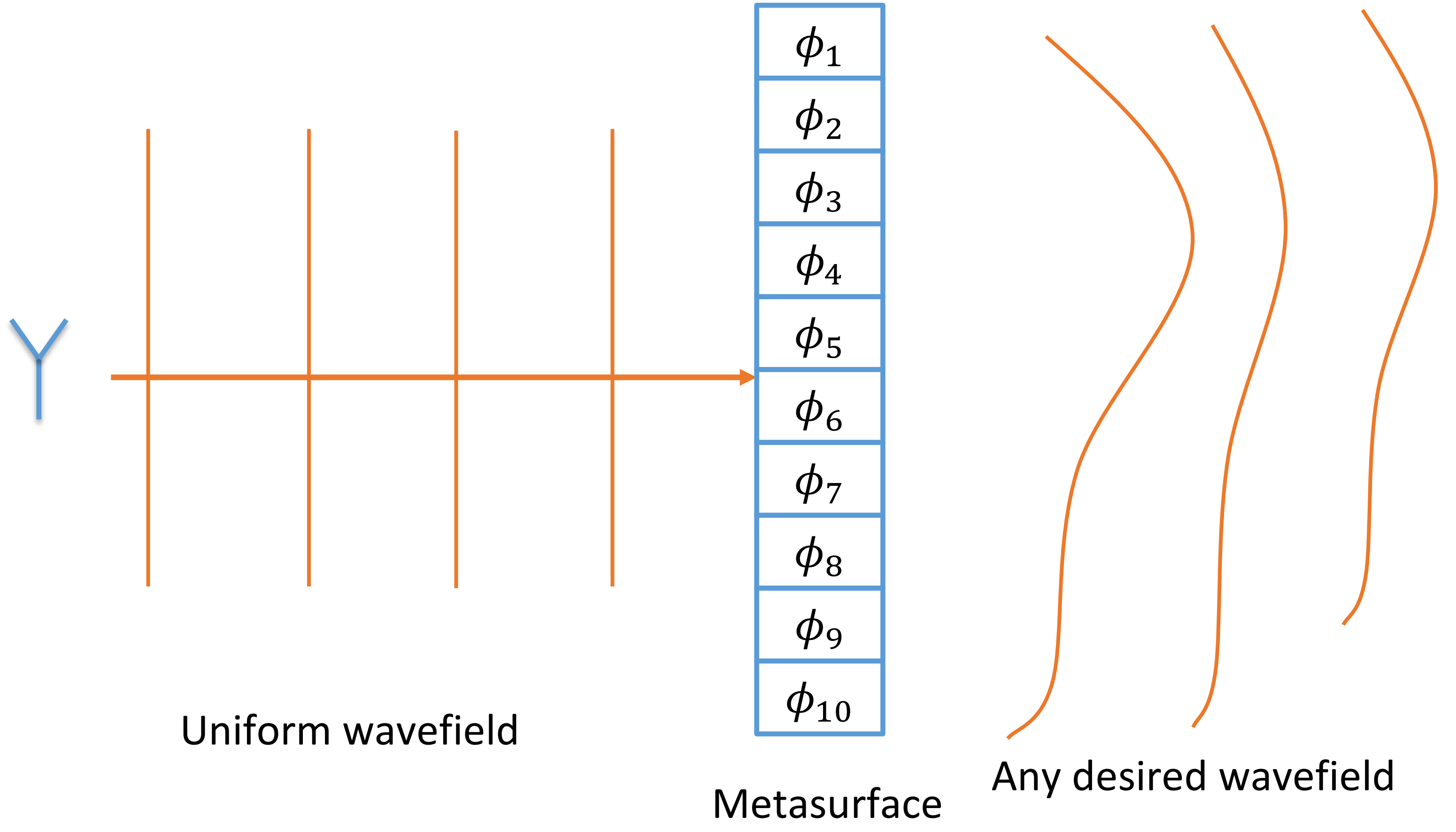


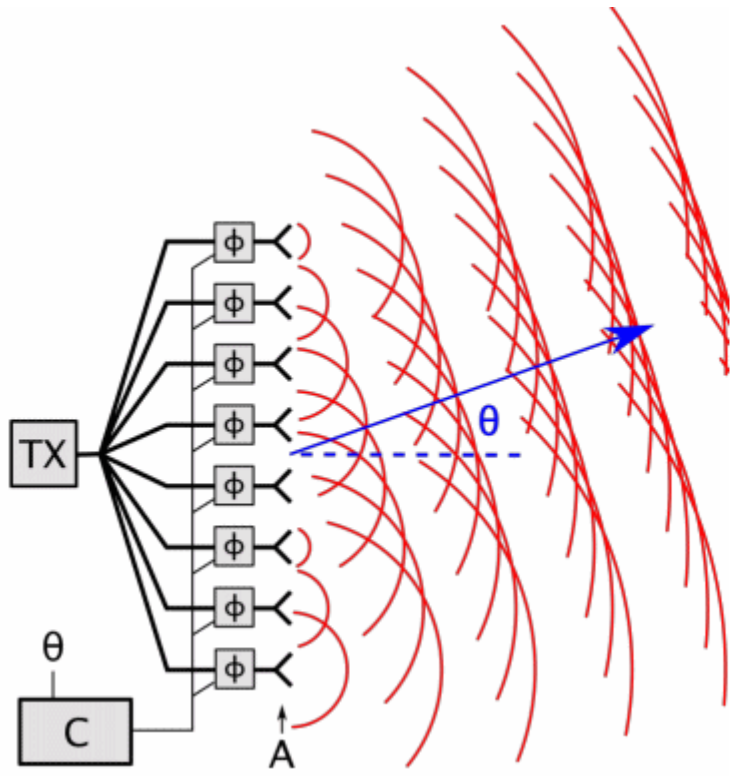
How do refractive metasurfaces work?

- Refractive metasurfaces (holograms) act as phase shifters to create a desired wavefield from a uniform field:

Refractive metasurface



Phased arrays



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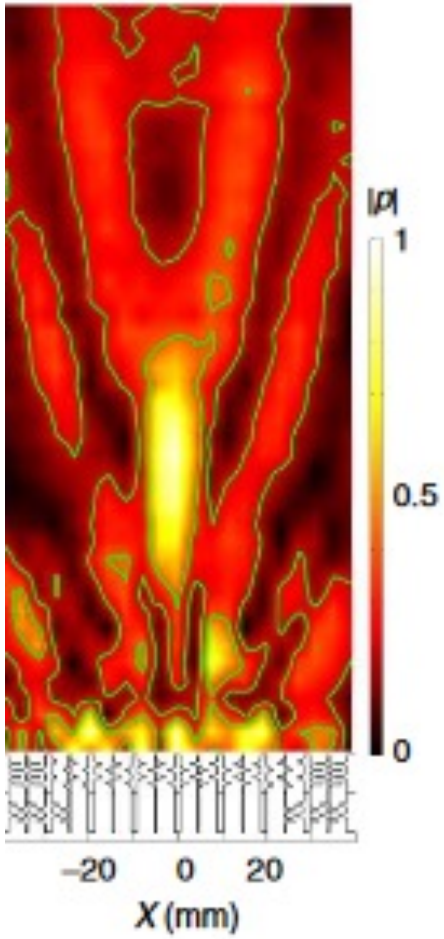
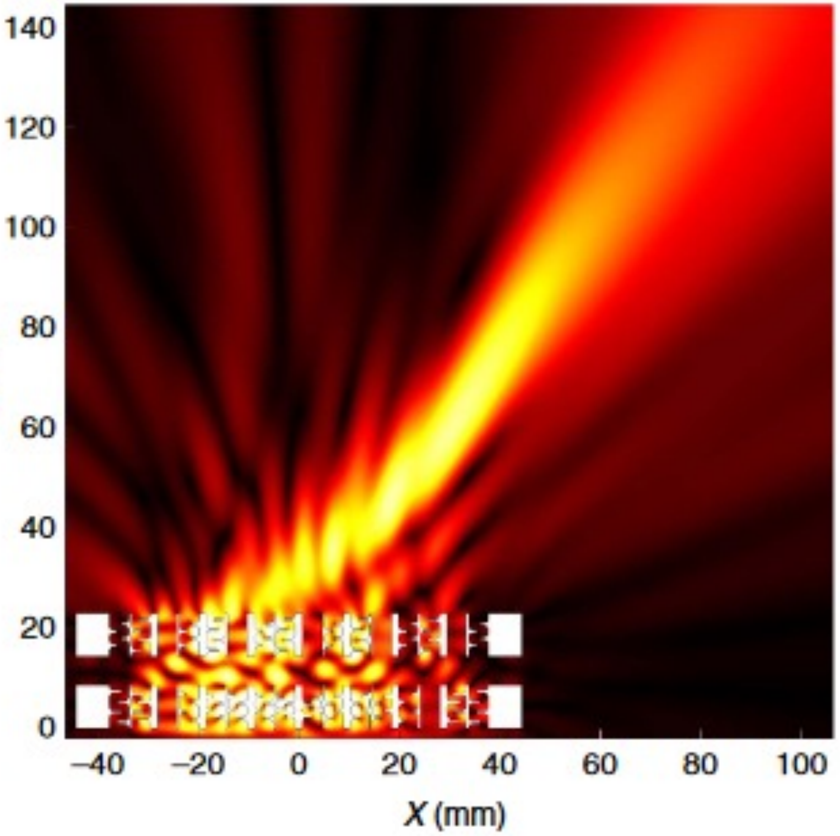
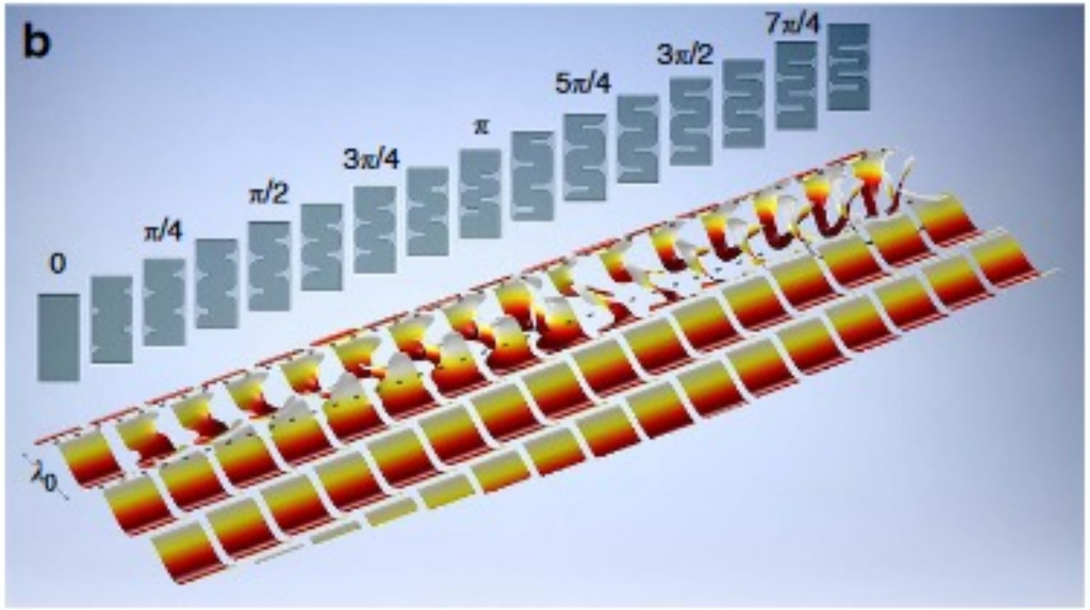


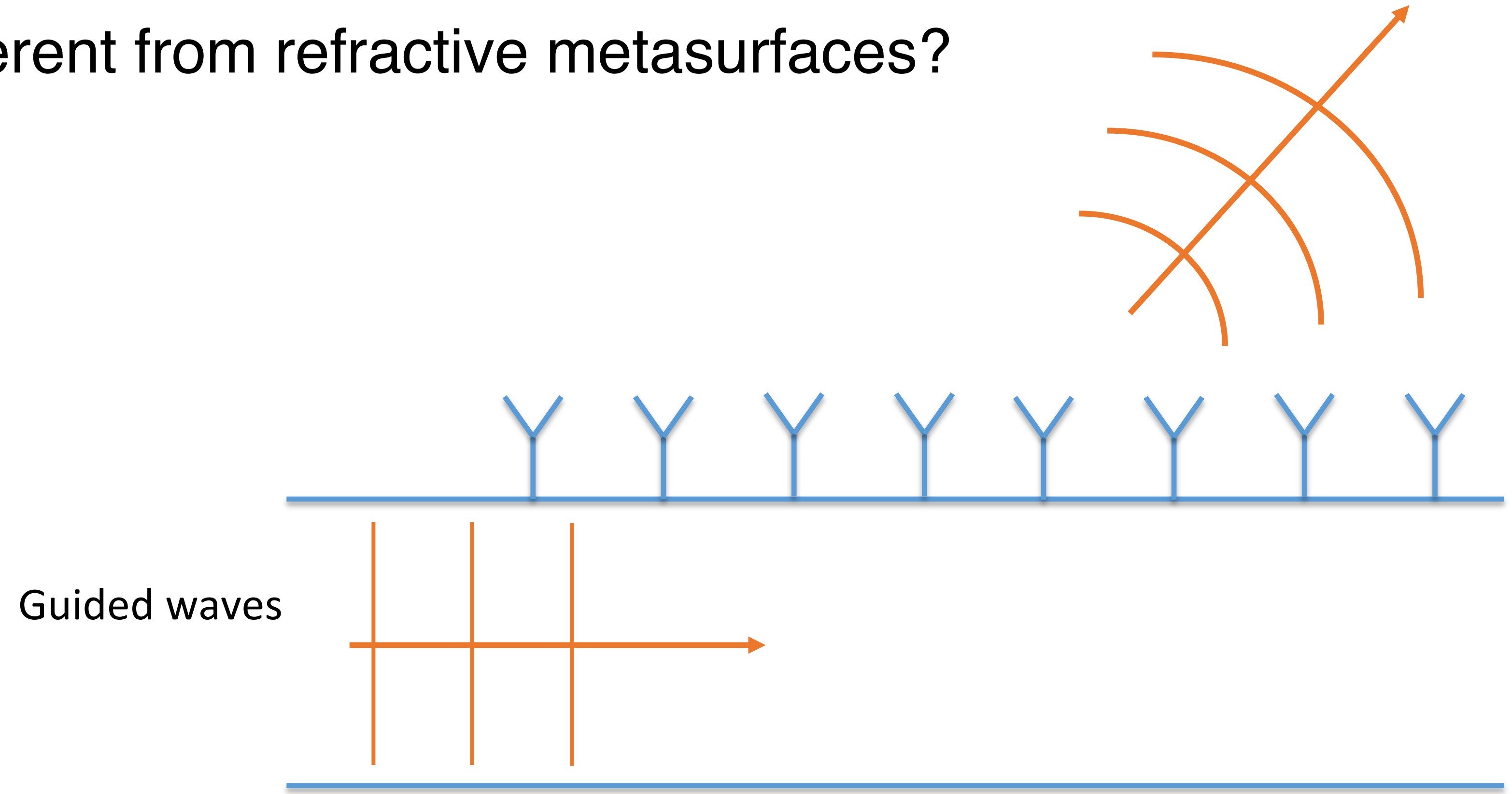




Quantized acoustic metasurfaces
[Memoli et al. 2017]

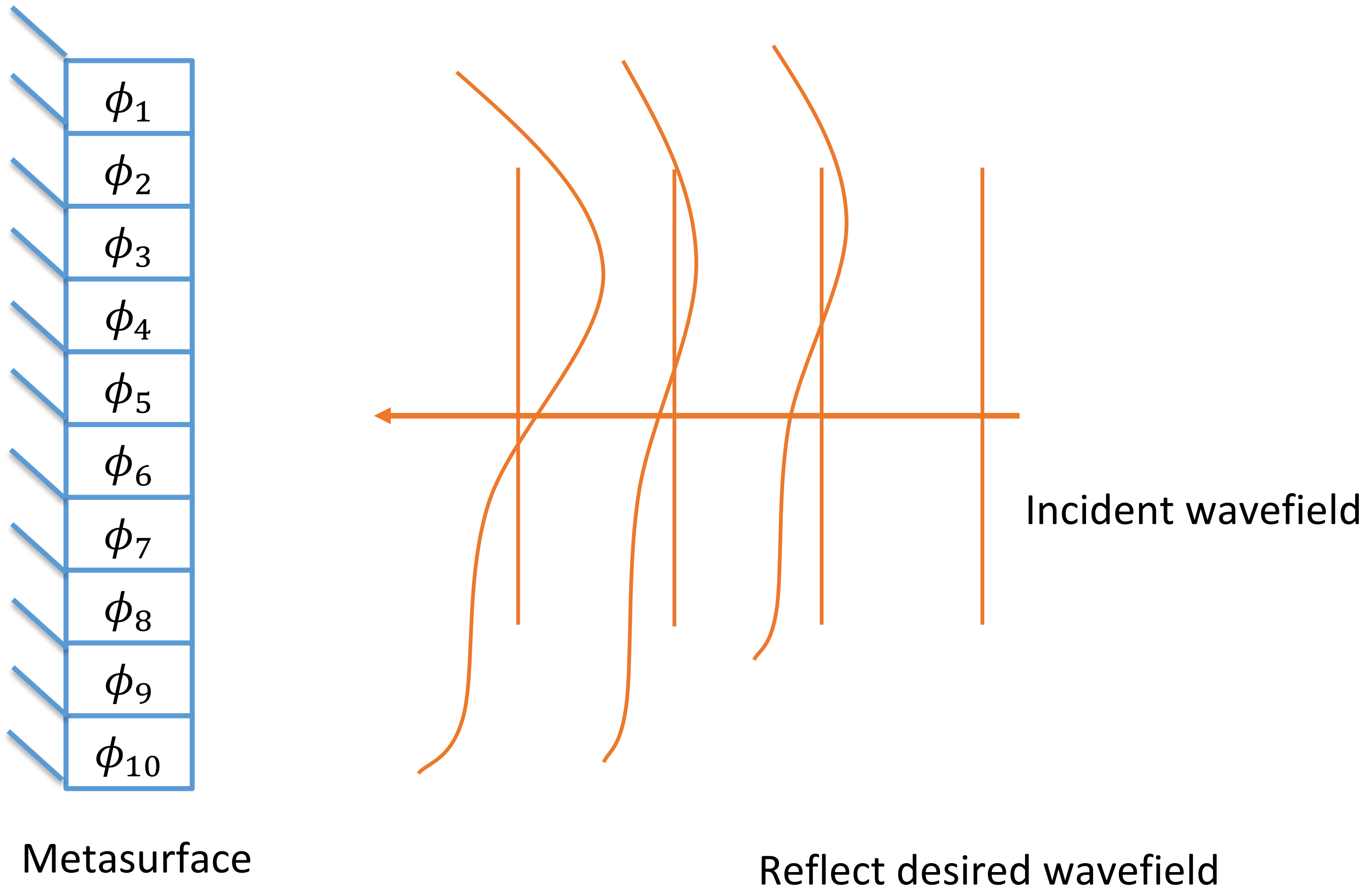
Diffractive metasurfaces: MSAT

- Idea: Use a metasurface instead of a phased array for satellite communications. Advantages?
  - Cost
  - Efficiency
  - Power
  - Weight
- How is MSAT different from refractive metasurfaces?

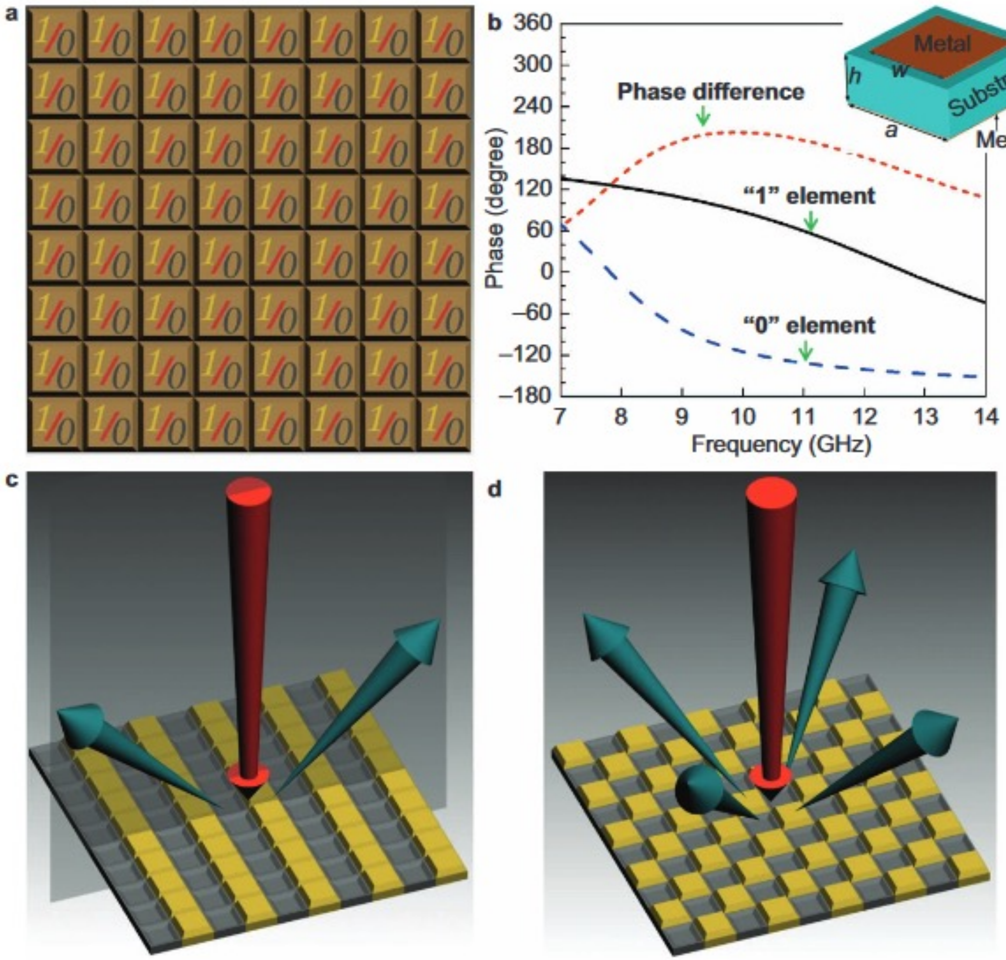


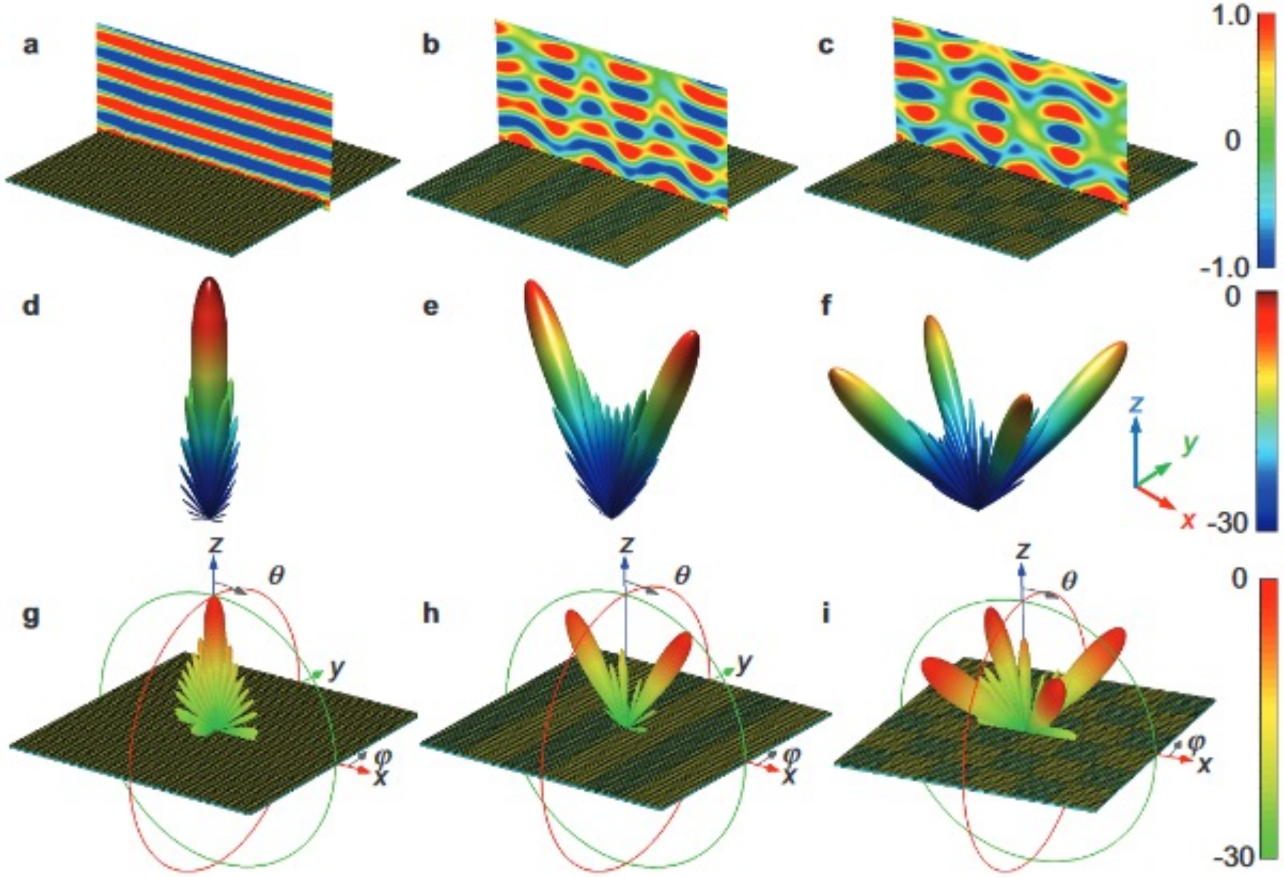
Reflective metasurfaces

- Reflective metasurfaces (holograms) act as phase shifters to create a desired wavefield by reflecting an incident field:



Reflective metasurfaces



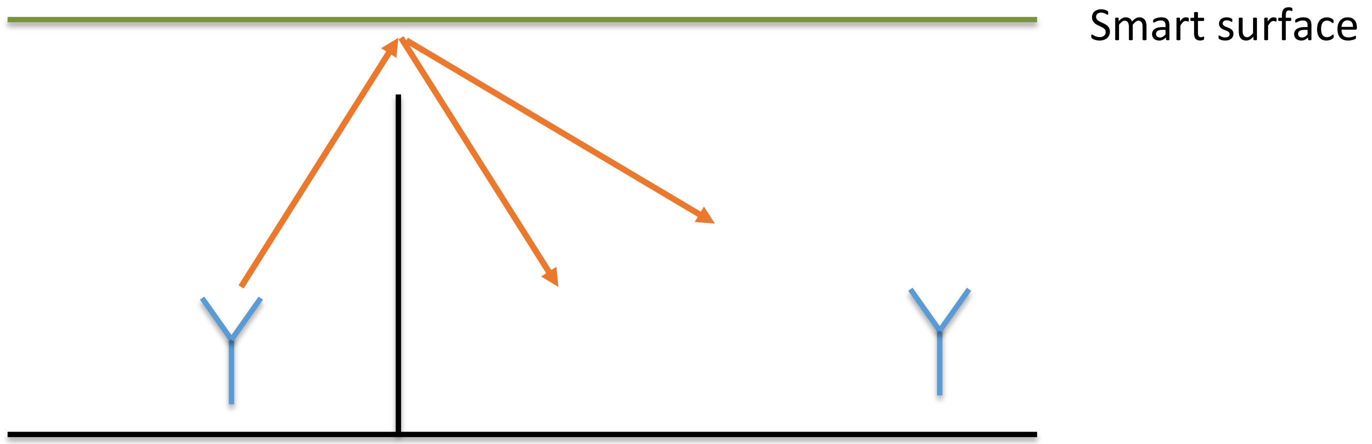


Coding metamaterials[Cui et al. 2014]

Reflective smart surfaces: PRESS

- Idea: Use metasurfaces to reconfigure the wireless environment
- What are the advantages of configuring the environment?

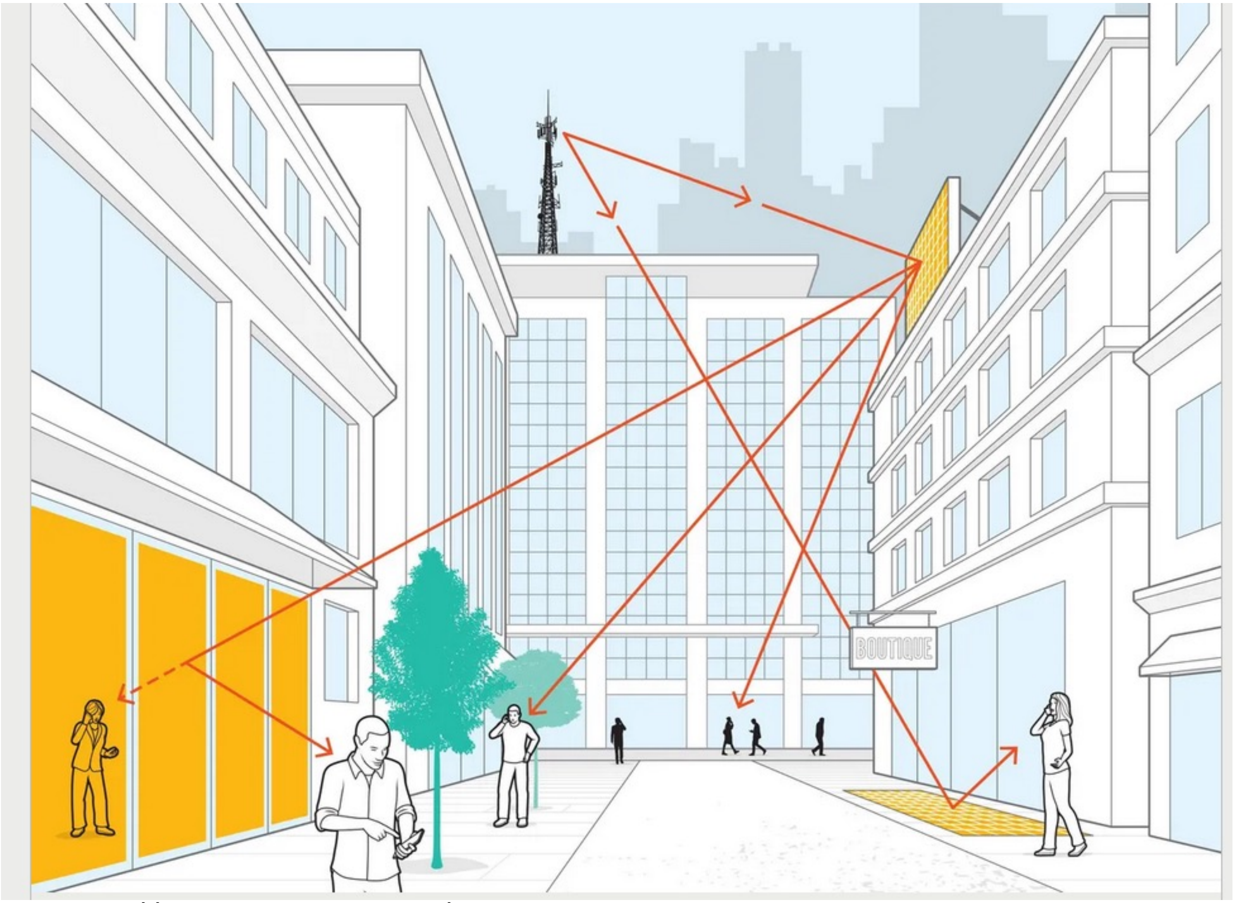
1. Enhance individual wireless links/ eliminate deadzones



Reflective smart surfaces: PRESS

- What are the advantages of configuring the environment?

2. Improve large MIMO performance/ improve spatial multiplexing

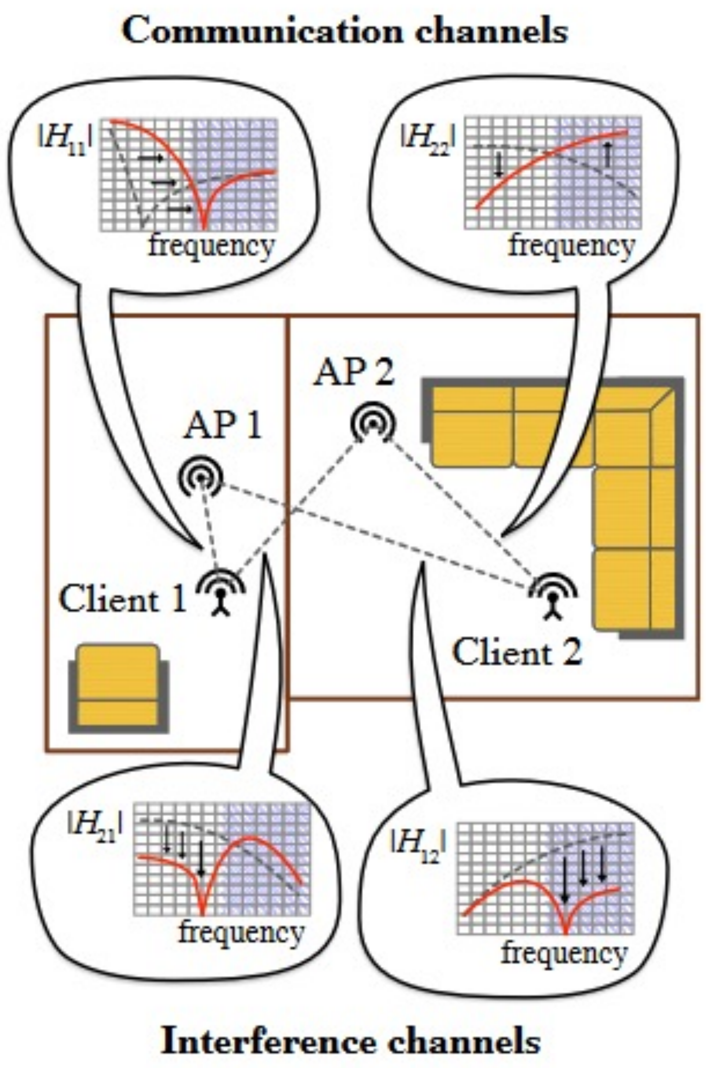


https://spectrum.ieee.org/metamaterials-could-solve-one-of-6gs-big-problems

Reflective smart surfaces: PRESS

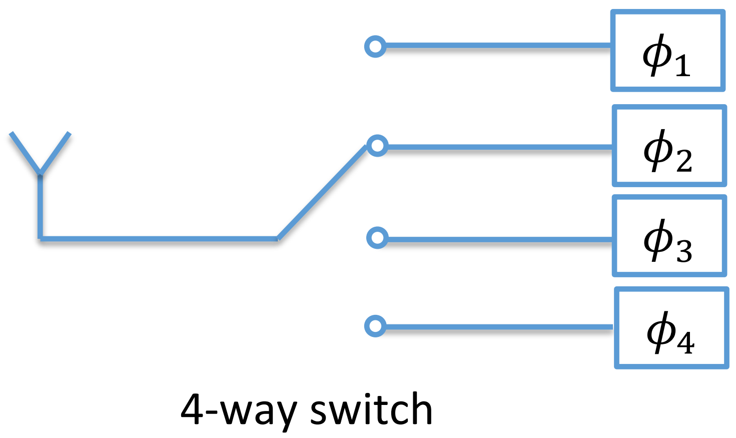
- What are the advantages of configuring the environment?

3. Mitigate interference/ achieve spatial partitioning



Reflective smart surfaces: PRESS

- How did they implement the reflective smart surface?
  - They used three passive backscatter nodes connected to RF waveguides with different lengths.
  - Explored the effect of switching on the wireless channel in non-line-of-sight configuration.
- How can their implementation be improved?



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Learn the fundamentals of **smart surfaces and metamaterials** applications, and implications on **wireless sensing.**

1. What are metamaterials? And how can we make one?
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Next Class: Sensor Fusion with Machine Learning

1) Required

- RF-Grasp: Robotic Grasping of Fully-Occluded Objects using RF Perception
- RFusion: Robotic Grasping via RF-Visual Sensing and Learning

2) Optional

- FuseBot: RF-Visual Mechanical Search
- X-Ray: Mechanical Search for an Occluded Object by Minimizing Support of Learned Occupancy Distributions
- RF-Annotate: Automatic RF-Supervised Image Annotation of Common Objects in Context