Brief intro to metasurfaces & Intelligent Reflecting Surfaces

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Cellular: how do we get more bandwidth?

Simple: go to higher carrier frequencies

We have already seen this in the recent past:

- 3G had f_c = {0.9, 2.1} GHz, BW ≤ 25 MHz

  Emails with big attachments

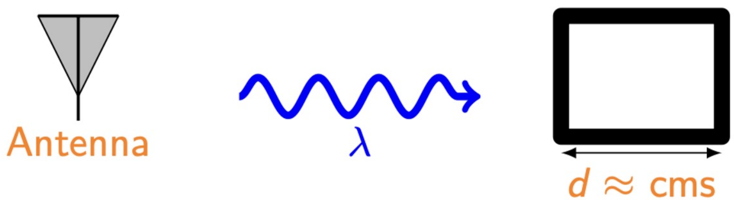
- 4G LTE has f_c = {0.85, 1.8, 2.3, 2.5} GHz, BW ≤ 100 MHz

  Video calls

- 5G has f_c = {3.5, 26} GHz, BW ≤ {400 MHz, 3000 MHz}

  HD movies and AR gaming

Why does coverage take a hit?



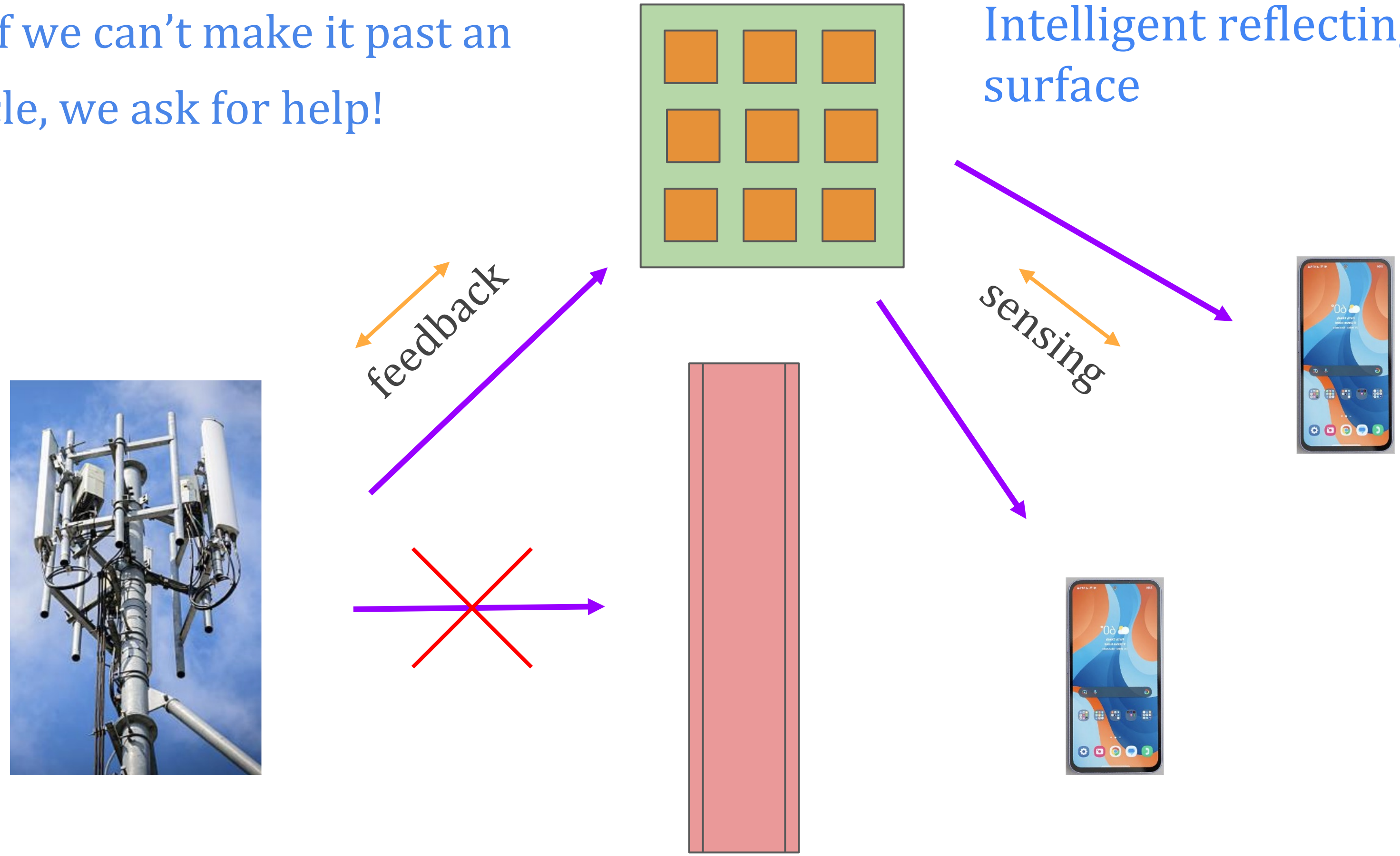
Talk in terms of wavelength λ (= c/f_c)
Recall: speed of light c = 30 GHz cm,
i.e. f_c = 1 GHz → λ = 30cm

Three regimes of wave-matter interactions		
$\lambda \gg d$	$\lambda \approx d$	$\lambda \ll d$
Huge antenna size, impractical	Wave nature, easily bends around obstacles	Ray nature, very little bending around obstacles
	Explains why you get network in your room	Explains why a laser pointer doesn't bend!
	Skin depth high ⇒ high penetration	Skin depth low ⇒ low penetration

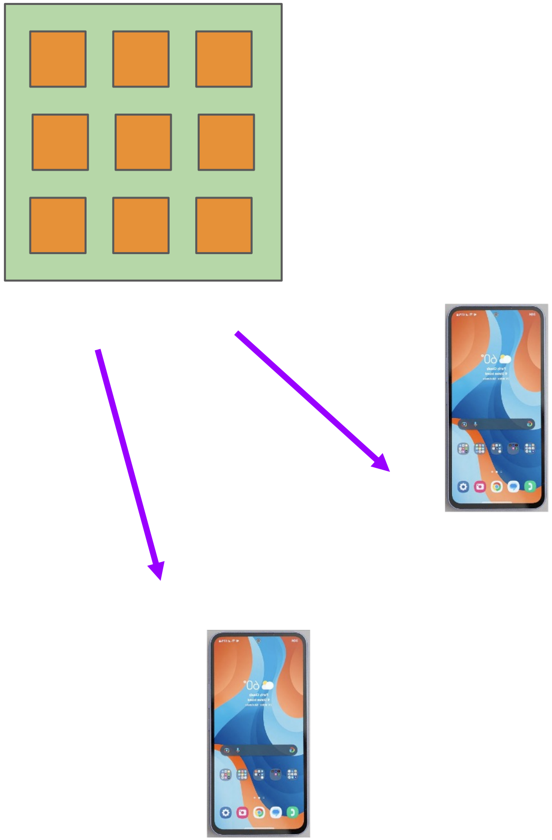
How do we restore coverage?

Idea: If we can't make it past an obstacle, we ask for help!

Intelligent reflecting surface



How do we restore coverage?



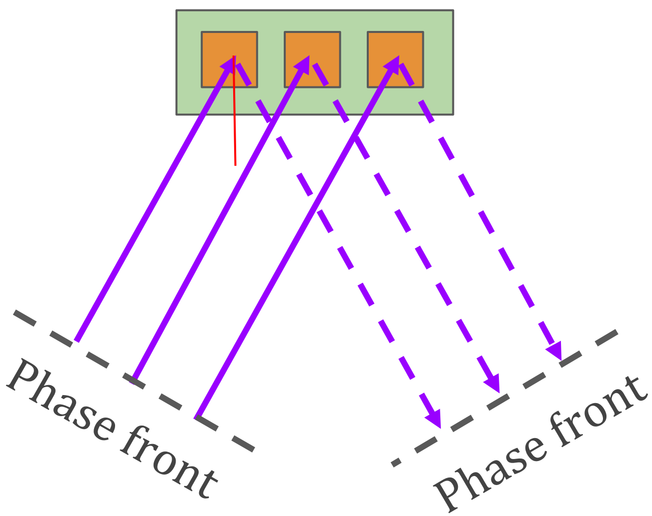
Some key considerations:

- IRS – redirects EM waves
- Should be able to change redirection angle
- Low complexity, low power
- Deploy on building sides or on drones
- Not a repeater – do not want to decode

How can we change the beam reflection angle?

Game of phases – play with constructive / destructive interference

Game 1: All elements have same reflection phase (say 0)



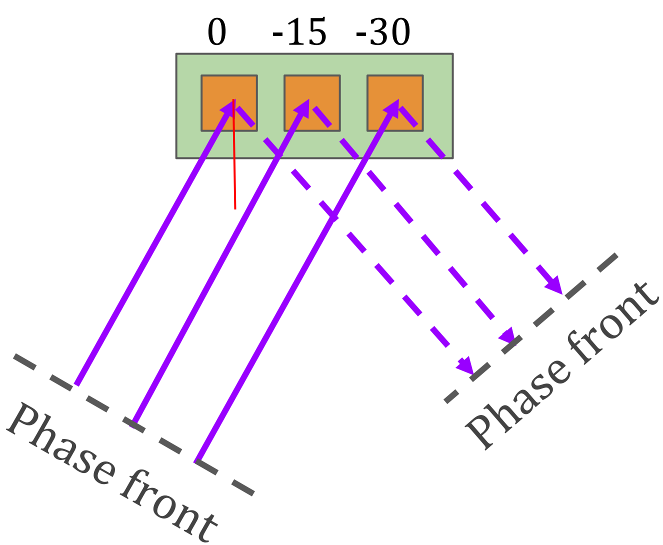
Wave: $|R|\exp[j(\vec{k}\cdot\vec{r}-\omega t)]$

- Physical path length for each ray (solid + dashed) is same
- Reminds us of high school Snell's law: *Angle of incidence = angle of reflection*

How can we change the beam reflection angle?

Game of phases – play with constructive / destructive interference

Game 2: Elements have progressive reflection shift (say -15°)



$$|R|\exp[j\phi_R]\exp[j(\vec{k}\cdot\vec{r}-\omega t)]$$

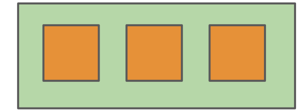
- Reflected phase front *must* rotate!
- Net path length for each ray (solid + dashed) is *still* same

- BUT: *Angle of incidence ≠ angle of reflection*

Parallels with beamforming in <u>phased antenna arrays</u>

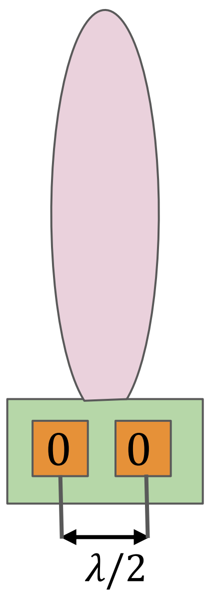
Changing the phases at each element → beam scanned in space electronically

IRS: What should each box do?

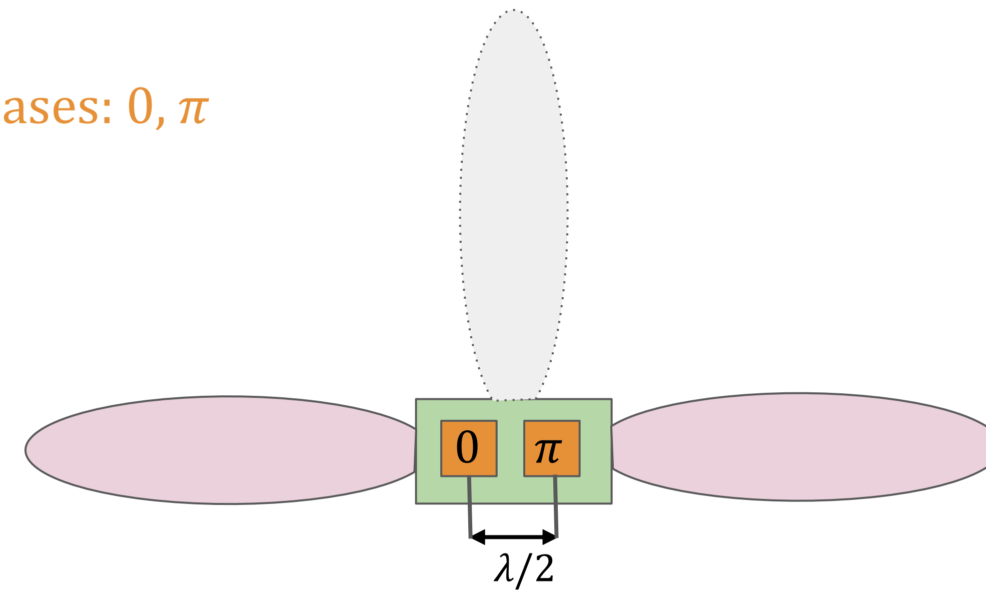


- An electromagnetic element → imparts a certain phase
- We should be able to control this phase
- Amplitude should be high for efficiency

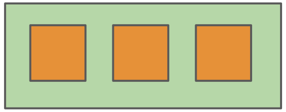
Phases: 0, 0



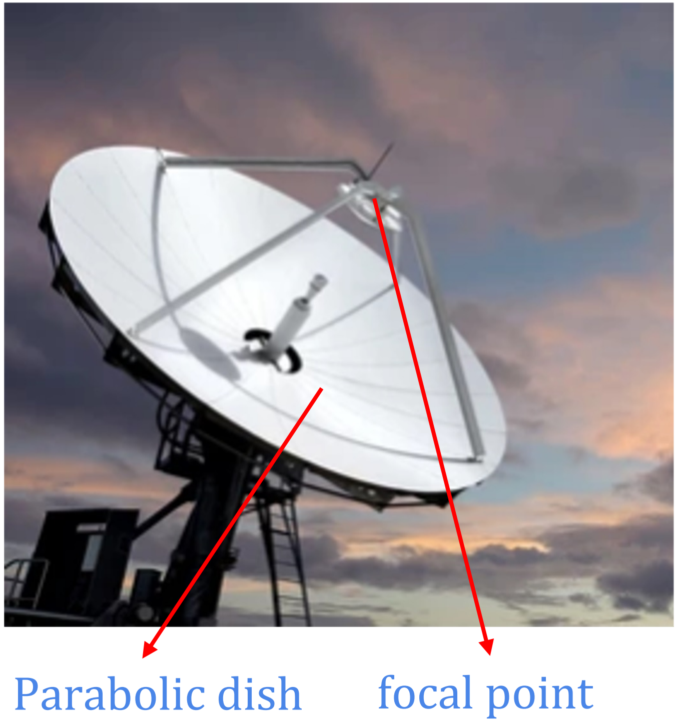
Phases: 0, π

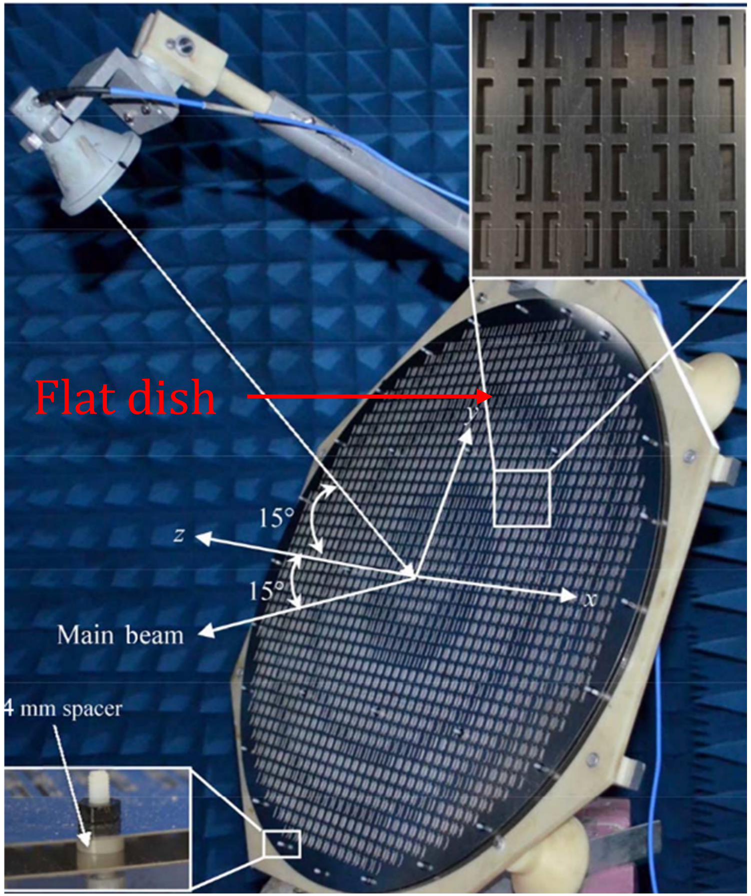


IRS: What is in each of the boxes?

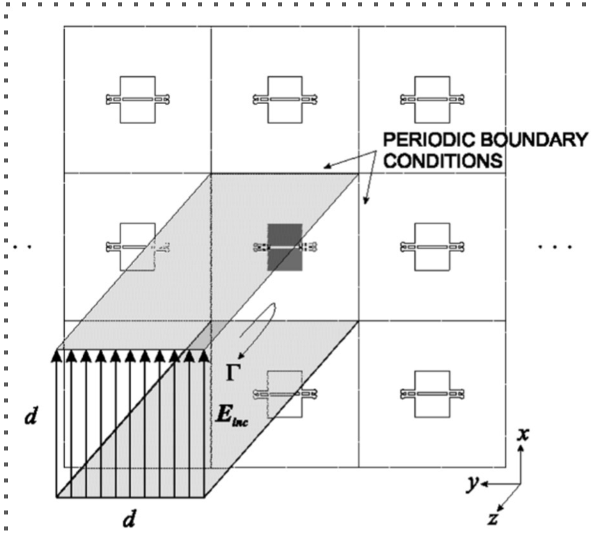


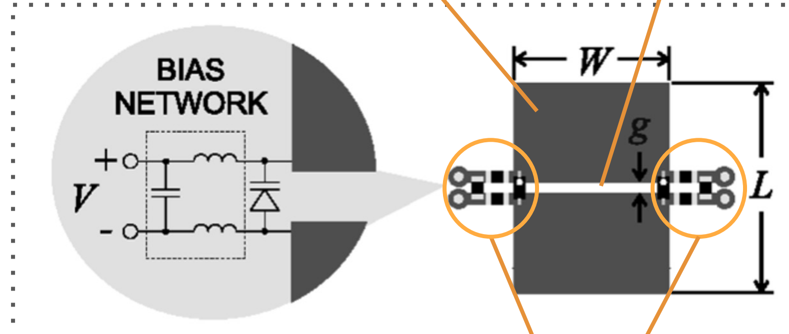
- Initial ideas - reflect array antennas





An example reflect array:

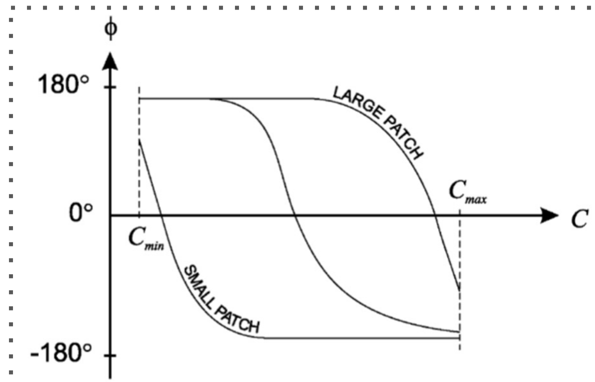




Metal

gap

Varactor diodes



Other possibilities – MEMS switches, PIN diodes, FET switches, etc

Changing V → C → ϕ (phase)

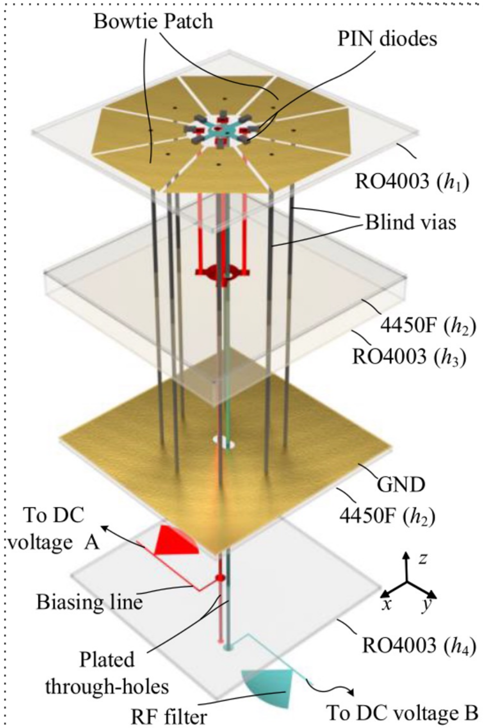
Hum, Sean Victor, Michal Okoniewski, and Robert J. Davies. "Modeling and design of electronically tunable reflectarrays." *IEEE Trans. on Antennas & Propagation* 55.8 (2007): 2200-2210.

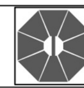
A modern hardware realization:

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 71, NO. 9, SEPTEMBER 2023

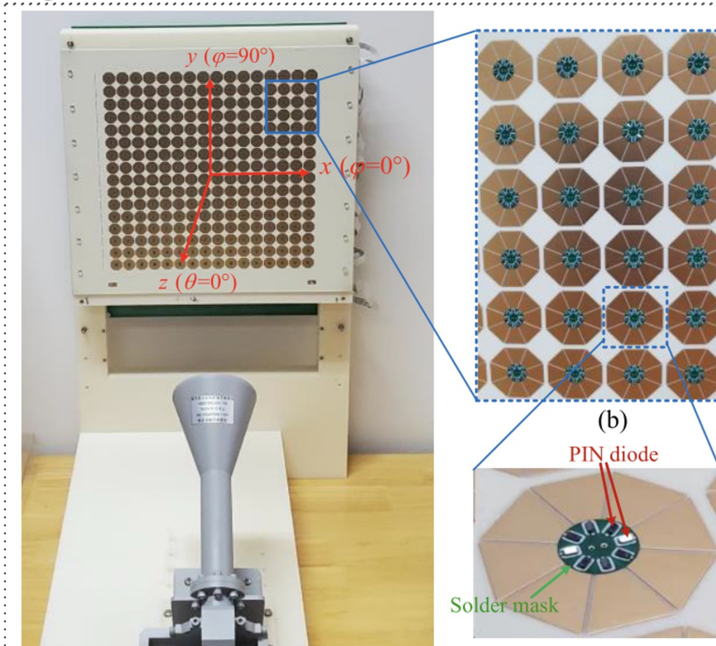
A 2 bit Circularly Polarized Reconfigurable Reflectarray Using p-i-n-Diode-Tuned Crossed-Bowtie Patch Elements

Fan Wu, *Member, IEEE*, Wu-Guang Zhao, *Student Member, IEEE*, Xiaoyue Xia, *Member, IEEE*, Jingxue Wang, *Member, IEEE*, Zhi Hao Jiang, *Member, IEEE*, Ronan Sauleau, *Fellow, IEEE*, and Wei Hong, *Fellow, IEEE*



Element state	DC voltage A	DC voltage B	Ideal element configuration	Reflection phase
#1	0	-V_f		0°
#2	+V_f	0		90°
#3	0	+V_f		180°
#4	-V_f	0		270°

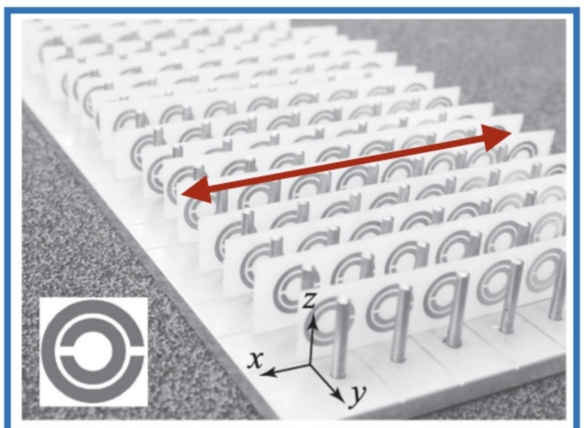
← size $\cong \lambda/2$



Recent move from reflect arrays to metasurfaces

Metasurfaces are 2D cousins of metamaterials

- Sub-wavelength periodic/quasi-periodic structures
- Macroscopic behaviour as though it is a new material (but its not)



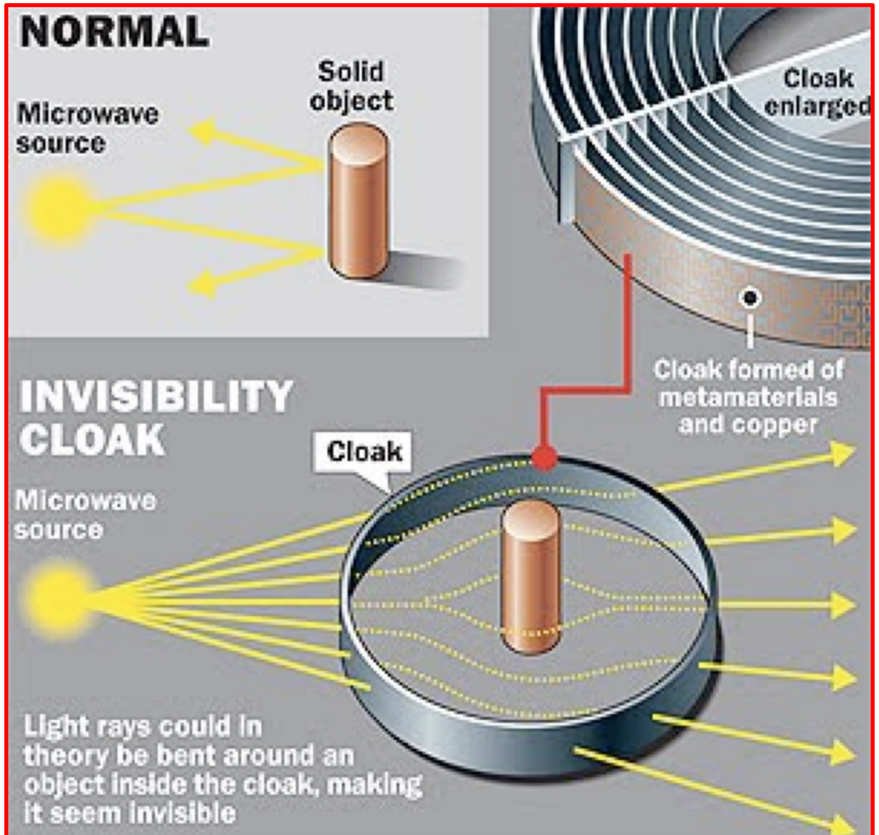
DOI: 10.1126/science.1058847 (2001)

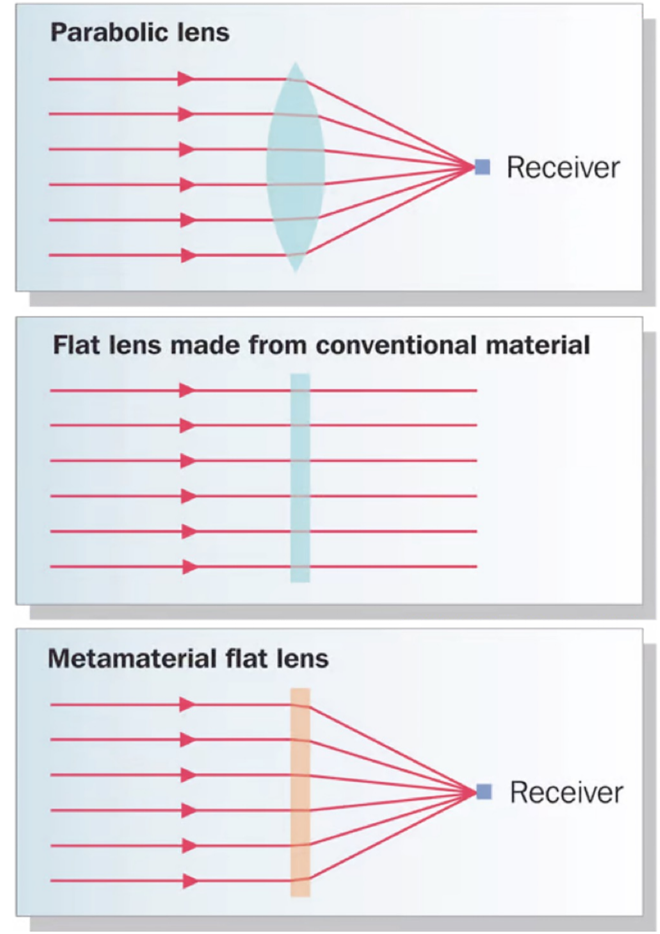
- Red arrow ≈ 1 wavelength
- EM wave doesn't "see" individual units
- Sees a "net" effect

⇒ Can tune refractive index, even make it -ve

- Made of "regular" materials

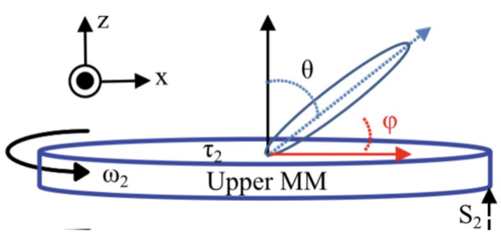
Some applications of metasurfaces

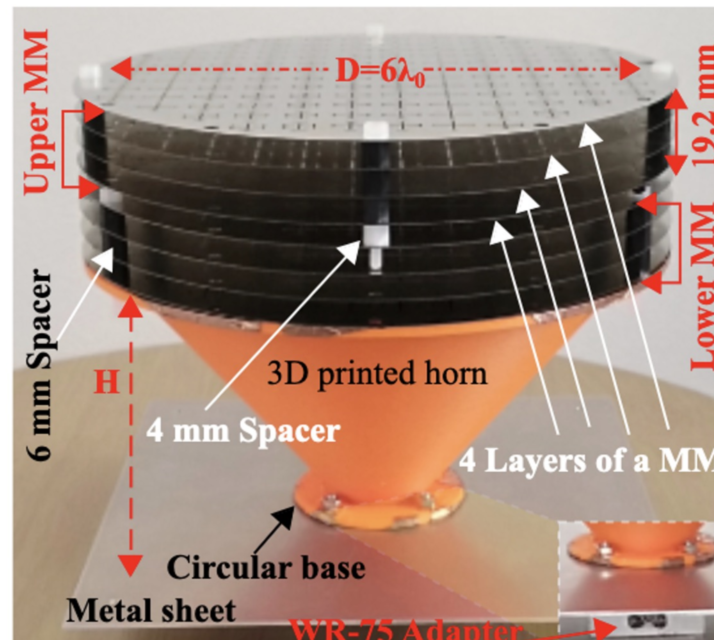




Advantages of metasurfaces

- Metasurfaces: sub-wavelength periodic structures in 2D
- Allows fine-grained manipulation of incident waves
  - Polarization conversion
  - Beam forming / shaping
  - Selective absorption/reflection
  - Radar cross-section reduction
  - Near field transformations →



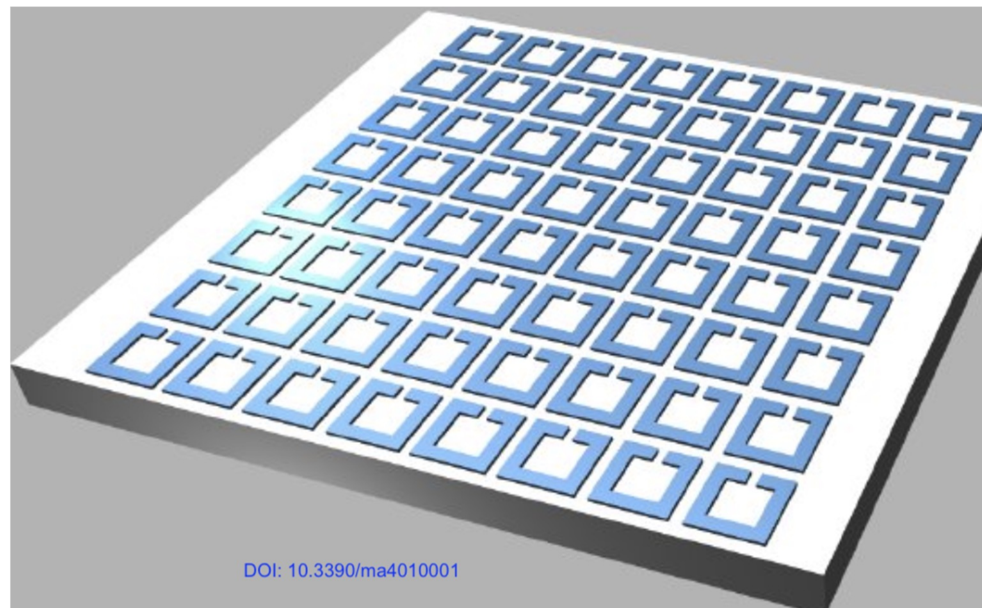


Ahmed, Foez, et al. "A near-field meta-steering antenna system with fully metallic metasurfaces." *IEEE Transactions on Antennas and Propagation* 70.11 (2022)

Electromagnetic modelling of a metasurface

It is sufficient to study one unit cell.

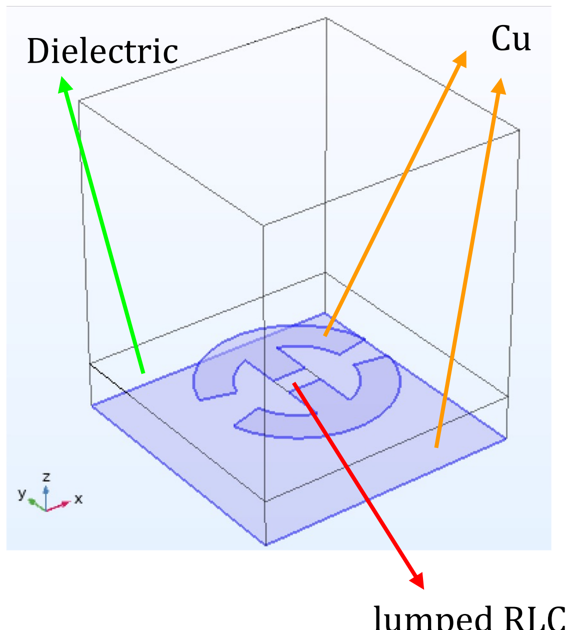
The structure is periodic, so EM fields can be expressed in terms of a Floquet series.

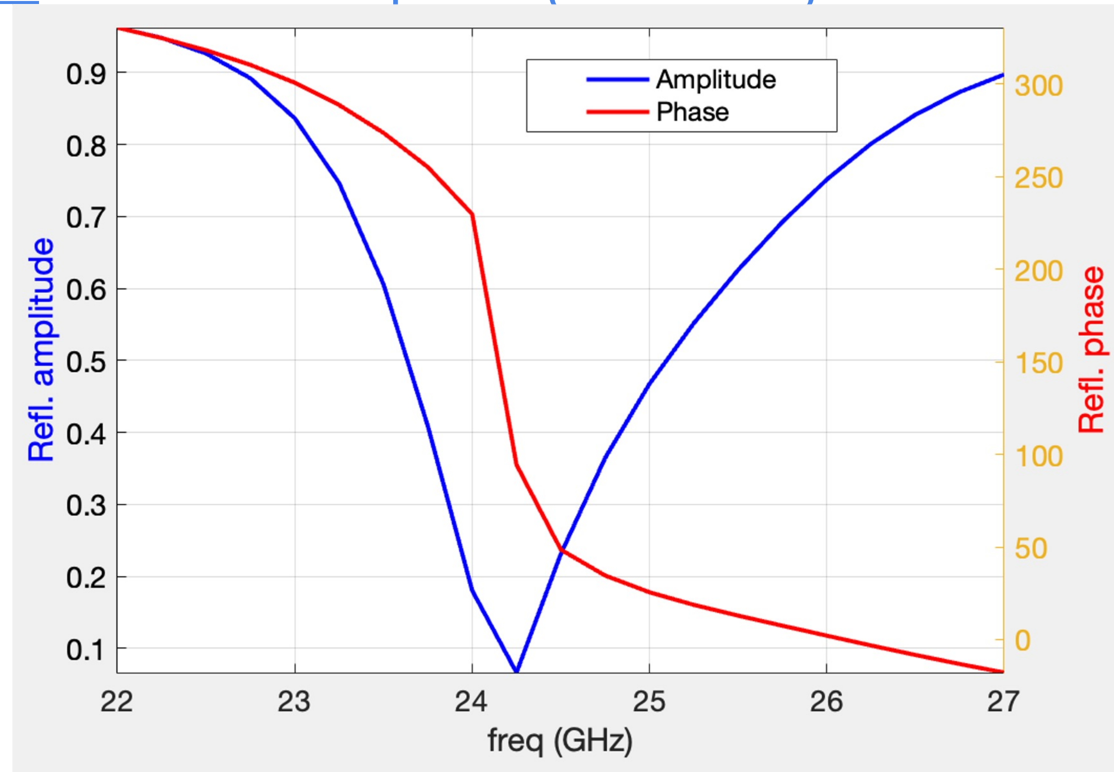


Generalization of Fourier series when a function is complex valued.

How does a metasurface work? EM resonance

Take an example of a unit cell and its EM response (refl. coeff.):





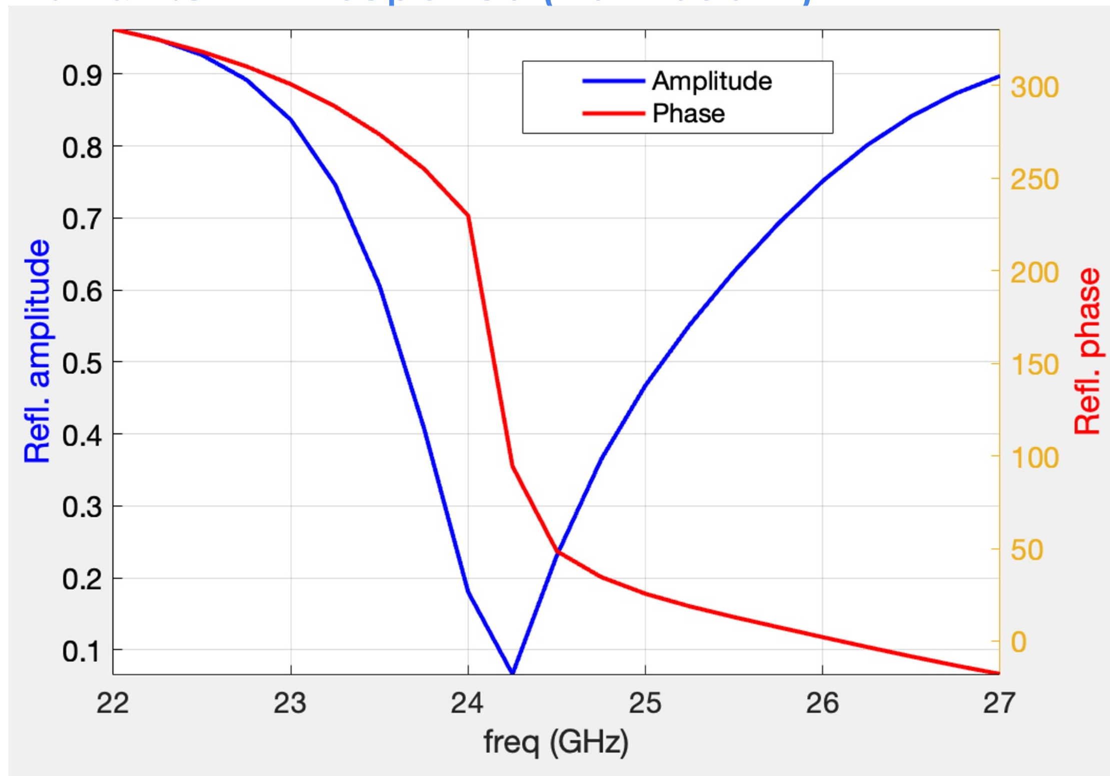
How does a metasurface work? EM resonance

Take an example of a unit cell and its EM response (refl. coeff.):

Note the behaviour:

- ❑ Near resonance
- ❑ Away from resonance

All action requires a resonance!



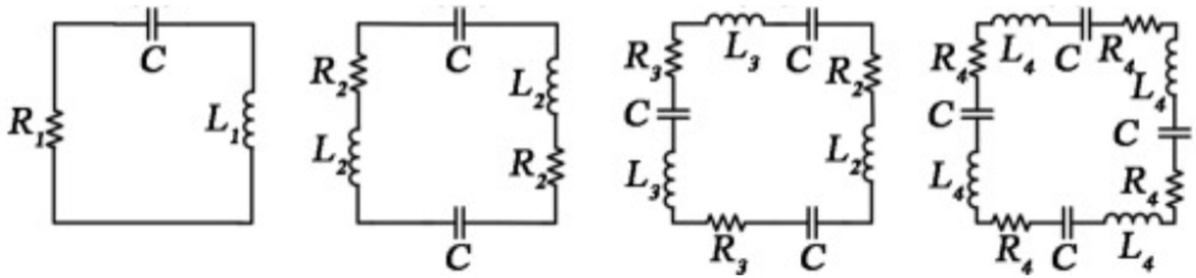
Many variants of unit cells possible

Can adjust location and width of resonance by varying design

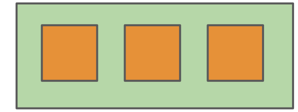
Physical Design →

DOI: 10.1016/j.rinp.2019.102321

Microwave Circuit Equivalent →

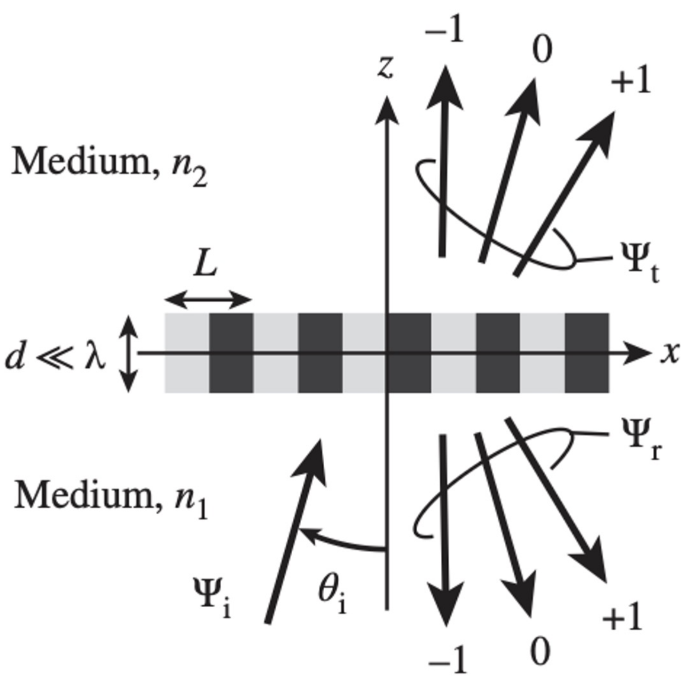


What size should a unit cell be?



i.e. how many units inside each orange box?

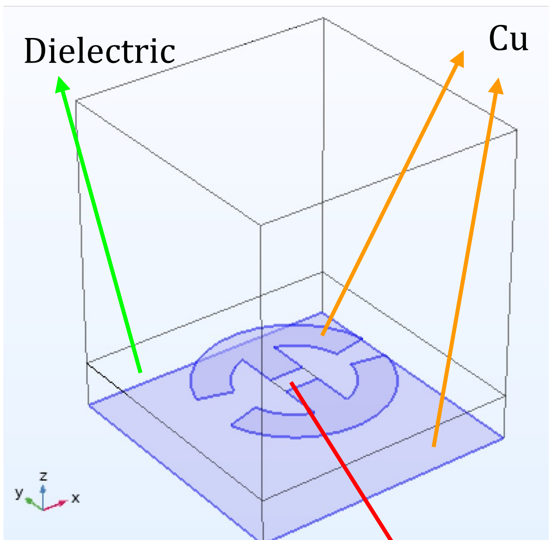
Well studied problem in the case of gratings …



- ➢ Incident beam is split into “grating” modes (Floquet mode theory)
- ➢ Would like to only retain m = 0 mode
- ➢ Approx, if $L < \lambda/2$, only m = 0 survives
- ➢ Further, if $L < \lambda/4$, ensures response does not depend on incidence angle

Now what about beam forming?

Recall: we need different phases for beam forming.



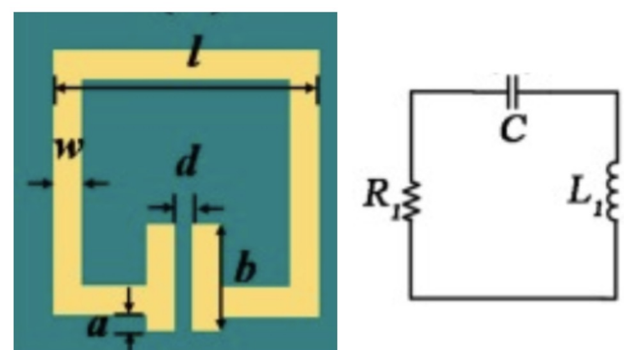
That's where this comes to play.

lumped RLC

For e.g. a varactor diode, PIN diode, MEMS

Bias voltage controls RF impedance

⇒ Resonance can be shifted



A simple 1-bit control of phase

Changing C on a varactor diode

gives two states

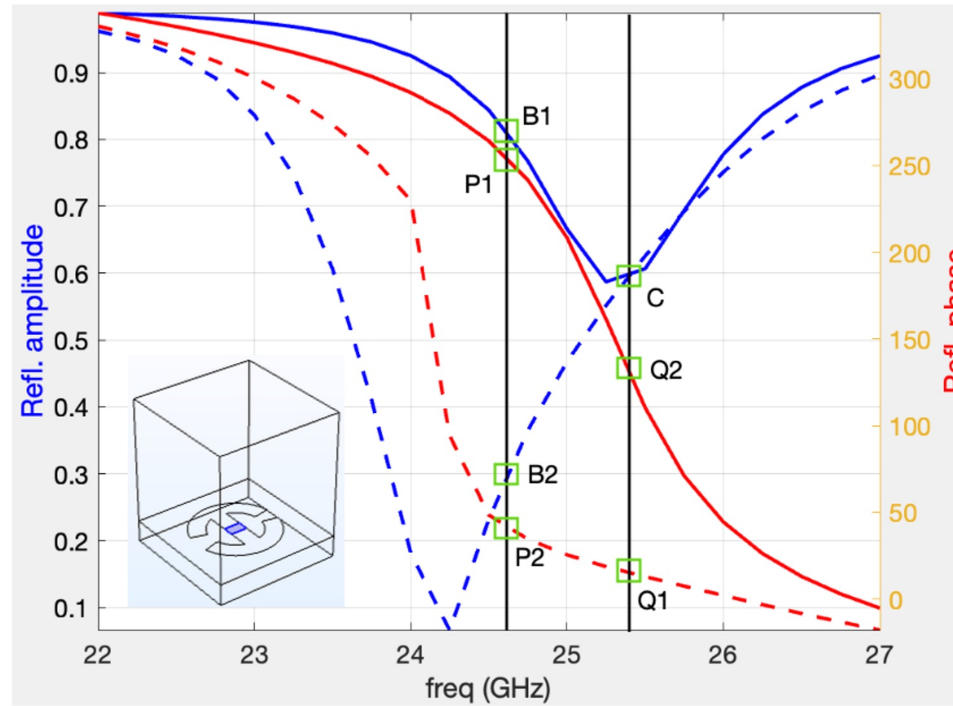
Consider the two operating freqs

(black vertical lines)

With frequency:

➔ Phase diff varies

➔ Amplitude varies

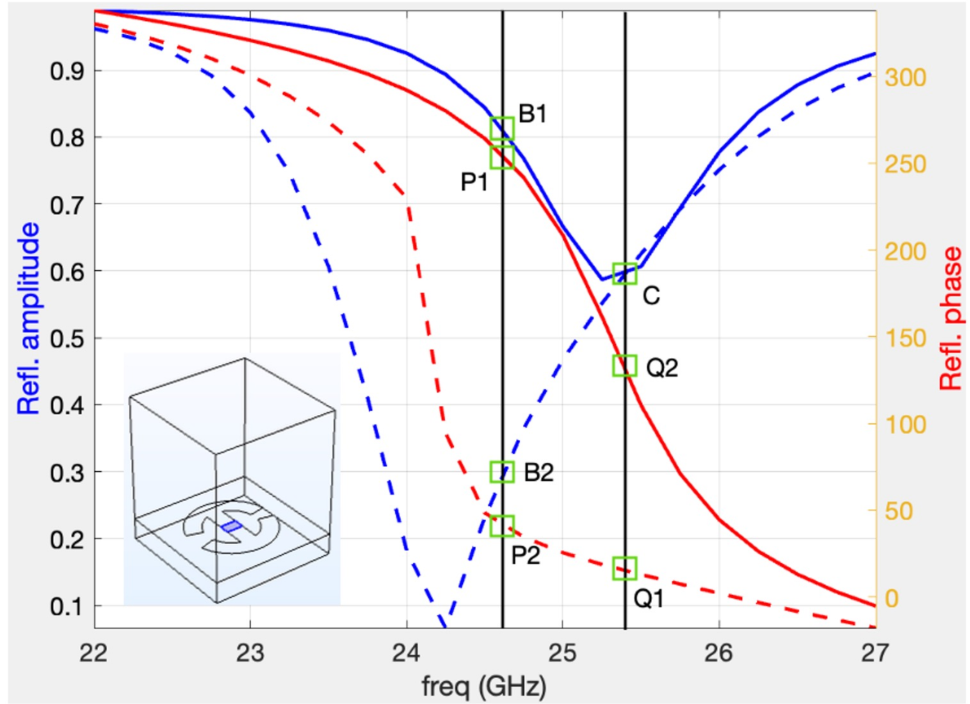


Ideally, we want a phase difference of π between the two states

A simple 1-bit control of phase – Optimization

With frequency:

- ➔ Phase diff varies
- ➔ Amplitude varies



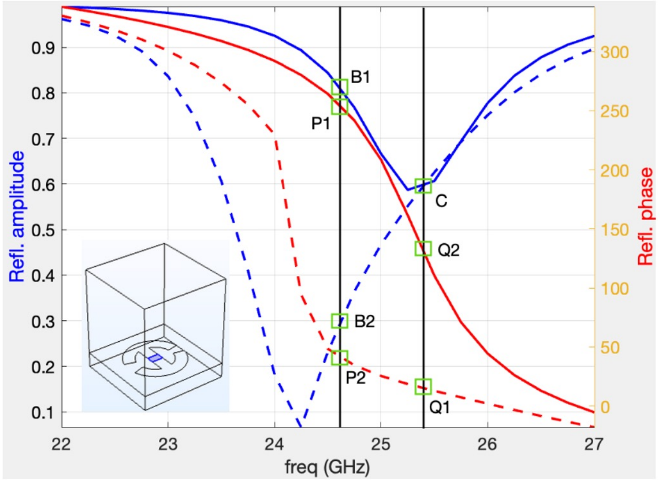
Design variables x, state s,

frequency ω, response $f(x,s,\omega)$,

Setup optimization problem:

$$\min_{x} \sum_{\omega} \{|\angle f(x, s_1, \omega) - \angle f(x, s_2, \omega)| - \pi\}^2 + \alpha\{(|f(x, s_1, \omega)| - 1)^2 + (|f(x, s_2, \omega)| - 1)^2\}$$

Optimization: a tough problem



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$$\min_x \sum_\omega \{|\angle f(x,s_1,\omega) - \angle f(x,s_2,\omega)| - \pi\}^2 + \alpha\{(|f(x,s_1,\omega)|-1)^2 + (|f(x,s_2,\omega)|-1)^2\}$$

Phase difference

Amplitude

Choose the required bandwidth in which phase swing is π

Regularization parameter

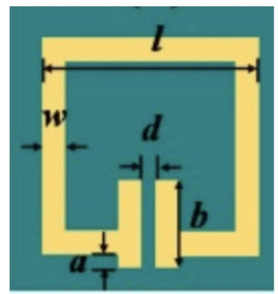
Some serious modelling challenges – part 1

- Given structure x, we can compute $f(x,s,\omega)$ (response)

  The traditional optimization approach, i.e.

$$\min_x \sum_\omega \{|\angle f(x,s_1,\omega) - \angle f(x,s_2,\omega)| - \pi\}^2 + \alpha\{(|f(x,s_1,\omega)|-1)^2 + (|f(x,s_2,\omega)|-1)^2\}$$

  gives you x, i.e. the values here →



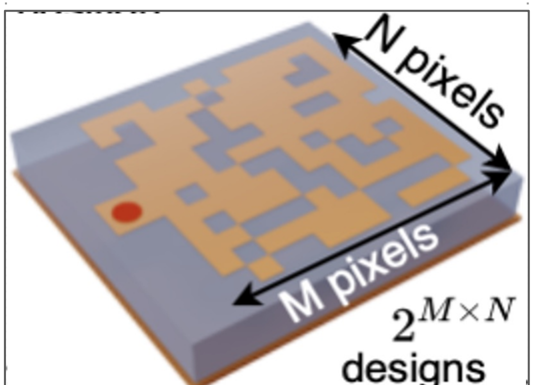
- But it doesn't give you a different structure!

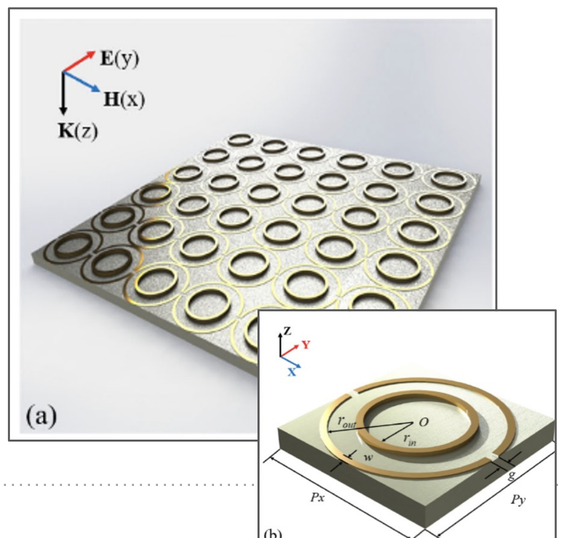
Some serious modelling challenges – part 2

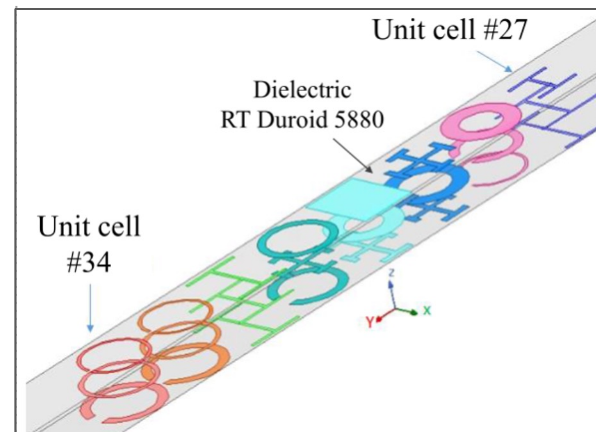
- An exciting new area of ML based “inverse design” has opened up;

  Different approaches, all using machine learning

Pixel based	*Template based*	*Hybrid template based*
IEEE TAP, 2023 10.1109/TAP.2023.3276524	*IEEE AWPL*, 2021 DOI 10.1109/LAWP.2021.3069713	IEEE TAP, 2021 DOI 10.1109/TAP.2021.3137496







Recap our simple 1-bit example

With frequency:

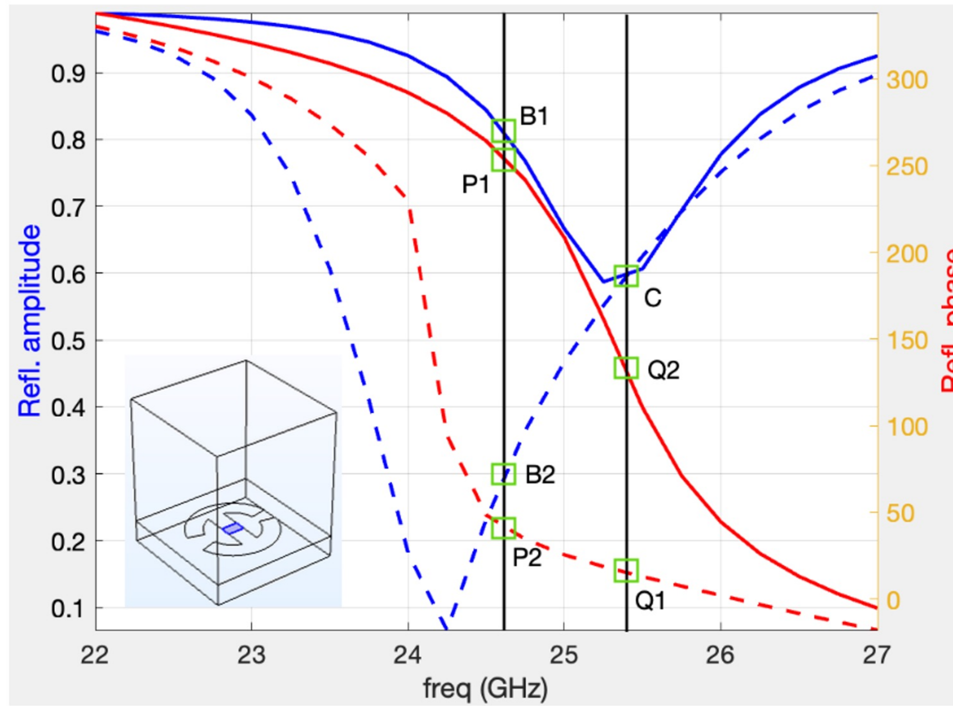
- ➔ Phase diff varies
- ➔ Amplitude varies

Design variables x,

state s,

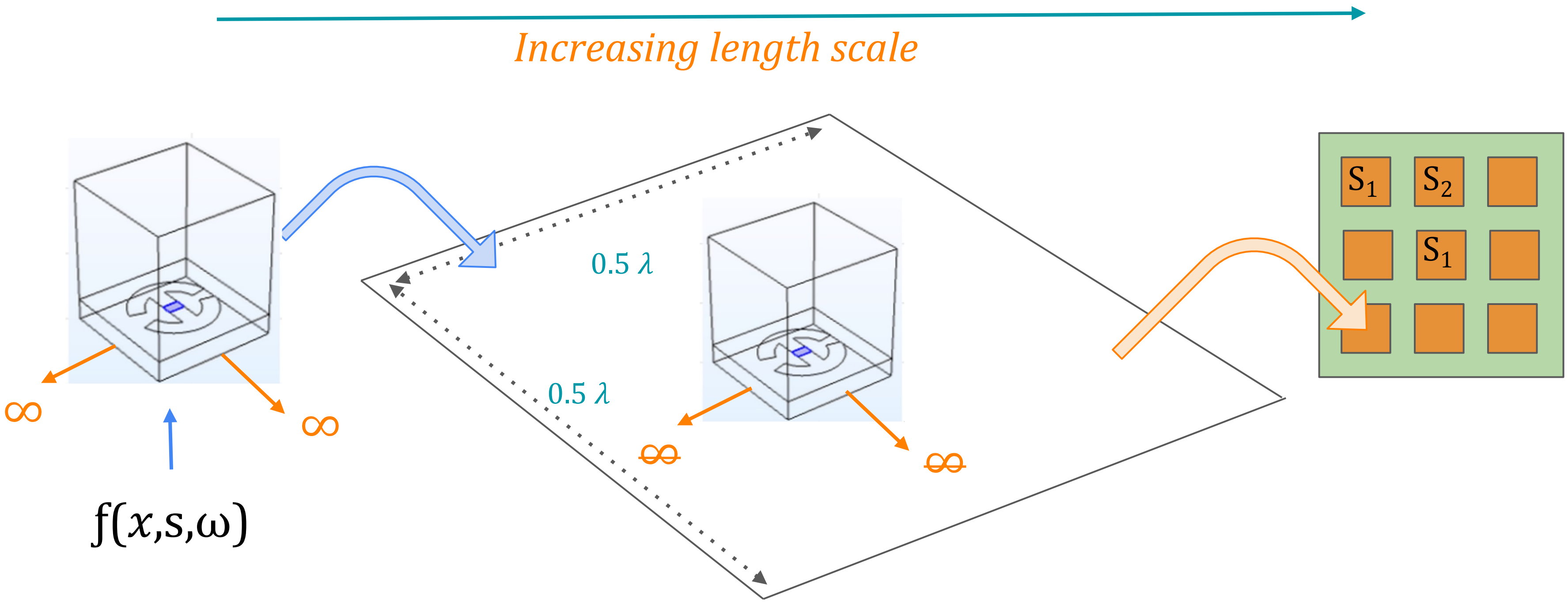
frequency ω,

response $f(x,s,\omega)$

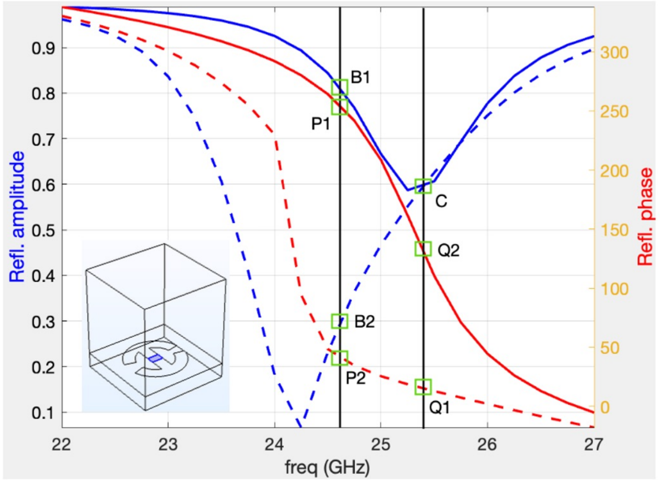


Some serious modelling challenges – part 3

- What exactly does $f(x,s,\omega)$ correspond to? Is it an approximation?
- Computing $f(x,s,\omega)$ takes time AND is nonlinear in x.



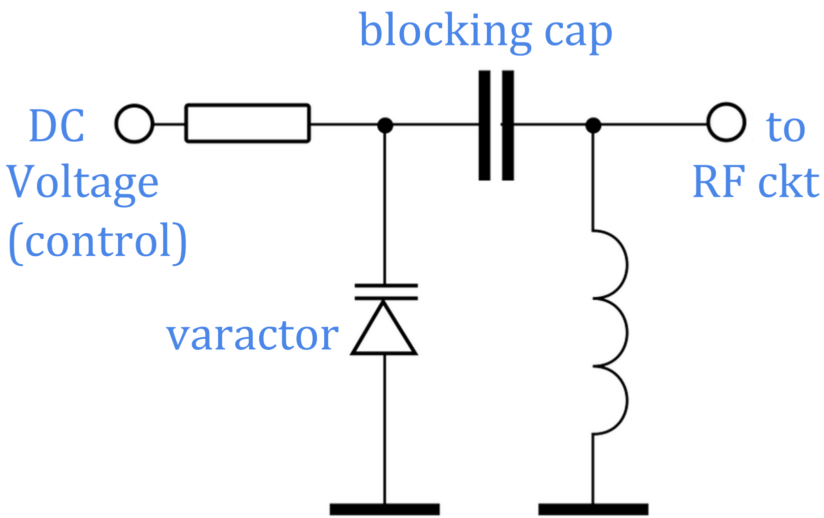
Hardware challenges – biasing



Changing C on a var/PIN-diode gives two states

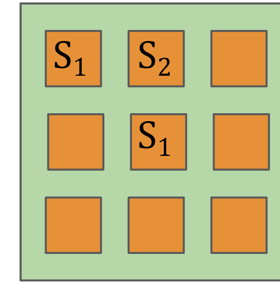
Design considerations:

- Biasing ckt
  Var diode needs DC bias voltage, then DC blocking cap, etc. also required



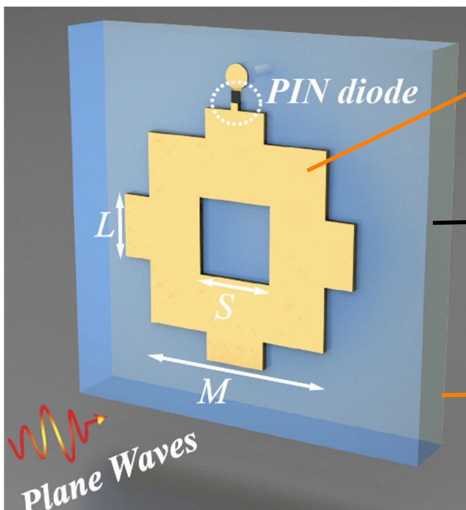
- Control ckt
  All unit cells need 2 states

Hardware challenges – multiple layers



- Each cell needs a bias voltage ⇒ a DC biasing network
- But, these lines will radiate! So, need to isolate them from RF

  ⇒ Multi-layer design. An example:



Top metal

Middle dielectric

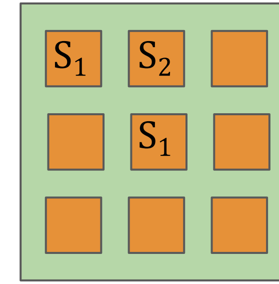
Bottom metal

Model the PIN as:

- Z_{ON}
- Z_{OFF}

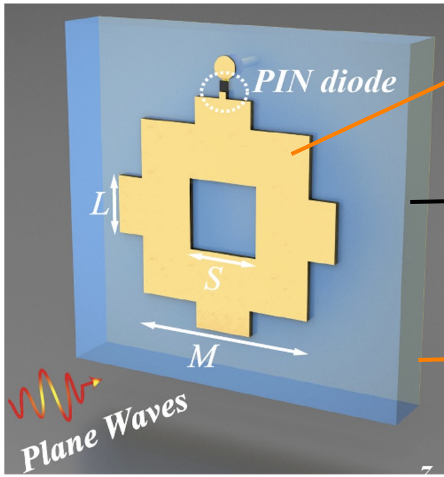
This is the ideal picture that folks who work on simulation-only see!

Wang, Di, et al. "Design of a 1 bit broadband space-time-coding digital metasurface element." IEEE Antennas and Wireless Propagation Letters 19.4 (2020)



Hardware challenges – multiple layers

- But actually:



Top metal

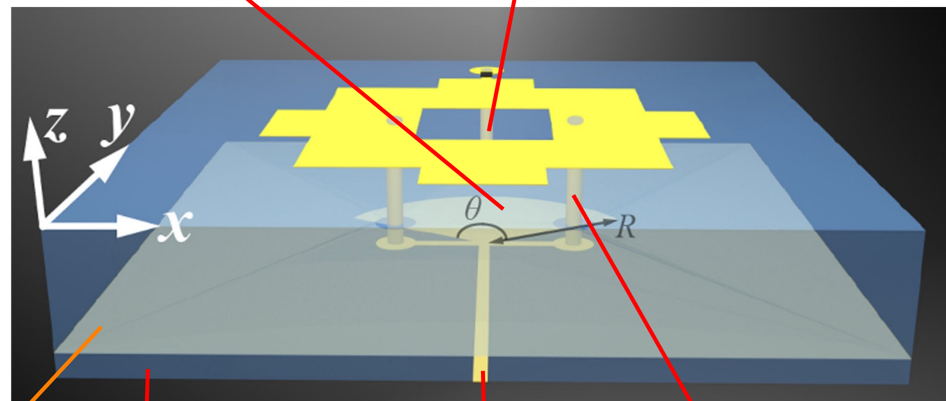
Middle dielectric

Bottom metal

3 layer design

RF choke (large L)

Via to RF gnd for PIN_2



RF ground

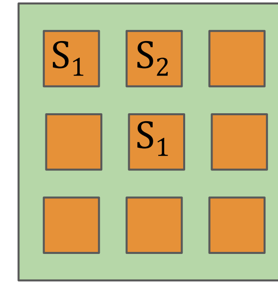
2nd dielectric layer

DC bias line

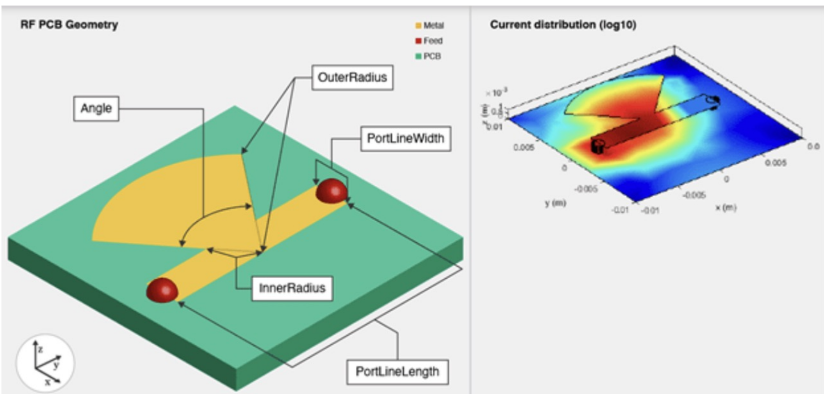
thru hole via For PIN_1

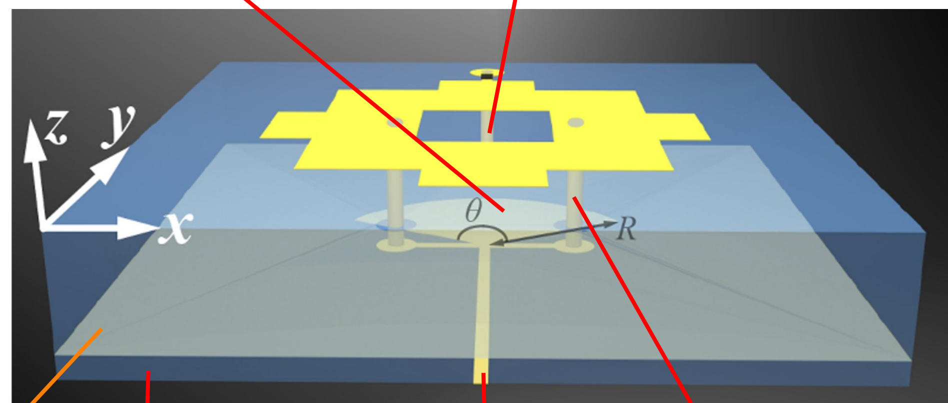
Wang, Di, et al. "Design of a 1 bit broadband space-time-coding digital metasurface element." IEEE Antennas and Wireless Propagation Letters 19.4 (2020)

Hardware challenges: Note on RF chokes



Easily designed in Matlab

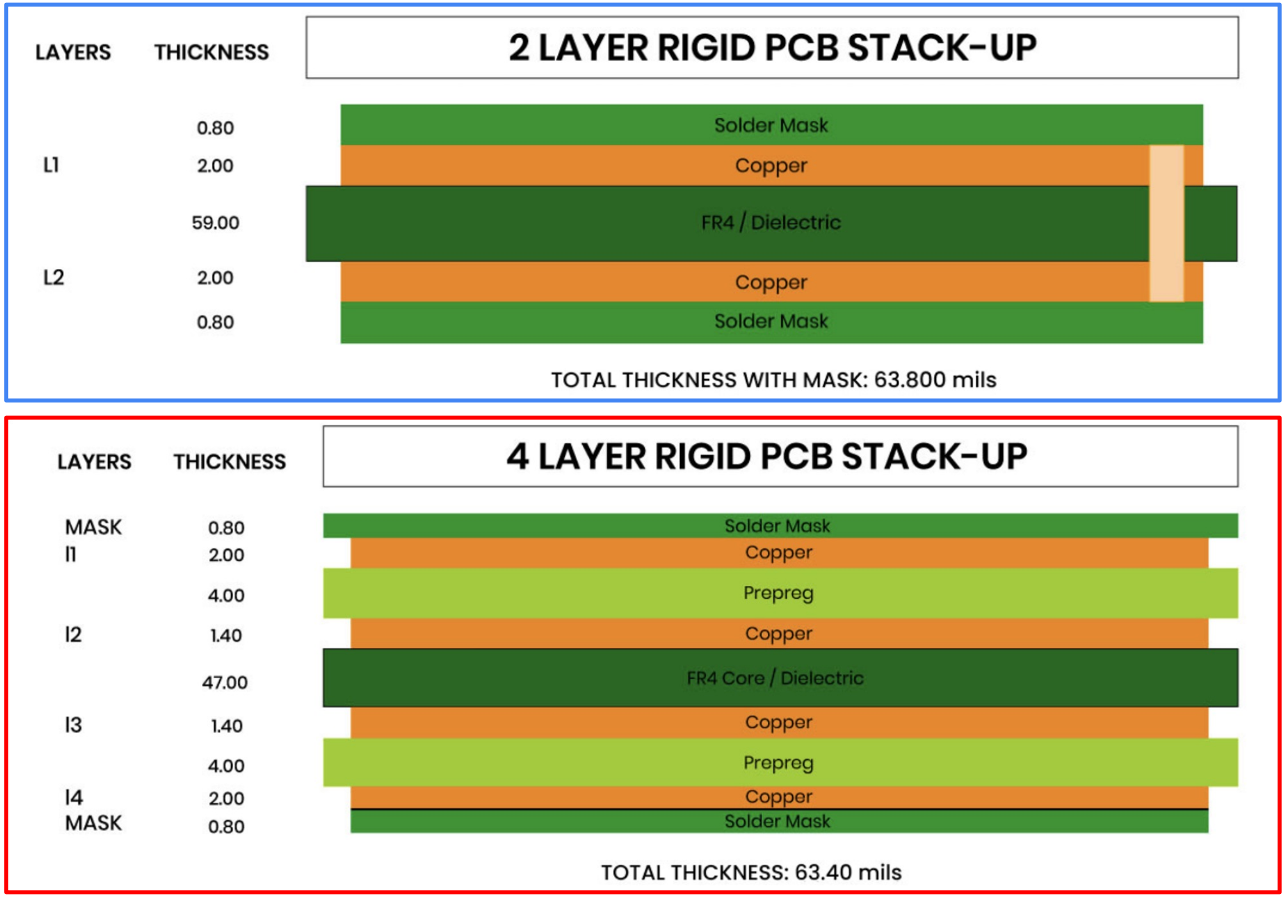




At lower frequencies, use lumped element instead

Wang, Di, et al. "Design of a 1 bit broadband space-time-coding digital metasurface element." IEEE Antennas and Wireless Propagation Letters 19.4 (2020)

Hardware challenges – usually even # layers available



Prepeg:
Insulating binding material

At 10 GHz:

- Wavelength = 30 mm (air) 14 mm (in FR4)
- Skin depth = 0.65 um (or 0.026 mil)

Big EM simulation challenge

https://www.sfcircuits.com/ **1 mil = 25.4 μm, 50 mil = 1.27 mm**

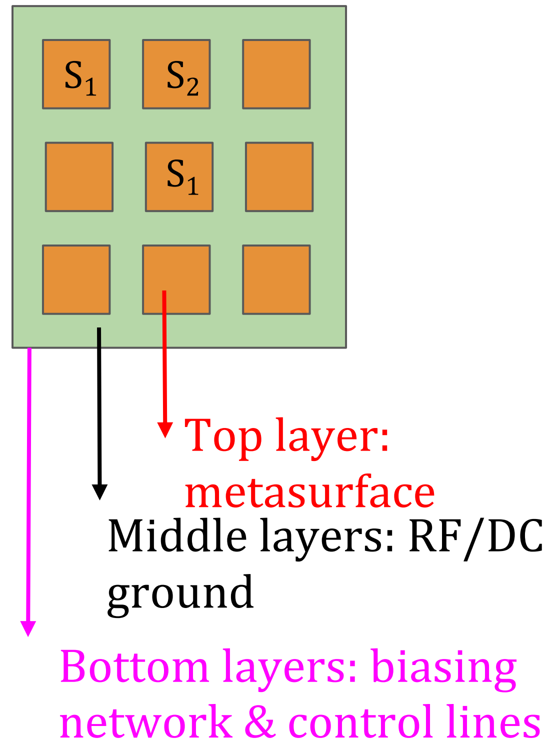
Putting the IRS together (like a phased array)

Given:

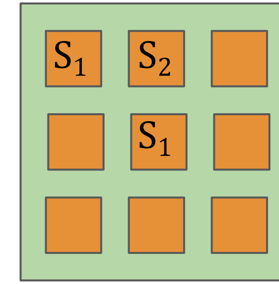
- incident beam direction,
- desired direction to redirect the beam (we can sense this)

Compute:

- State of bias network (the S_i values) to beamform in desired direction



Beamforming algorithms

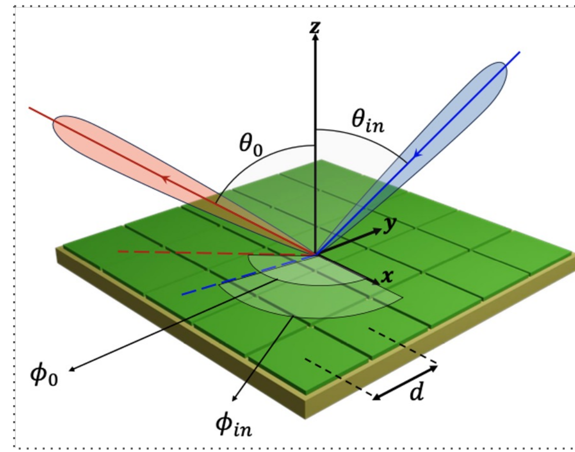


How do we assign values $\{S_1, S_2\}$ to the tiles?

Take simpler problem of getting a beam maxima at $(\boldsymbol{\theta}_0, \phi_0)$ when tiles take *any* set of values:

$$G(\theta,\phi) = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} w_{m,n} e^{j\varphi_{m,n}(\theta,\phi)}, \text{ with,}$$

$$\varphi_{m,n}(\theta,\phi) = \frac{2\pi d}{\lambda}\Big(m\sin\theta\cos\phi + n\sin\theta\sin\phi + m\sin\theta_{in}\cos\phi_{in} + n\sin\theta_{in}\sin\phi_{in}\Big),$$



Easiest solution: $$w_{m,n} = \exp\big(-j\varphi_{m,n}(\theta_0,\phi_0)\big)$$

But, this is challenging when the values are constrained $w_{m,n} \in \mathcal{S}_{m,n}$,

Common approaches to solve this problem

Threshold the conts. valued solution

Compute $w_{m,n} = \exp\big(-j\varphi_{m,n}(\theta_0, \phi_0)\big)$
if $\angle w_{m,n} \in [-\frac{\pi}{2}, \frac{\pi}{2})$ **then**
$\quad \widetilde{w}_{m,n} \leftarrow 1$
else
$\quad \widetilde{w}_{m,n} \leftarrow -1$

(For e.g. Yang et al., *IEEE AWPL* 2017)

- Method is heuristic, i.e. no proof
- Can fail in corner cases

Employ an evolutionary algorithm

i.e. solve this optimization problem:

$$\max_{w_i} \quad \big|w_1 z_1 + \cdots + w_n z_n\big|$$
$$\text{s.t.} \quad w_i \in \{1, -1\}, \quad \forall i = 1, \ldots n$$

(For e.g. Fan et al., *Nanophotonics* 2020)

- Can add more constraints, e.g. nulls in specified directions etc
- Gives good solutions
- Can be very time consuming

Common approaches to solve this problem

Threshold the conts. valued

Compute $w_{m,n} = \exp\big(-j\varphi_{m,n}(\theta_0, \phi_0)\big)$
if $\angle w_{m,n} \in [-\frac{\pi}{2}, \frac{\pi}{2})$ **then**
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8540 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 72, NO. 11, NOVEMBER 2024

Our approach: →

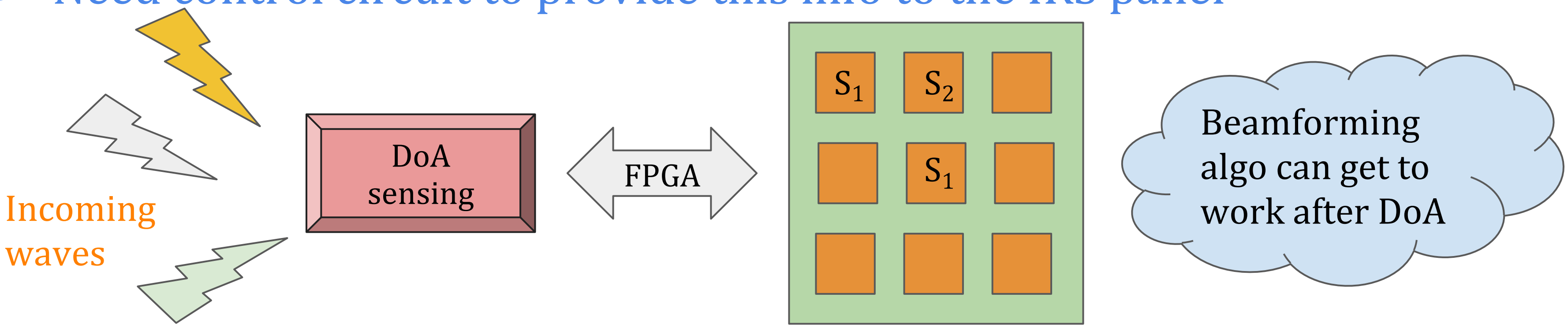
Optimum Beamforming and Grating-Lobe Mitigation for Intelligent Reflecting Surfaces

Sai Sanjay Narayanan, Uday K. Khankhoje, *Senior Member, IEEE*, and Radha Krishna Ganti, *Member, IEEE*

Present a <u>provably optimal</u> solution to this problem,
codes are on github: https://github.com/udaykdk/opa

What about the "I" in IRS?

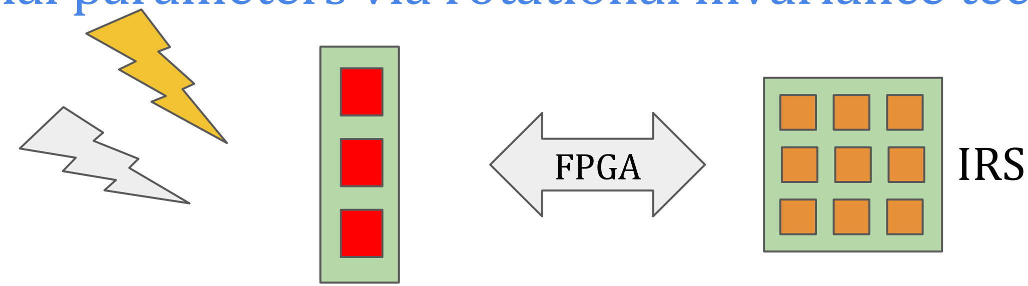
- "Intelligent," i.e. must be able to sense the UE location
- Need control circuit to provide this info to the IRS panel



- Typically two ways for Direction of Arrival (DoA) sensing:
  a. Dedicated DoA sensor (multi-mode antenna or phased array)
  b. IRS itself (integrated sensing and communication, ISAC)

Incorporating direction of arrival estimation

Traditional way – use MUSIC (multiple signal classification), ESPRIT (estimating signal parameters via rotational invariance techniques), etc.



- Need an array of antennas, & amplitude+phase data
- Data is collected in terms of snapshots in time
- Both are subspace algorithms, i.e. decompose the signal's covariance matrix into signal & noise subspaces, and process them for DoA

IRS summary

- IRS is a fascinating area of interdisciplinary research
  - Microwave physics, Antennas, RF devices
  - Wireless communication, Information theory
  - Signal processing (beamforming & DoA)

  } AI/ML at several levels

- Can be leveraged to improve capacity in LOS scenarios
- The only solution to restore coverage in nLOS