mmWall: A Reconfigurable Metamaterial Surface for mmWave Networks

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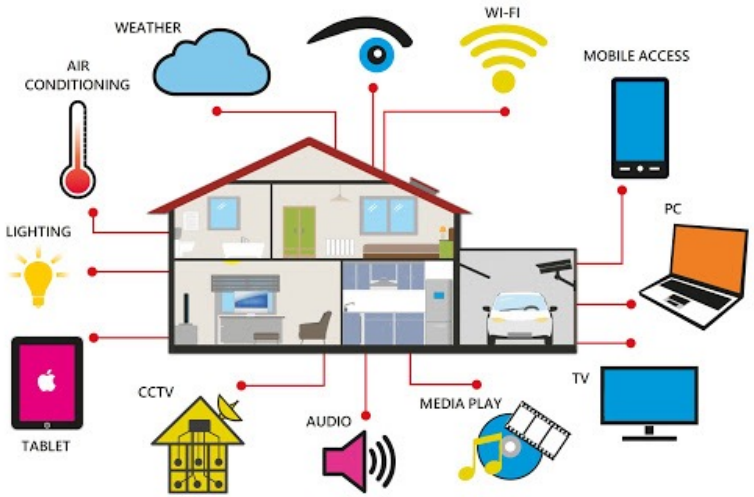
5G Communication

Demand for 5G network surges as bandwidth requirement of wireless applications grow

VR and AR



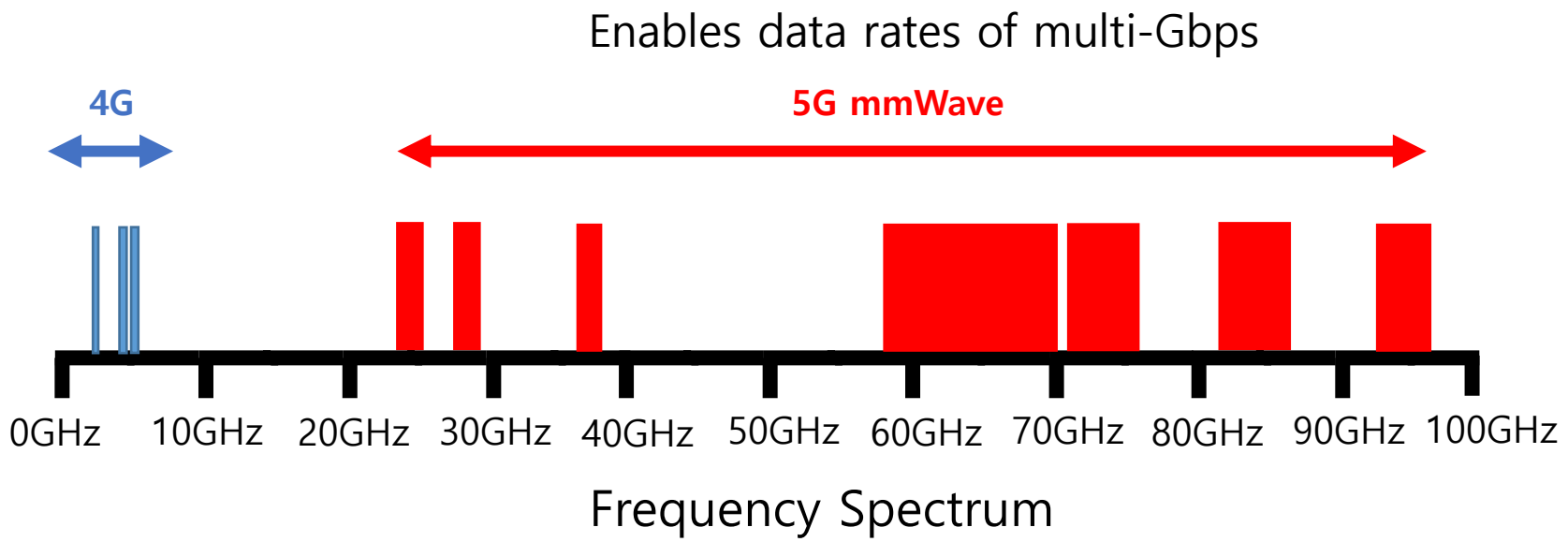
Smart Home

Robotic Automation/ Collaboration Tasks

Millimeter Wave (mmWave) Technology

Huge bandwidth available at mmWave frequency

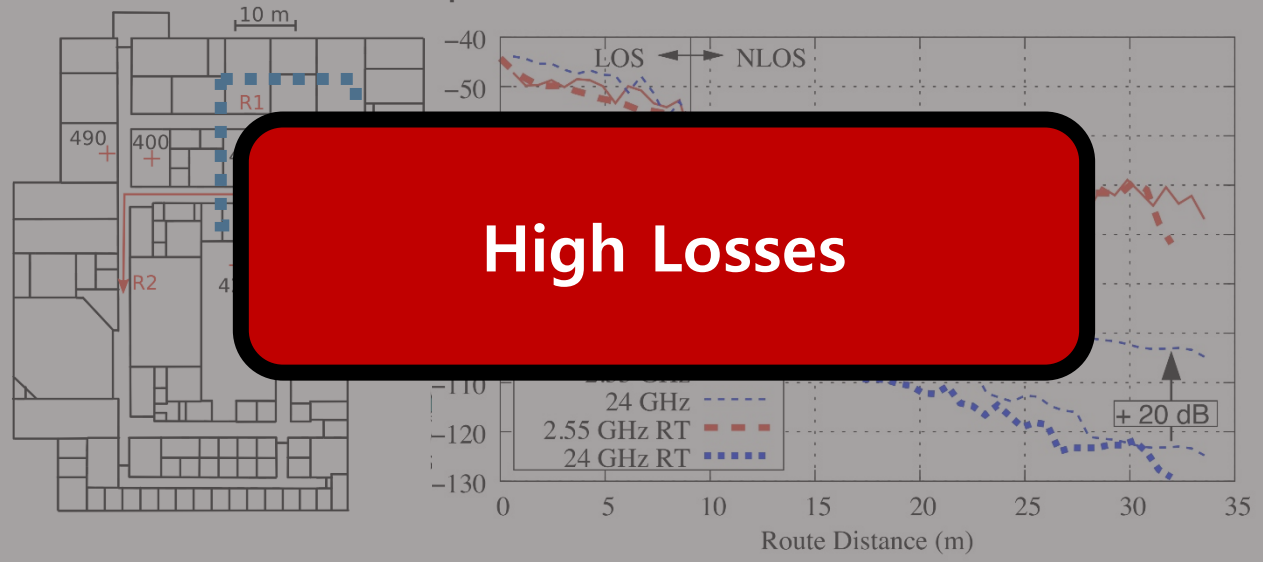
- 2 GHz 4G with 100 MHz bandwidth vs 28 GHz 5G with 1 GHz bandwidth
- Currently used bands are already extremely crowded



Fundamental Challenge of mmWave

- Electromagnetic waves have weak ability to **diffract around obstacles** with a size significantly larger than the wavelength
  - Wall Penetration
  - Body Blockage

Wall penetration at 24 GHz [1]



High Losses

Dynamic human-body blockage at 60 GHz [2]

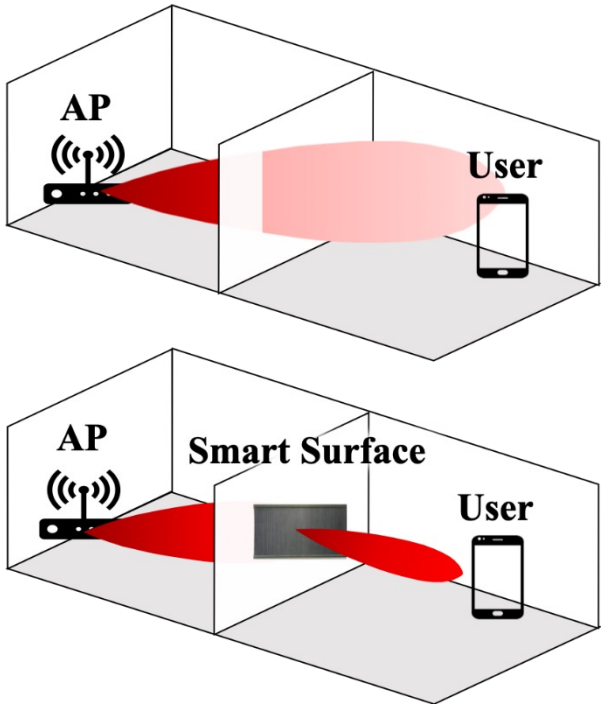
Communication Glitches

[1] Wallace, Jon W., et al. "A Comparison of Indoor MIMO Measurements and Ray-Tracing at 24 GHz and 2.55 GHz."
[2] Slezak, Christopher, et al. "Empirical effects of dynamic human-body blockage in 60 GHz communications." *IEEE Communications Magazine* 56.12 (2018): 60-66.

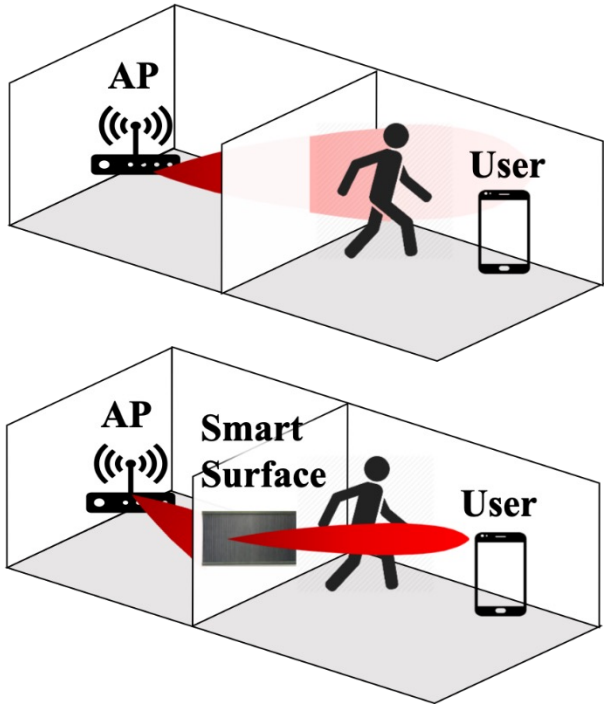
Our Approach

Solution: Delegate the task of the AP to Smart Surface

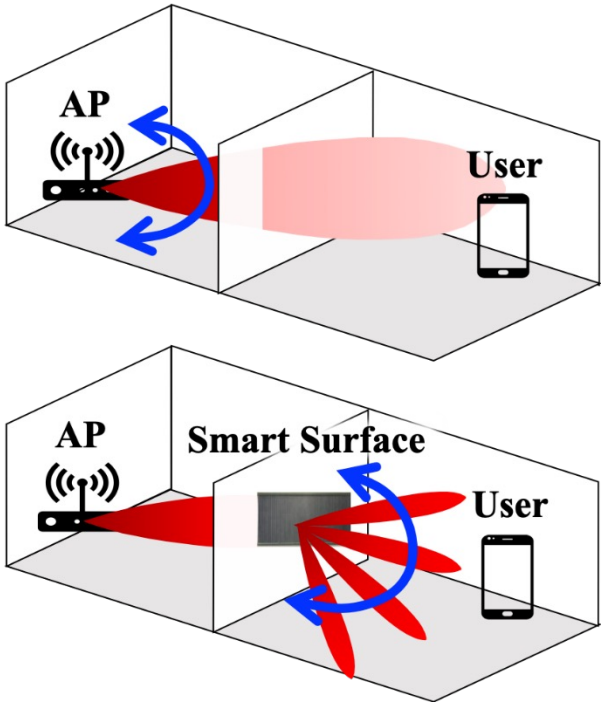
- Wall penetration → Beam relay via smart surface, embedded on the wall
- Human body → Steer the beam to provide a path diversity



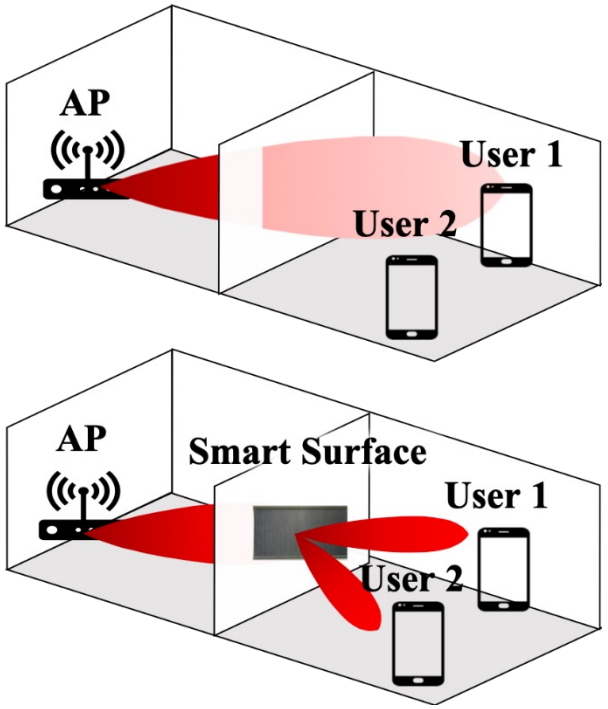
Beam Relay and Focusing



Path Diversity



Beam Searching



Multicast

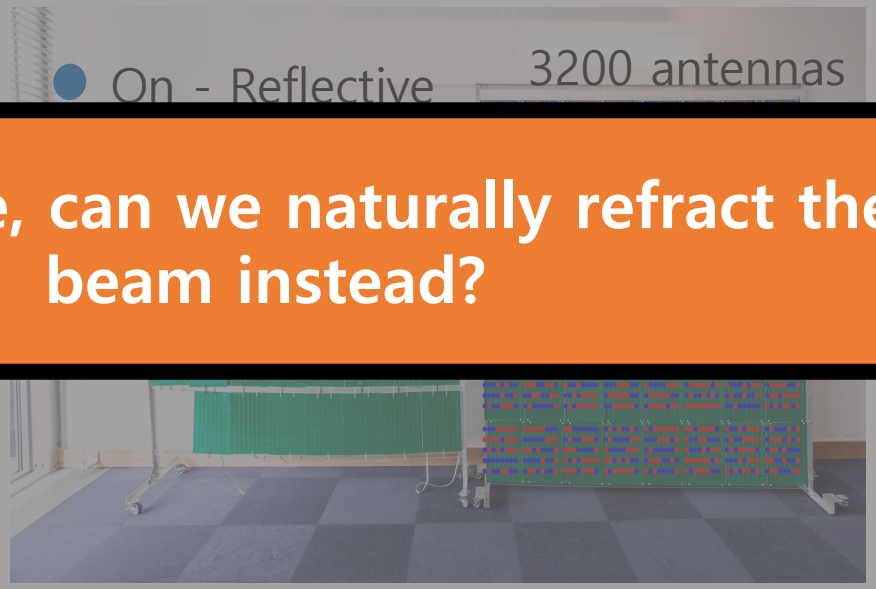
Related Work: LAIA, Rfocus, MoVR

LAIA [1]

Control board

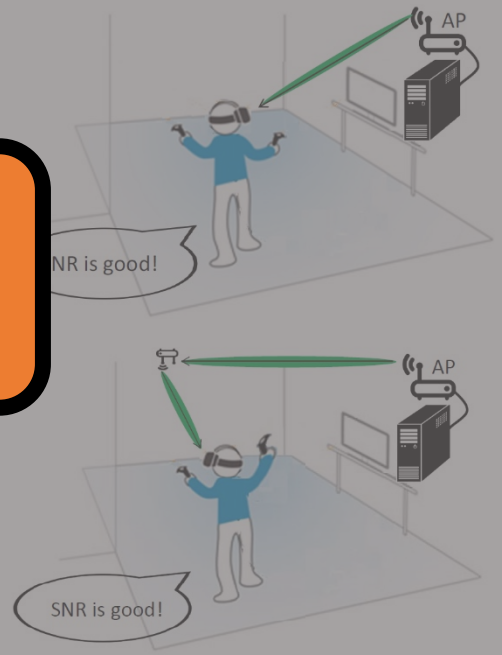
AP side

RFOCUS [2]



At mmWave, can we naturally refract the beam instead?

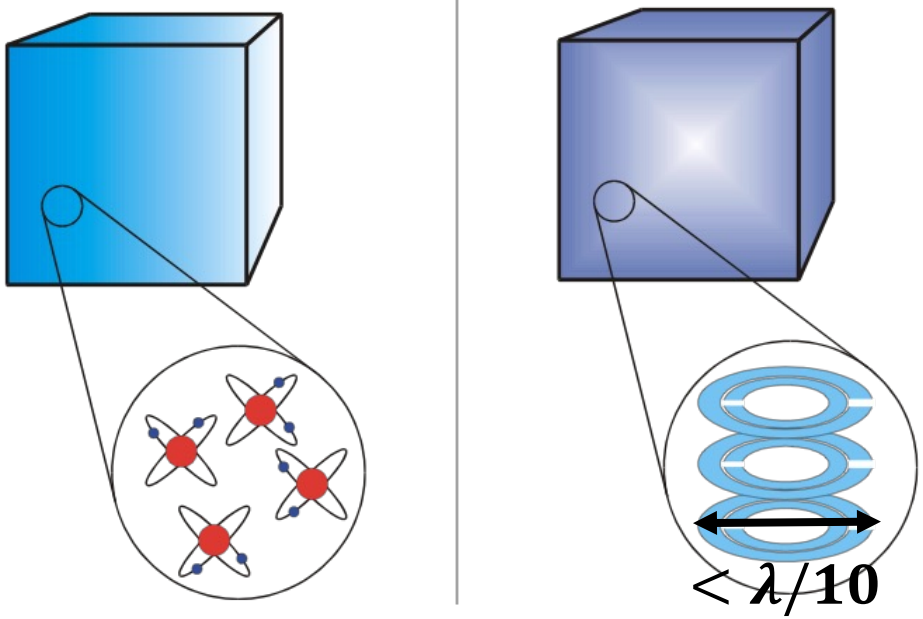
MoVR [3]

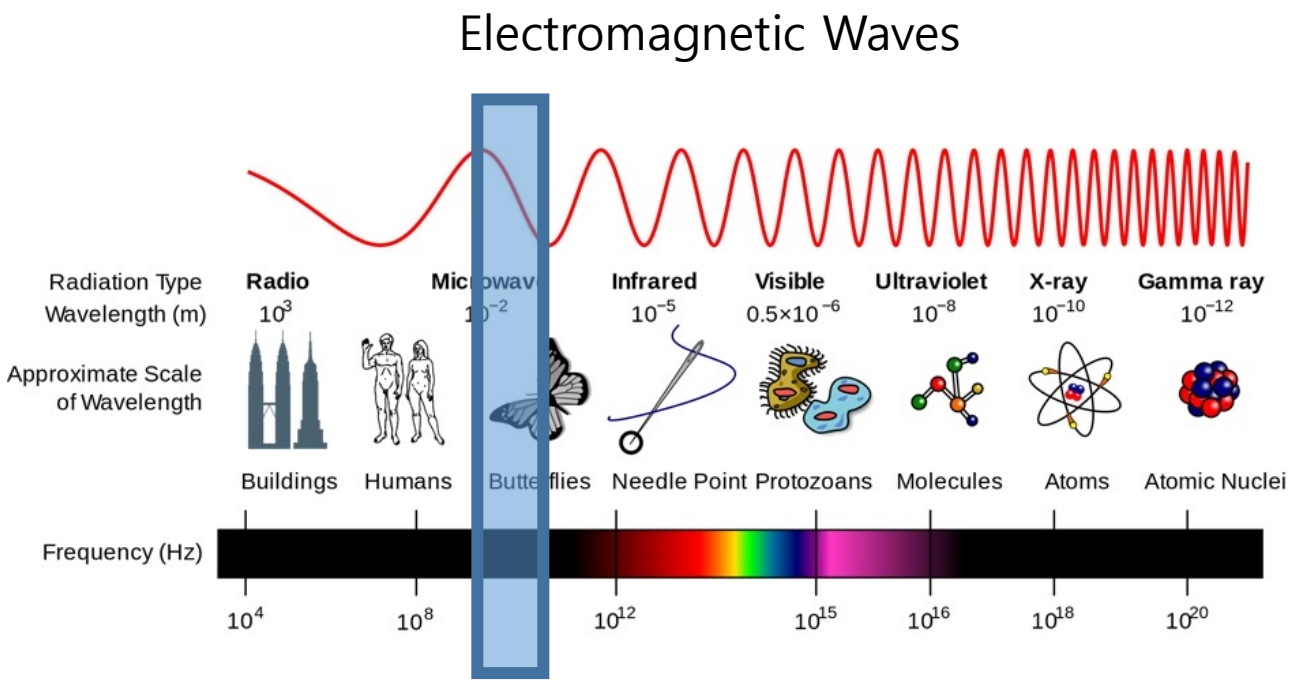


[1] Li, Zhuqi, et al. "Towards programming the radio environment with large arrays of inexpensive antennas." *16th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 19)*. 2019.
[2] Arun, Venkat, and Hari Balakrishnan. "RFocus: Beamforming using thousands of passive antennas." *17th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 20)*. 2020.
[3] Abari, Omid, et al. "Enabling high-quality untethered virtual reality." *14th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 17)*. 2017.

Metamaterial: a new field

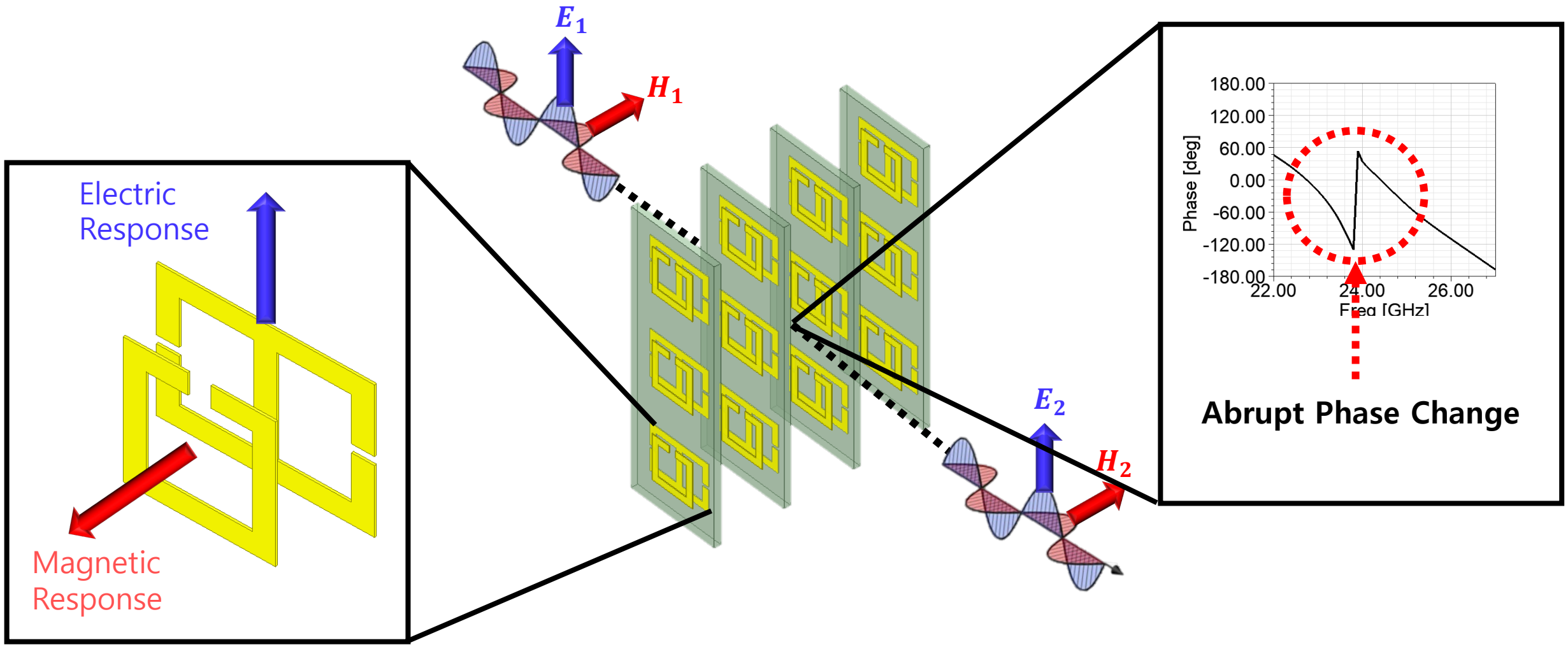
- **Artificially engineered materials** that exhibits electromagnetic properties that do not exist in naturally occurring material
  - Each meta-atom has a size less than $\lambda/10$





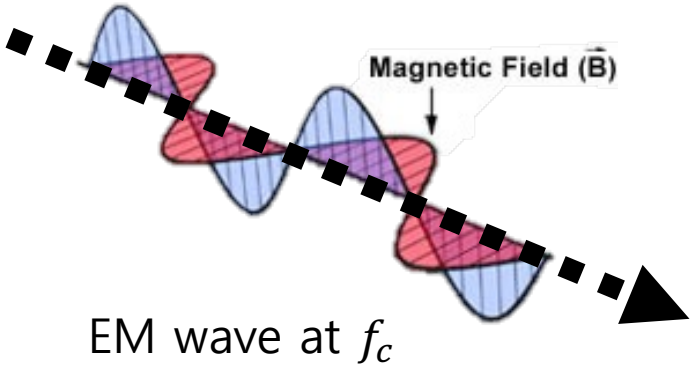
mmWave has 12.5 mm~3 mm wavelength

Huygen's Metasurface (HMS)

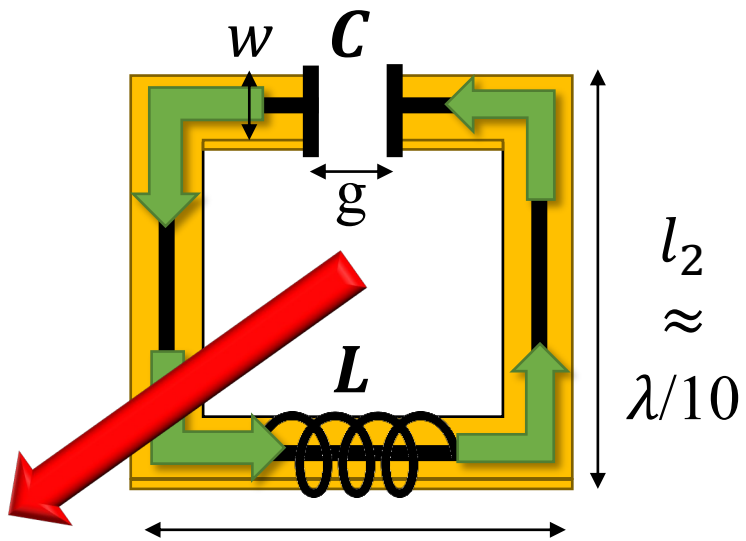


Magnetic Meta-atom

- Induce magnetic response by acting as **a resonant LC circuit**
- Magnetic field passing the metallic rings induces the rotating current
  - Due to rotating current, the ring produces its own magnetic field.



EM wave at f_c



Magnetic field

Resonant Freq.

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

Electric Meta-atom

- Induce electric response by acting as **a resonant LC circuit**
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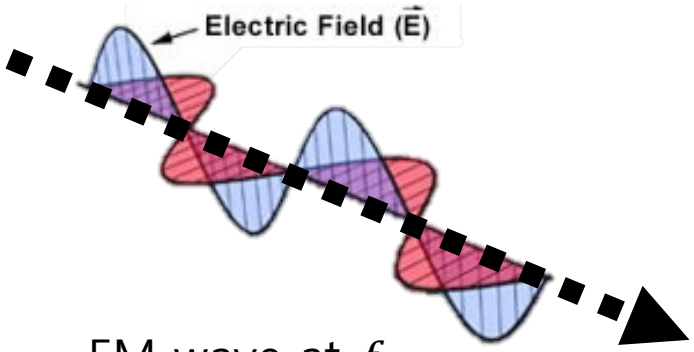
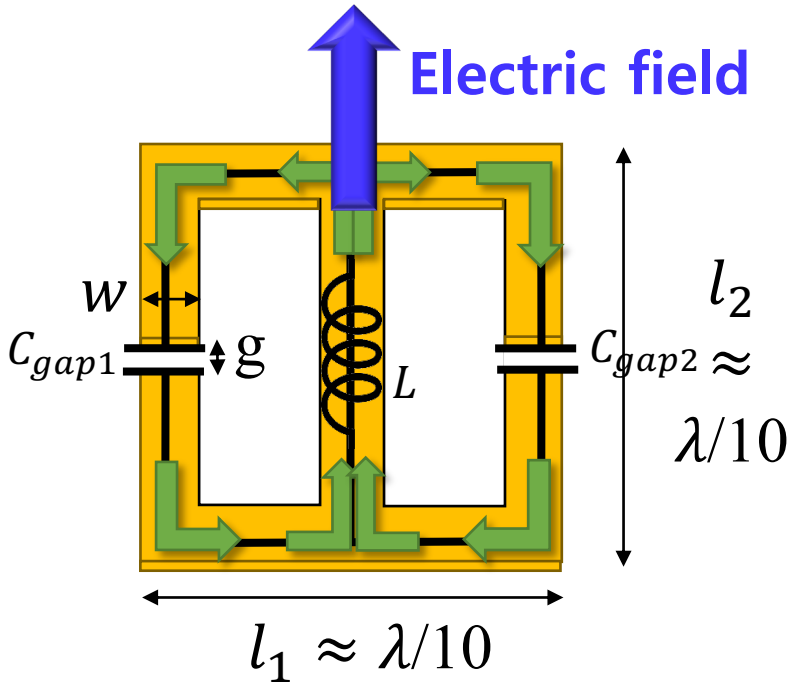


EM wave at f_c

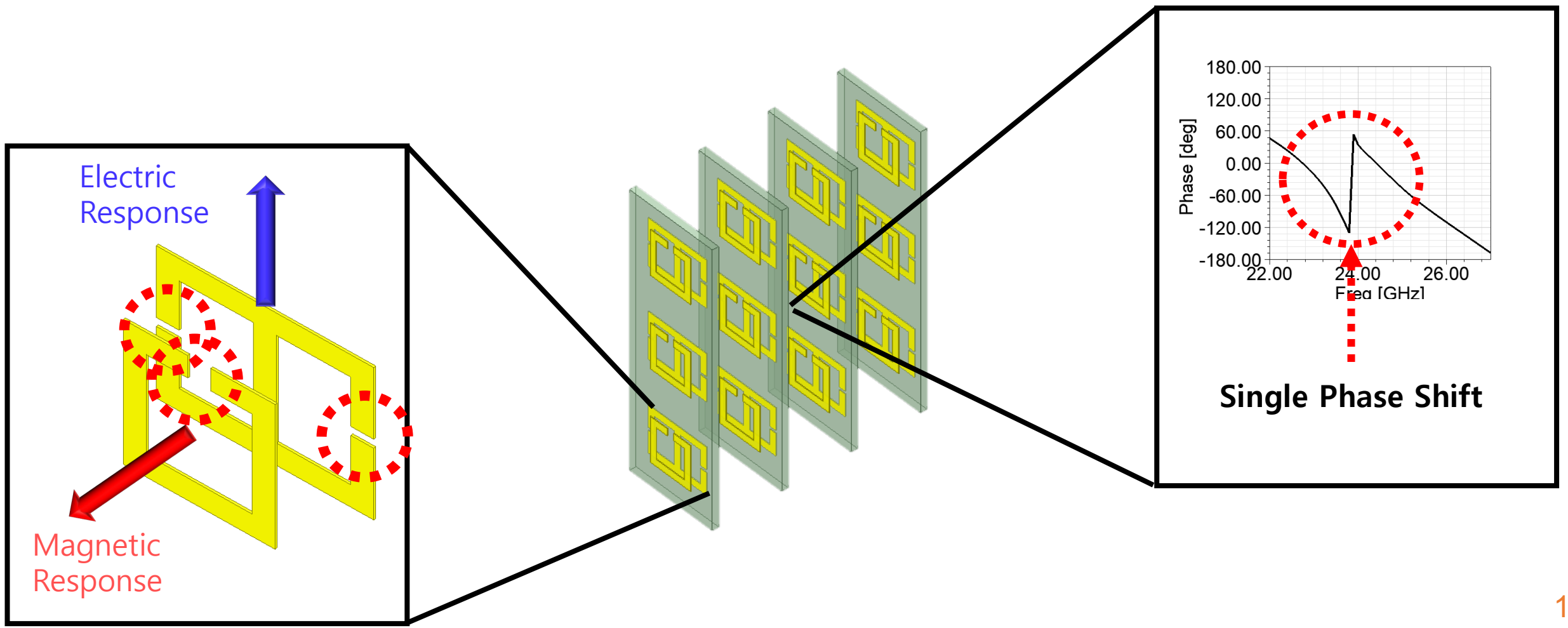


Resonant Freq.

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

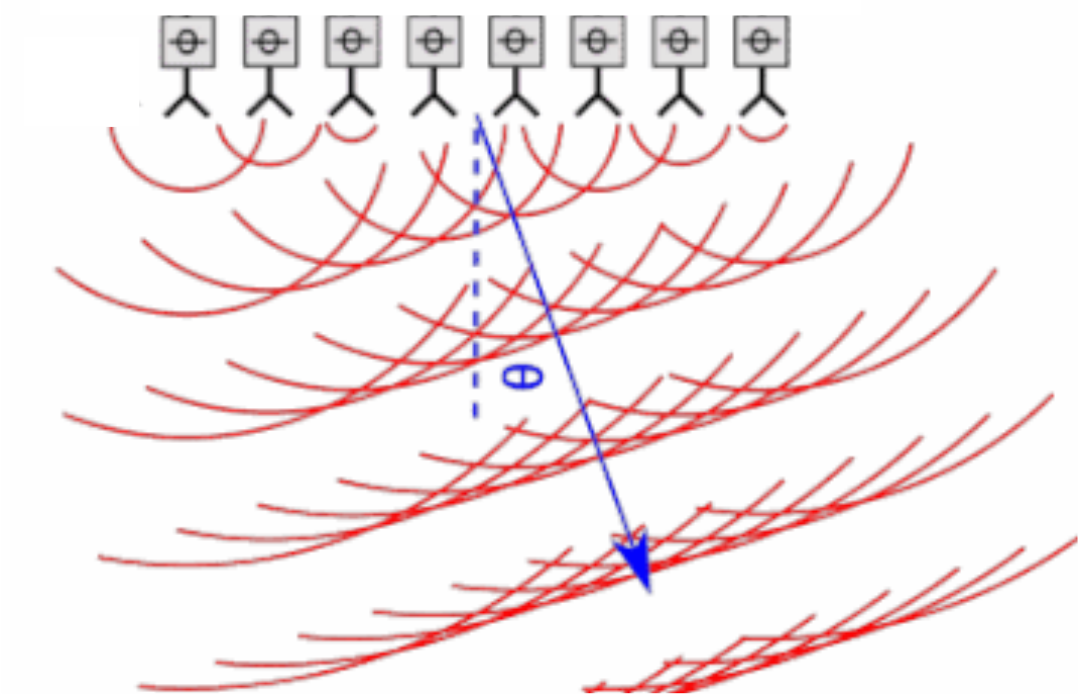
Huygen's Metasurface (HMS)

- This design is **not reconfigurable!**
  - Only one abrupt phase shifting available for every meta-atom



Revisit: Phased Array Antenna

Different phase shift to each antenna

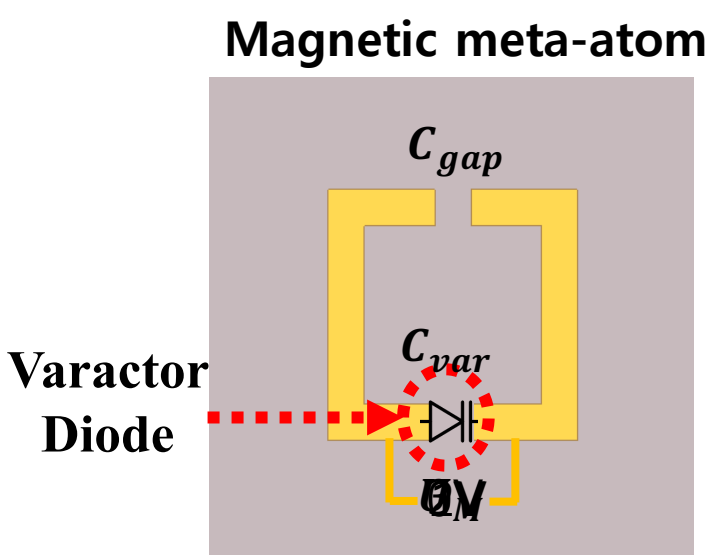


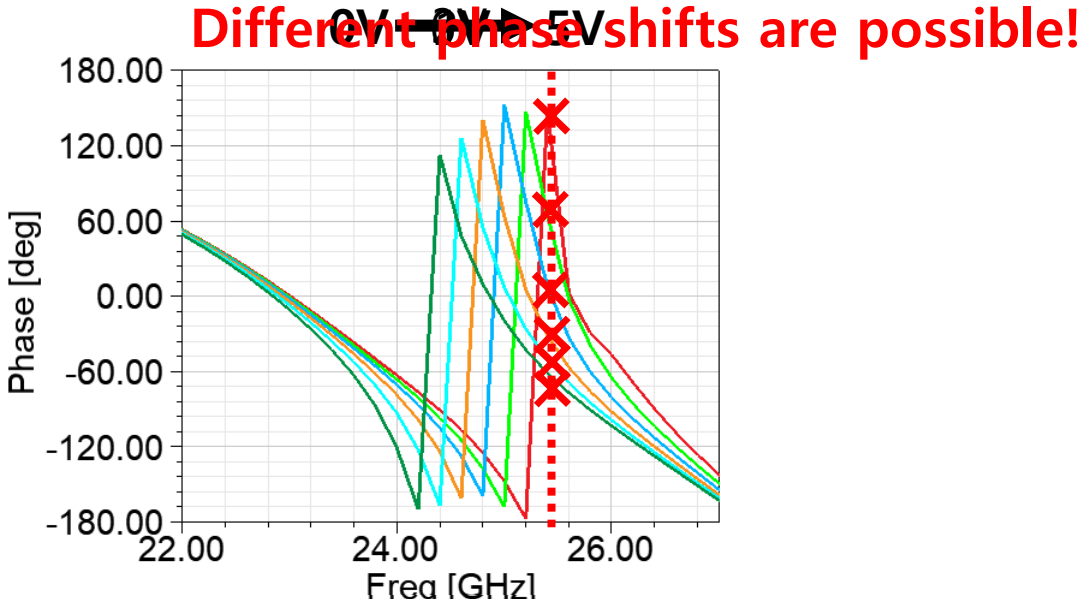
Tunable Huygen's Metasurface

- Varactor diode
  - **Tunable electrical components** that varies the capacitance of meta-atom

Total capacitance $C_{\text{total}} = \frac{1}{\frac{1}{C_{gap}}+\frac{1}{C_{var}}}$

Resonance frequency $f_0 = \frac{1}{2\pi\sqrt{LC_{total}}}$





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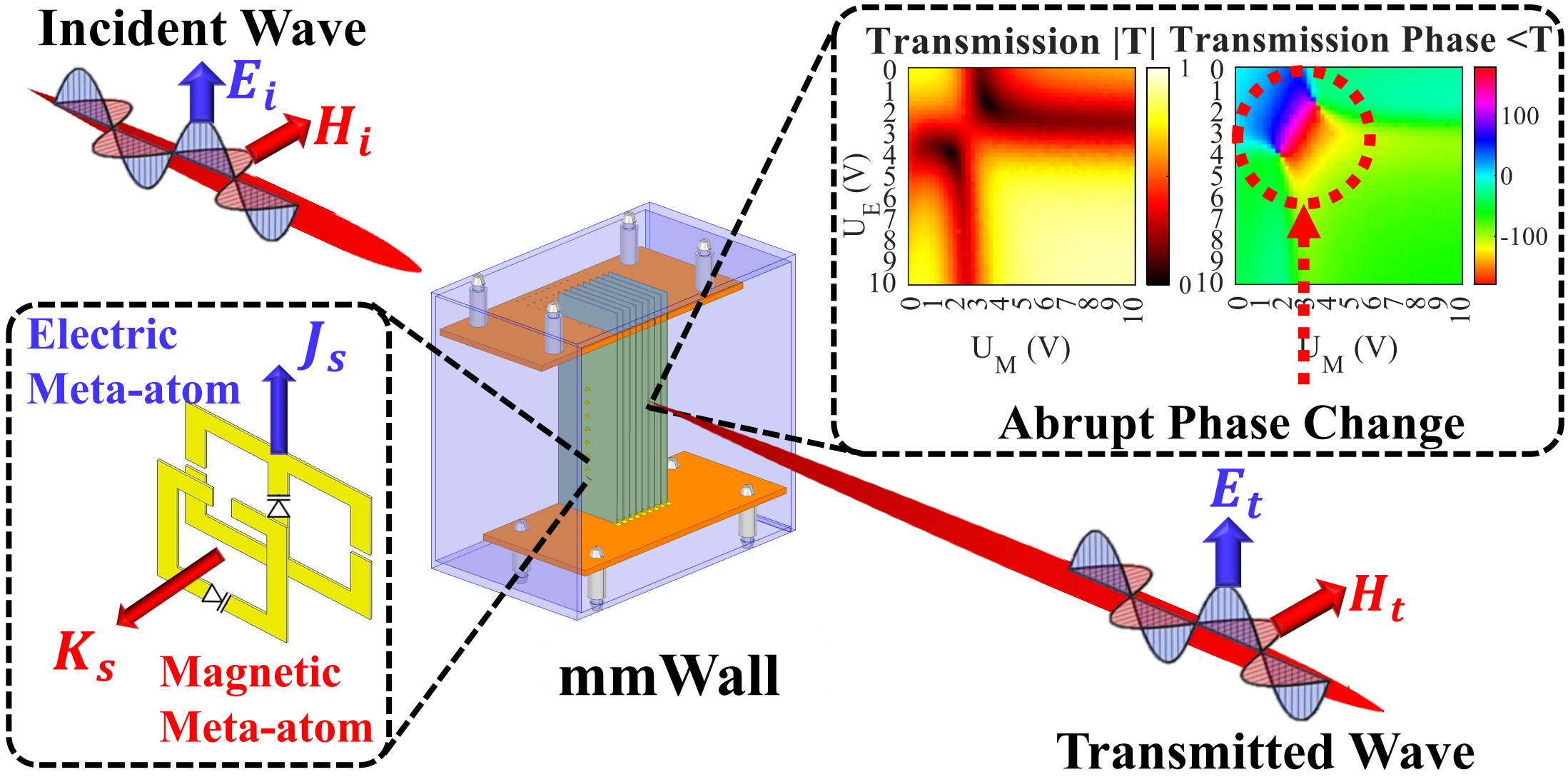
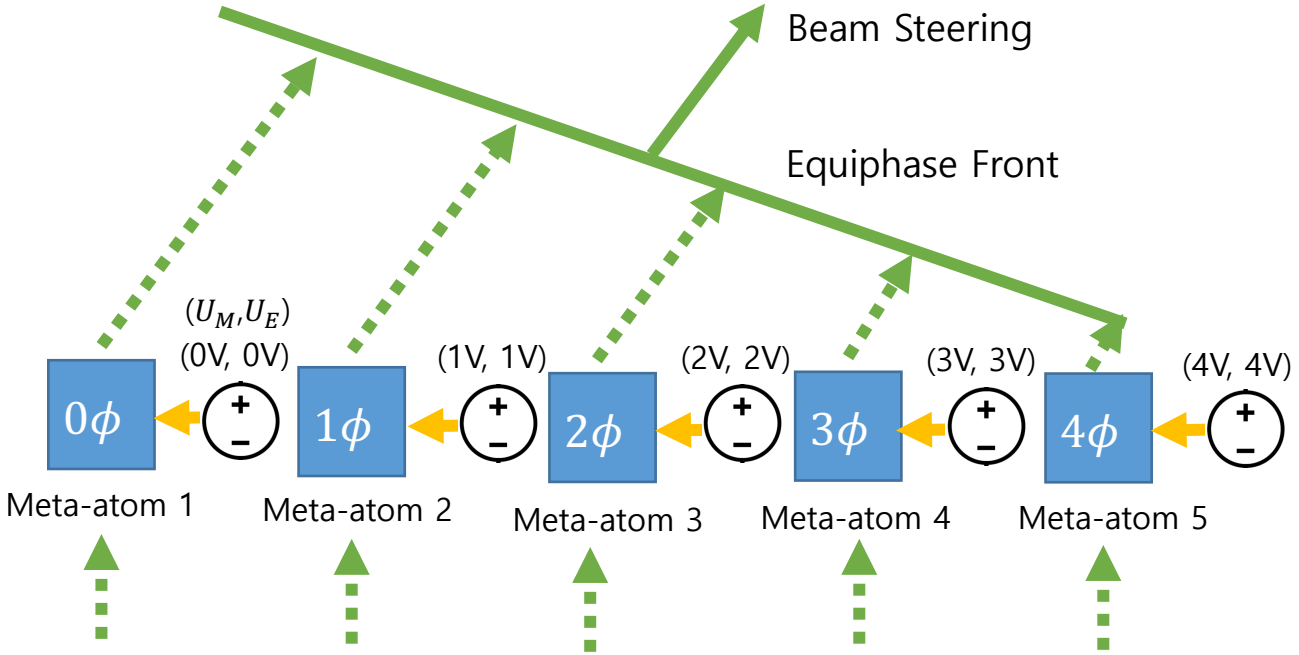
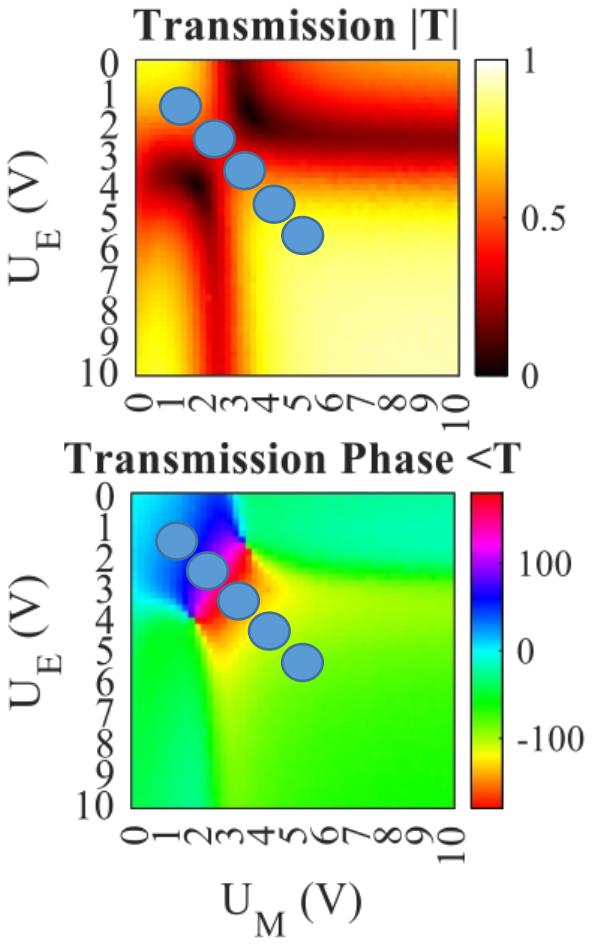


Tunable Huygen's Metasurface

- How does Tunable HMS steer the beam?



Huygen's Pattern



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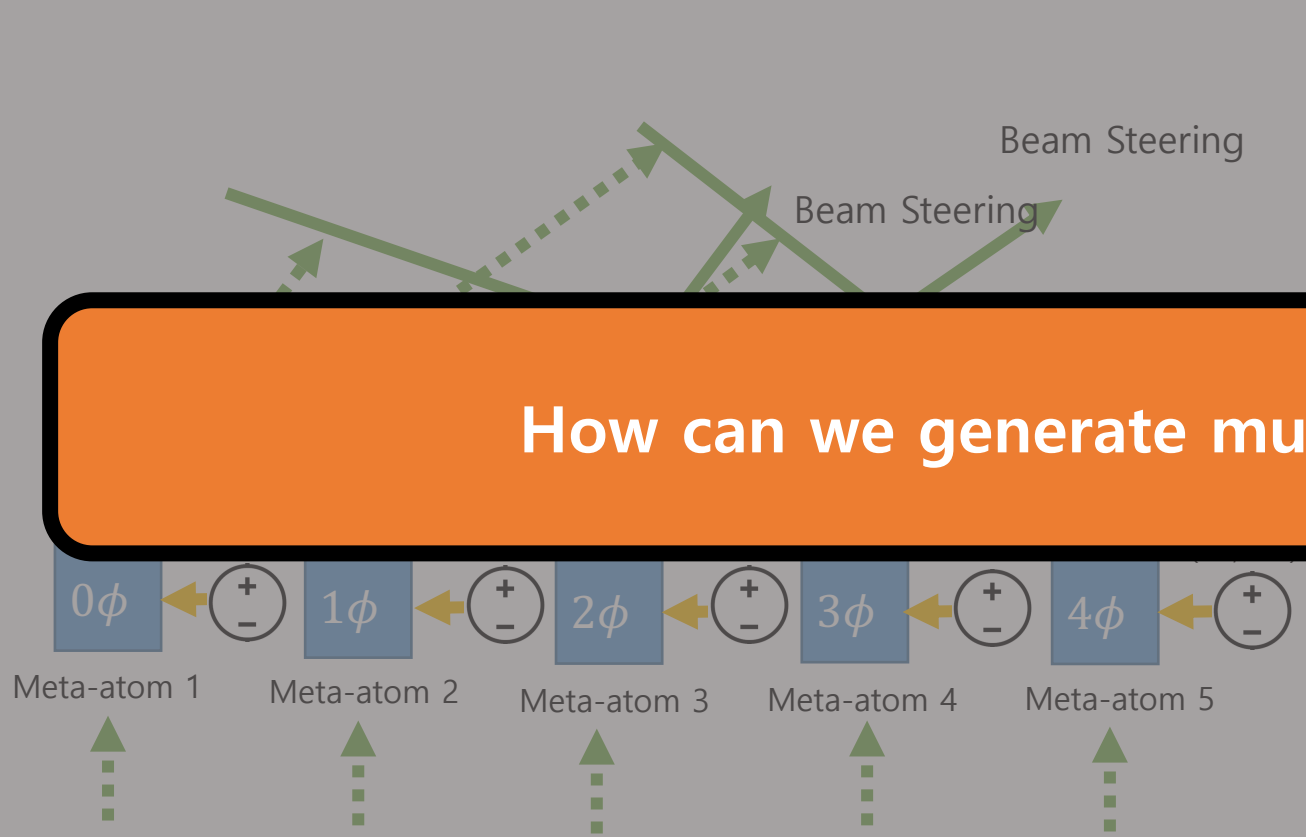
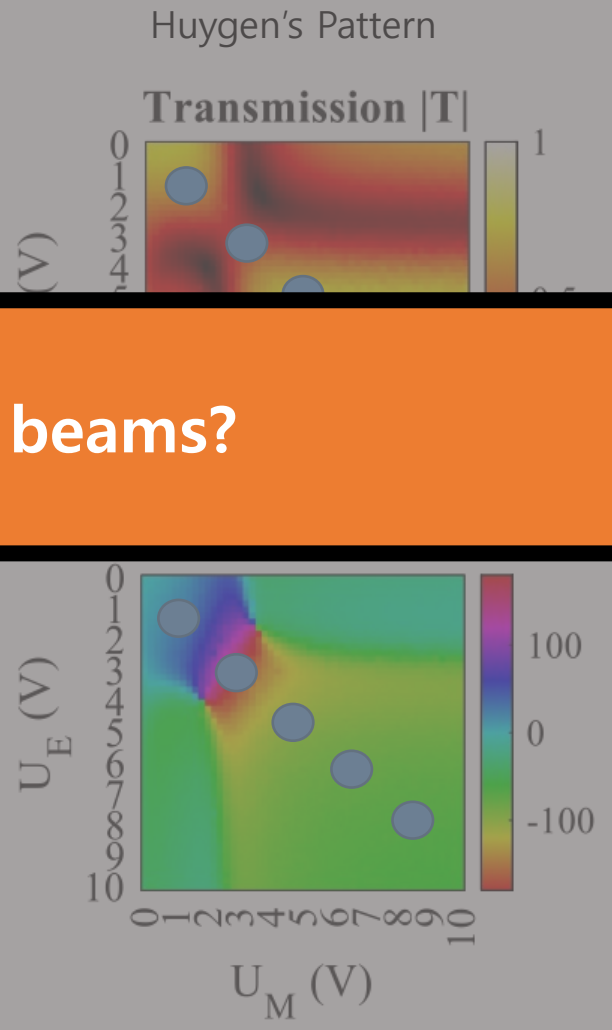
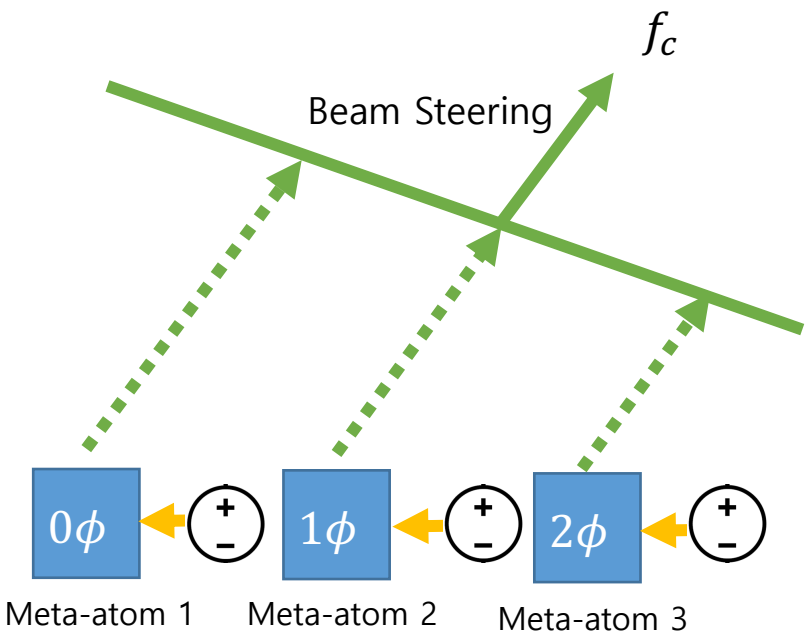


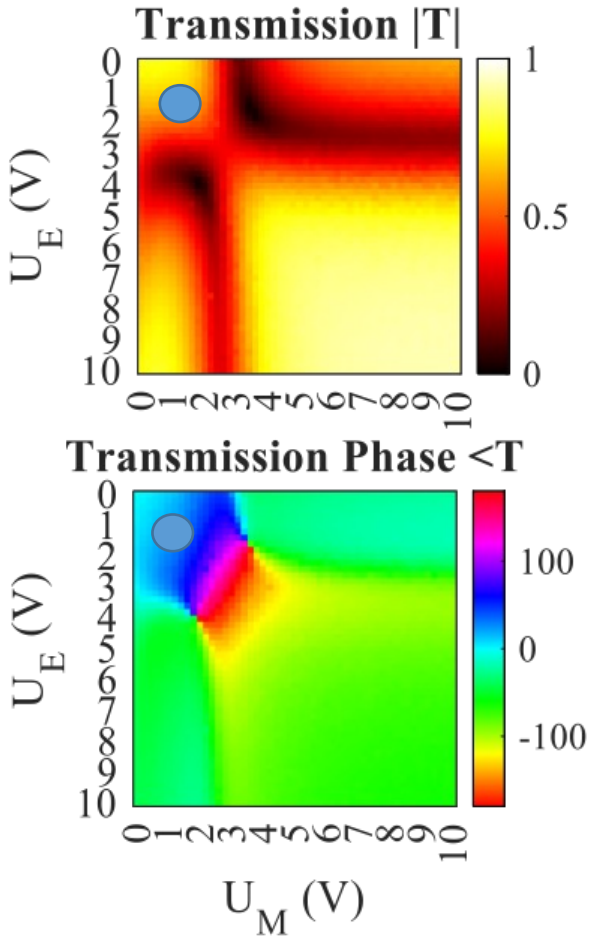
How can we generate multiple beams?

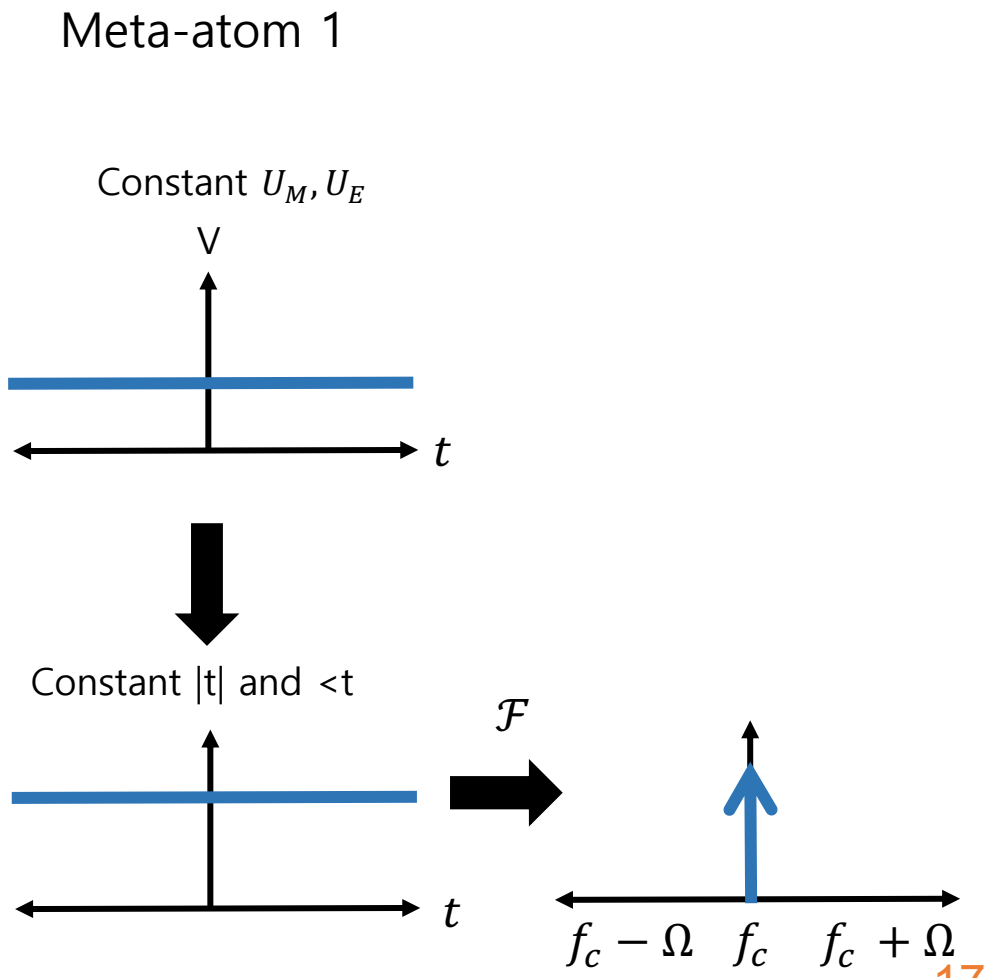


Time-modulated Huygen's Metasurface

- Introduce additional degree of freedom: **time**







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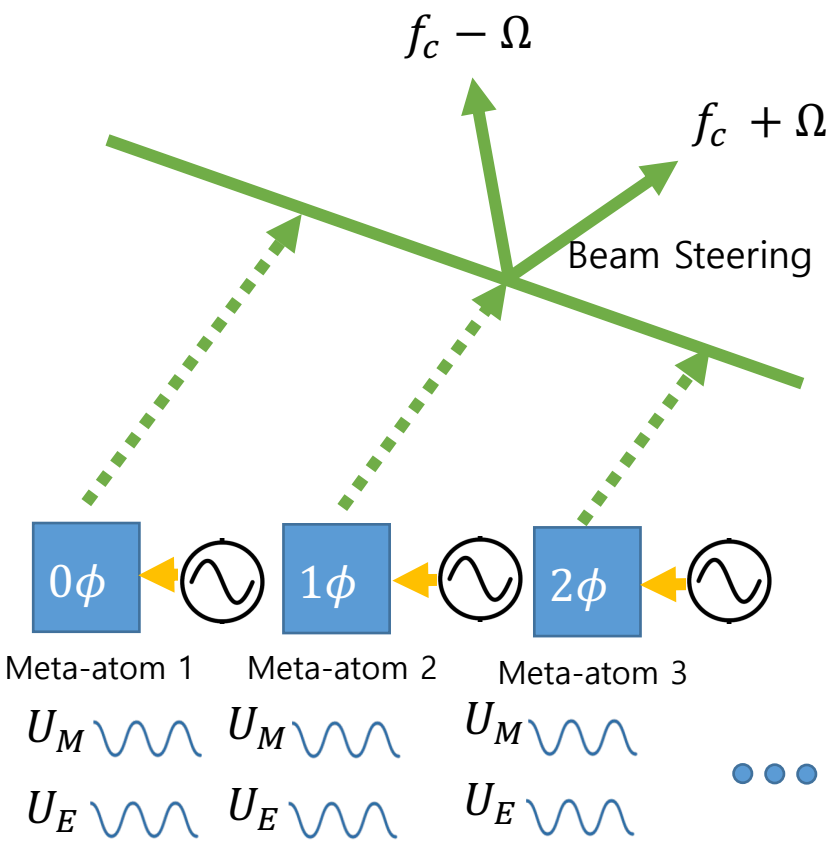
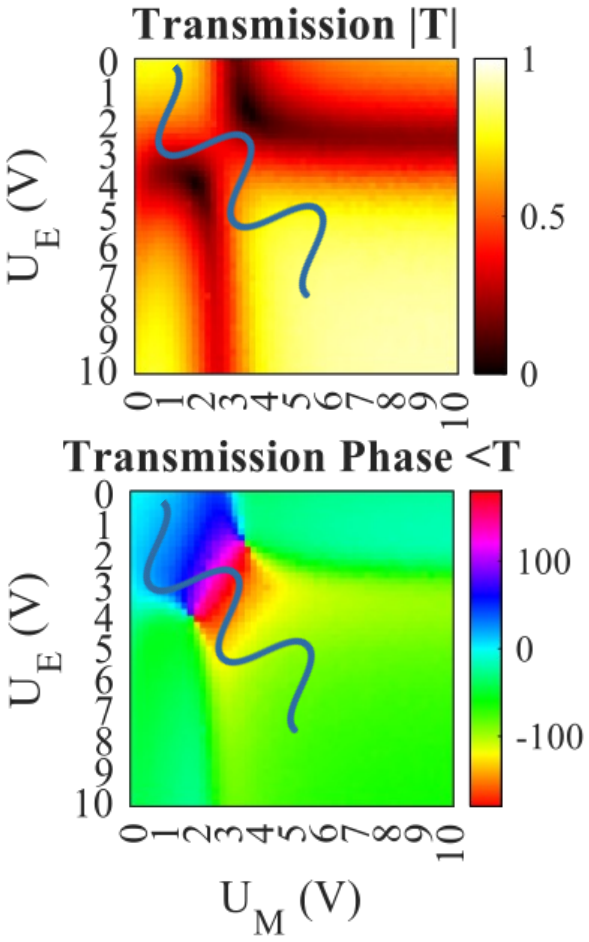
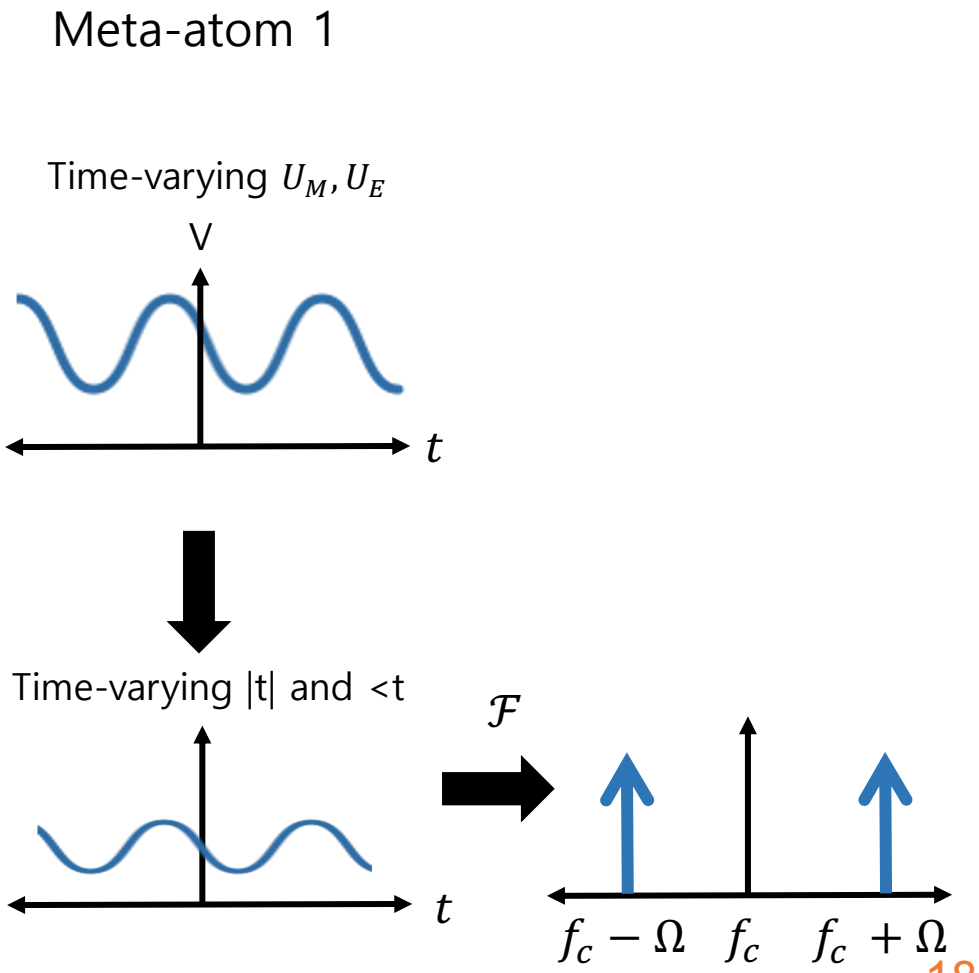
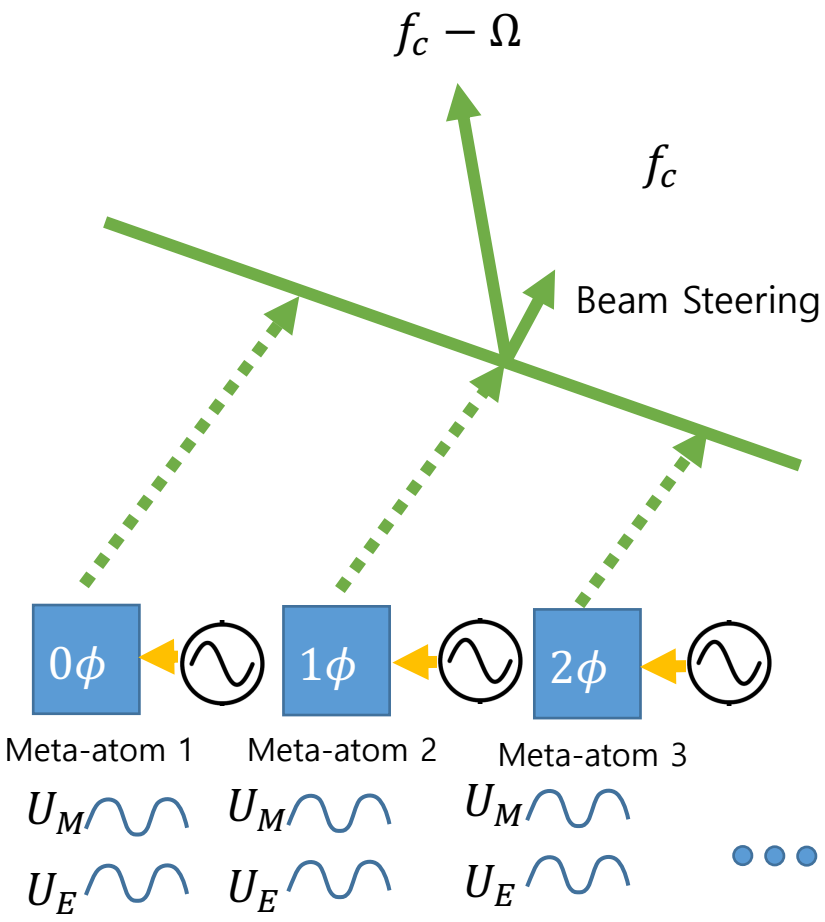


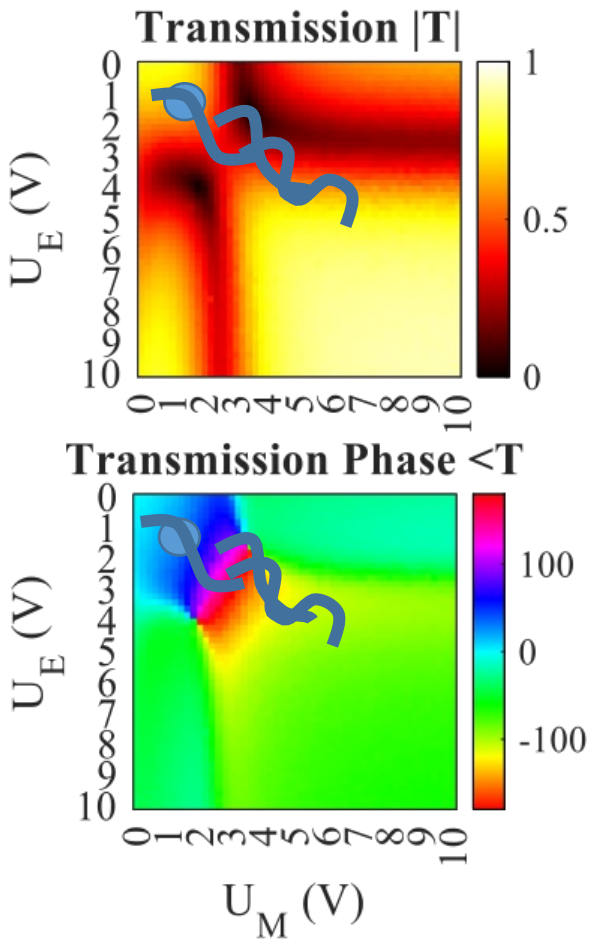


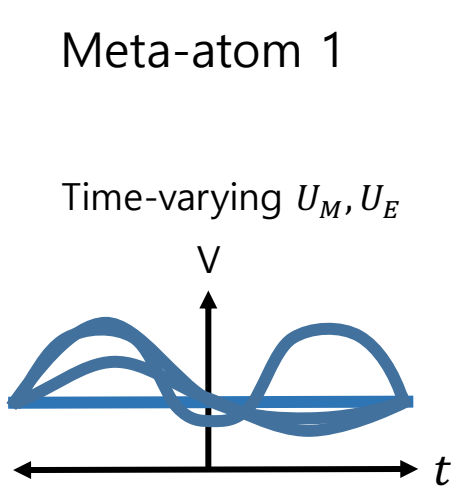


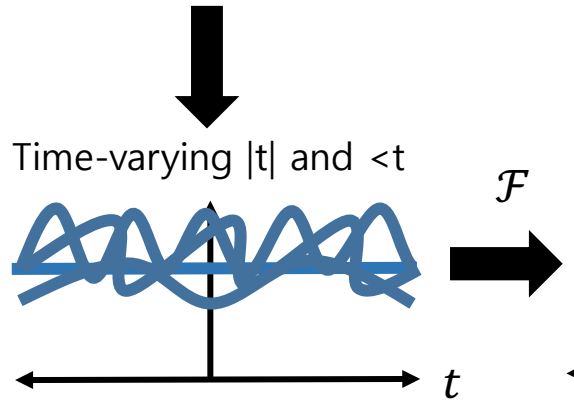
Time-modulated Huygen's Metasurface

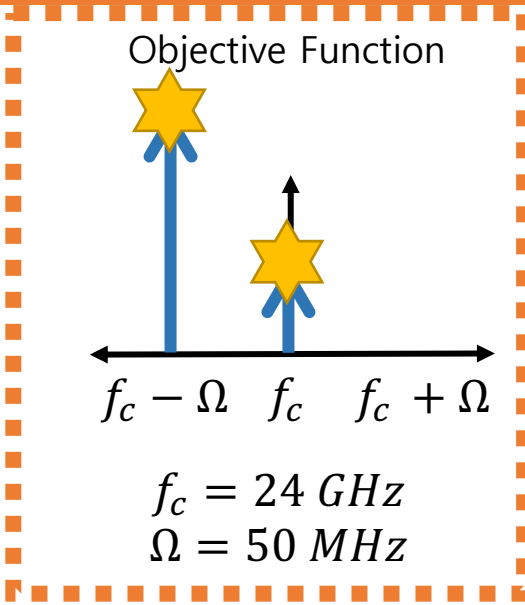
- How to apply HMS to the smart surface?





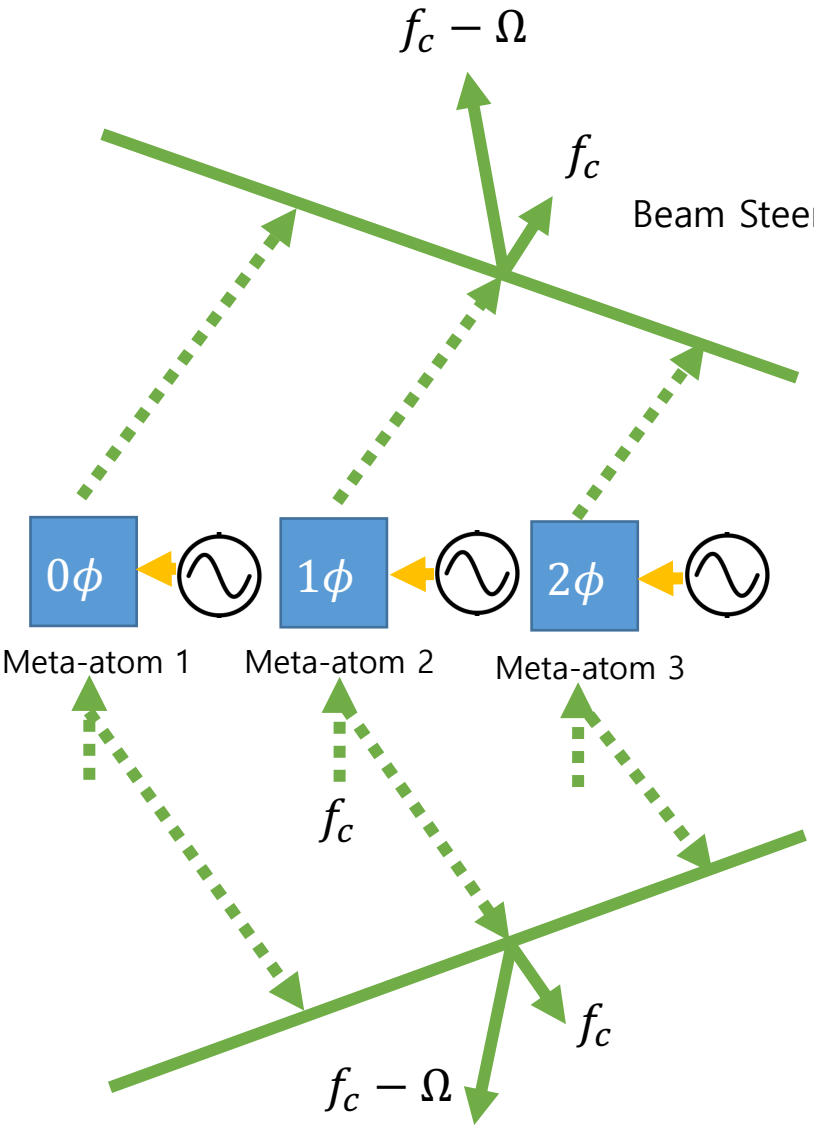


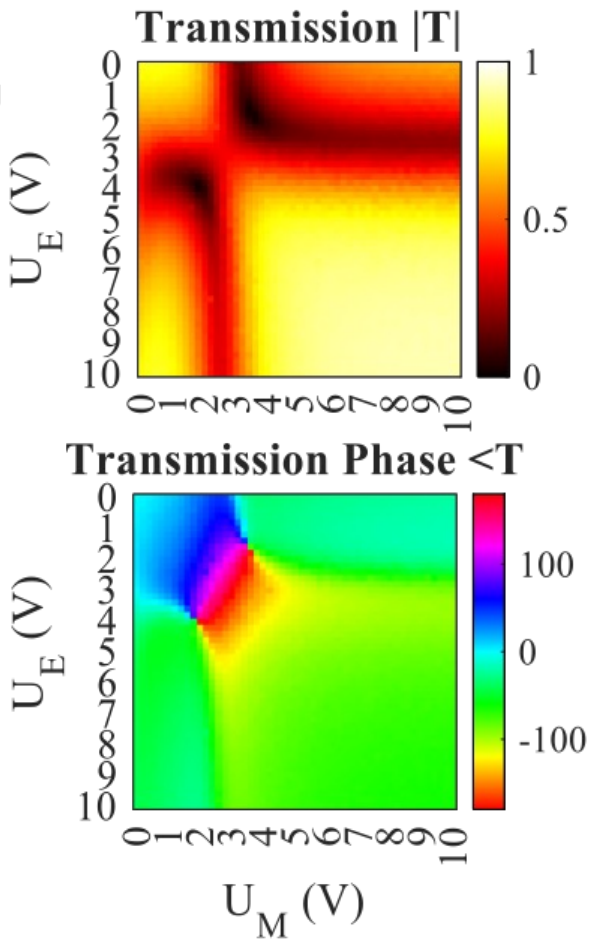




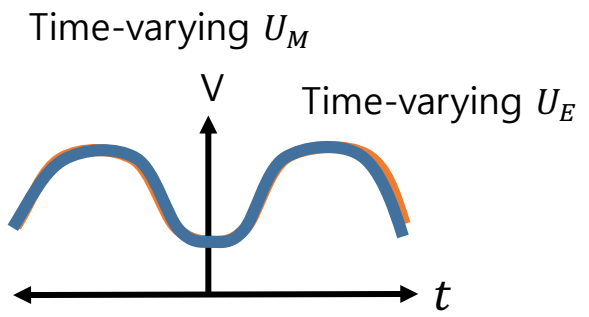
Time-modulated Huygen's Metasurface

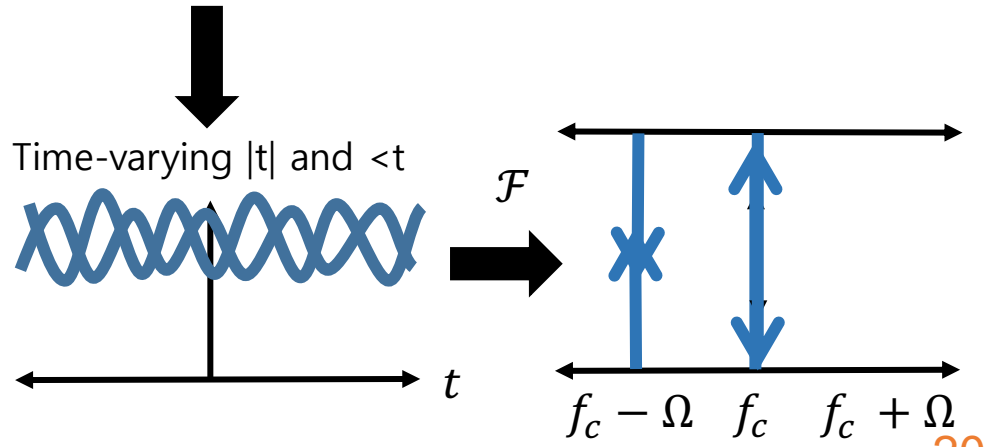
- Transition from “lens” mode to “mirror” mode





Meta-atom 1

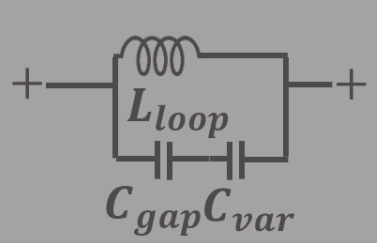




How can we it scale to mmWave?

- Resonance Frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$
- Inductance $L = \mu_0 \frac{l_1 l_2}{t}$ where μ_0 is free-space permeability
- Capacitance $C_{gap} = \varepsilon_0 \frac{wt}{g}$ where ε_0 is free-space permittivity
- $LC \propto (\mu_0 \frac{l_1 l_2}{\quad}$ $\frac{wt}{\quad}$ $\frac{1}{\quad}$ $l_1 l_2$ $\frac{w}{\quad})$
- Goal
  - Resc
  - Minimize LC
    - Reducing area $l_1 l_2$ and/or width w
    - Increase gap g

Varactor packaging distorts the tailored surface properties



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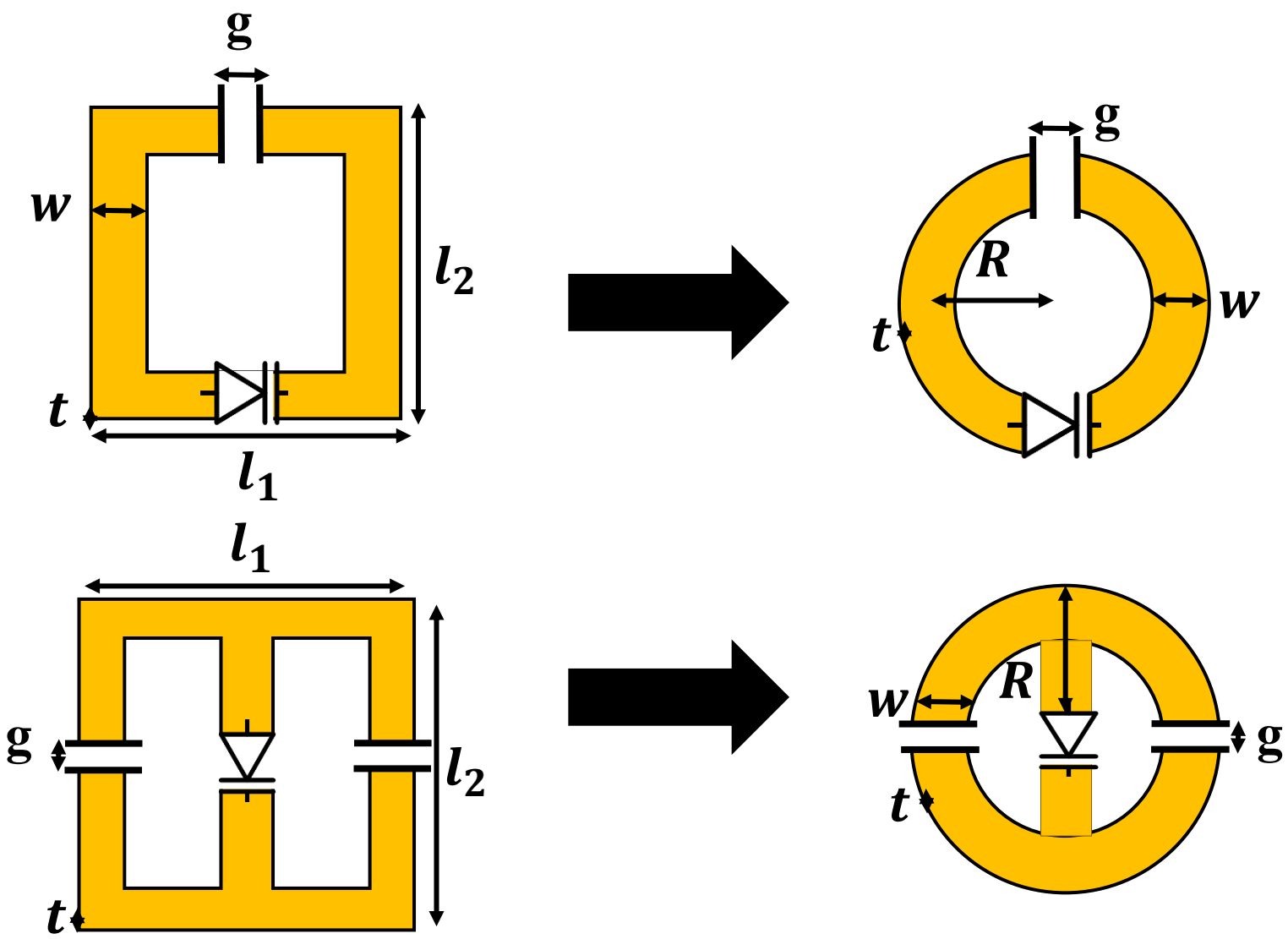
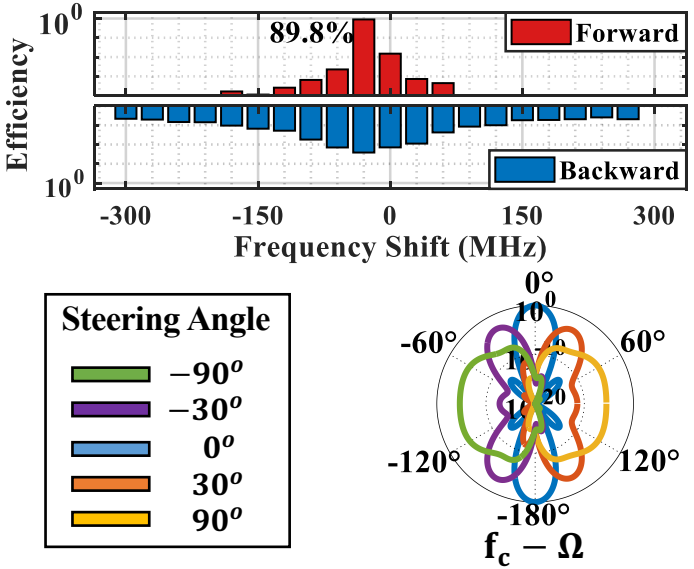
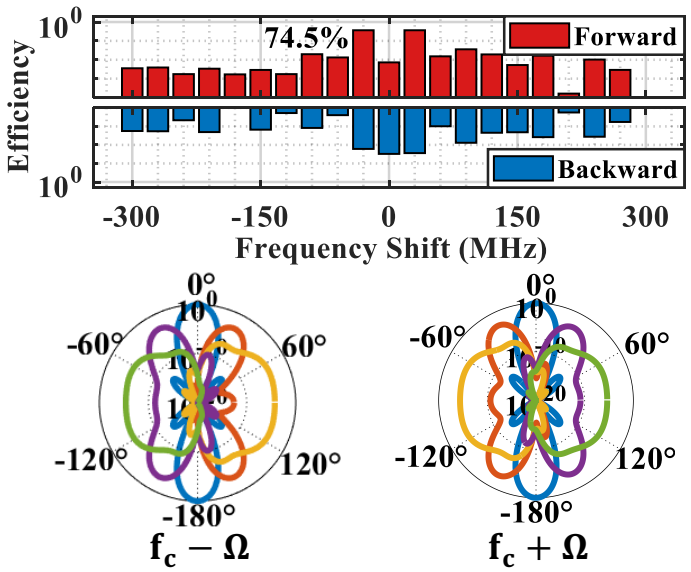


Results: Beam Efficiency and Steering

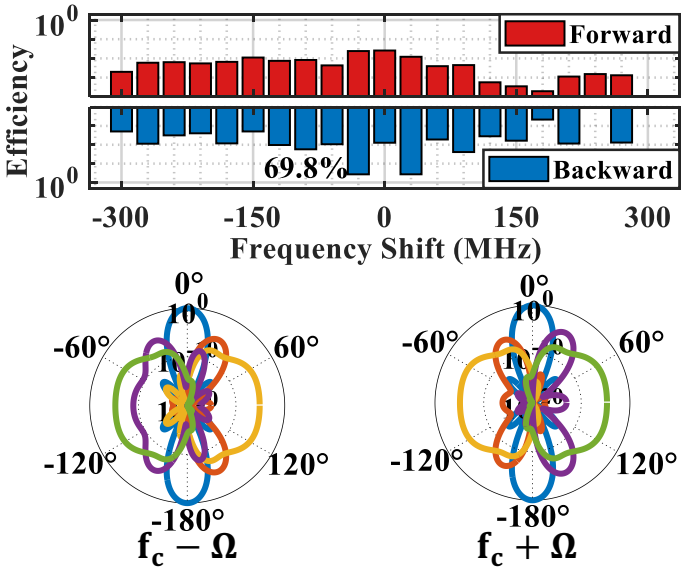
Single Beam



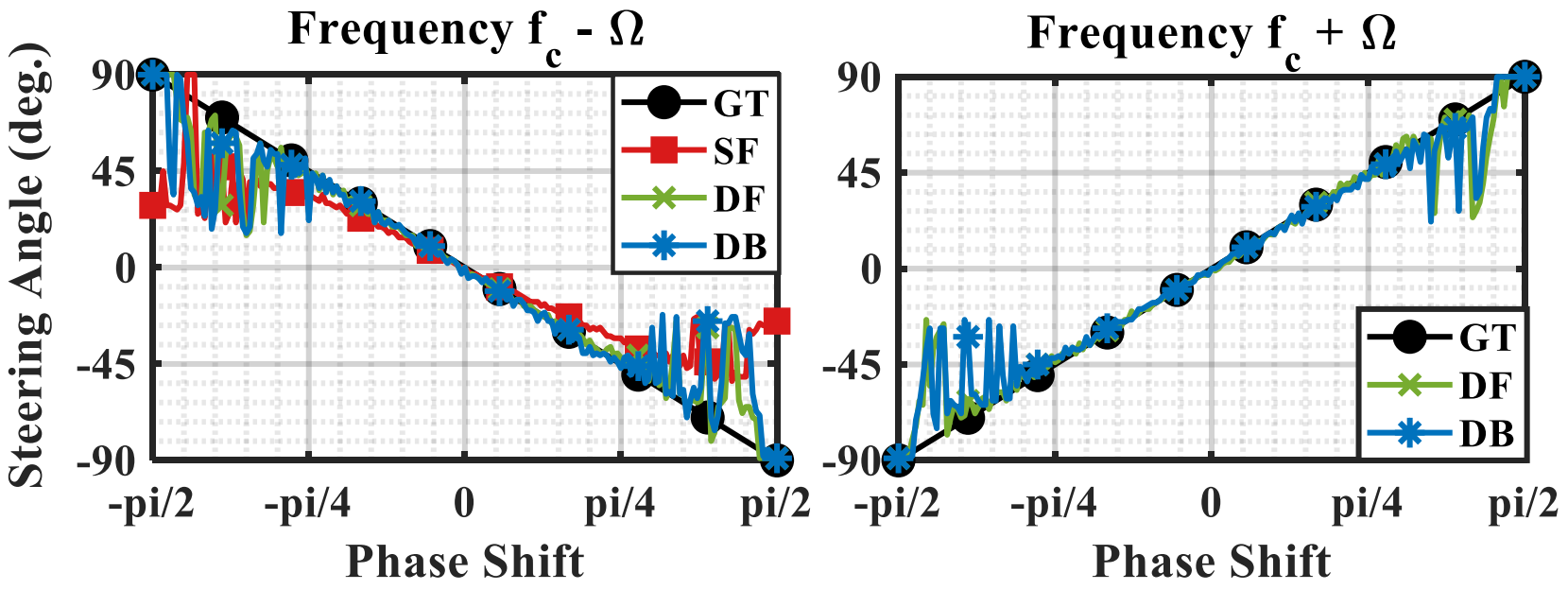
Double Beams



Double Reflective Beams



Results: Steering Accuracy



Conclusion

- The first step towards programming the mmWave radio environment via the metamaterial surface
- We will fabricate this design to build an real smart surface prototype, and focus on refining its system architecture