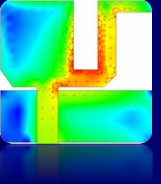


Recent Progress in Metasurface Antennas Using Characteristic Mode Analysis

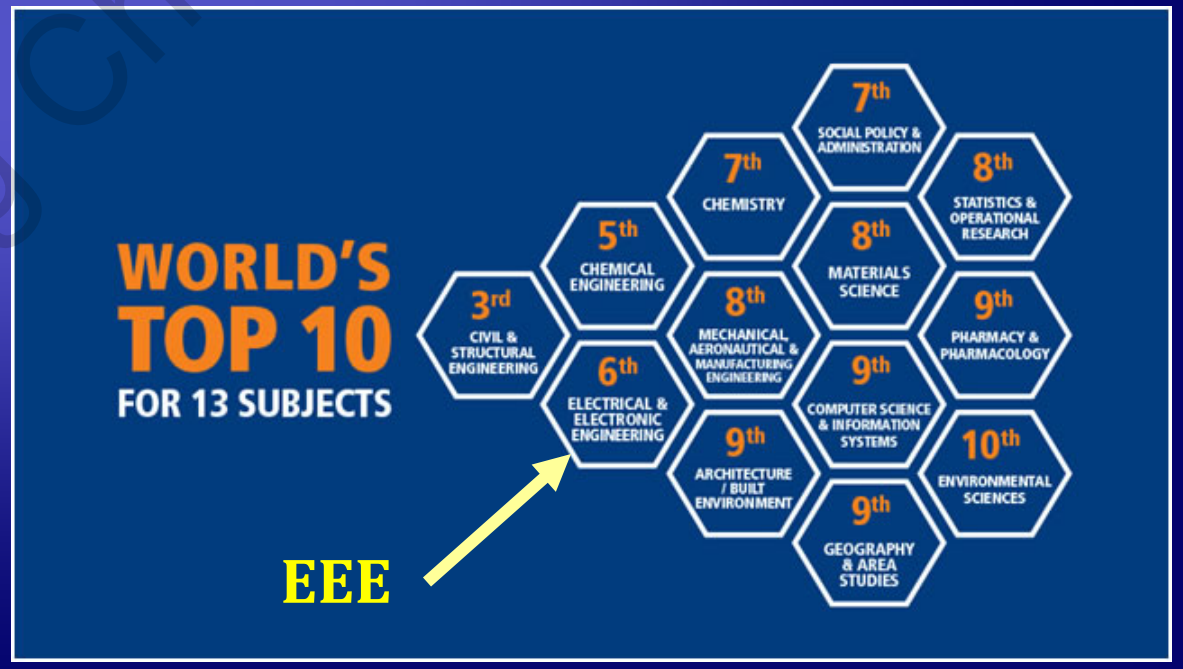
Feng Han Lin, Teng Li, and Zhi Ning Chen*
National University of Singapore (NUS)
EuCAP 2019 Krakow

Zhi Ning Chen NUS

Zhi Ning Chen (陈志宁)

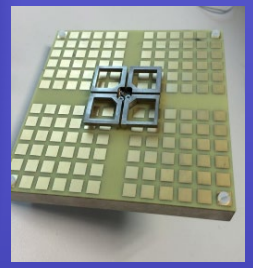
PhDs & Professor & Program Director (Industry)
IEEE Fellow (2007), Fellow of SAEng (2019)
IEEE CRFID VP and DL
长江学者讲座教授（东南大学）

- 16 faculties and schools
- Over 37,000 students from 100 countries
- 3 Research Centres of Excellence
- 22 university-level research institutes and centres.



Zhi Ning Chen NUS

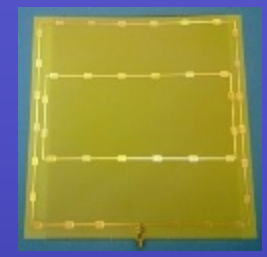
Antenna R&D&C

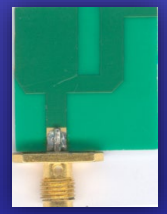


Mobile

WLAN&WiFi

RFID





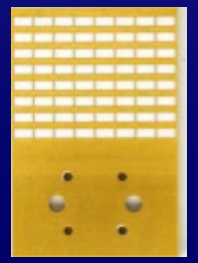
UWB

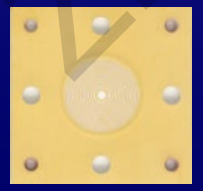
Technologies
- Substrate-integrated
- Metamaterials-based
- Multiple-element/Arrays

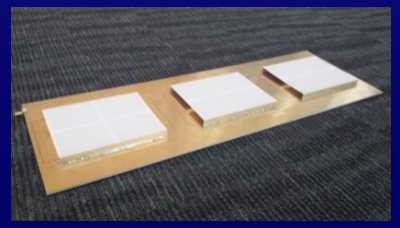
WBAN/
MICS/MRI

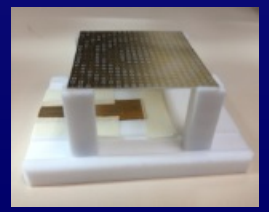
mmW/THz
24GHz-10THz

Radar
-UAV/Vehicle







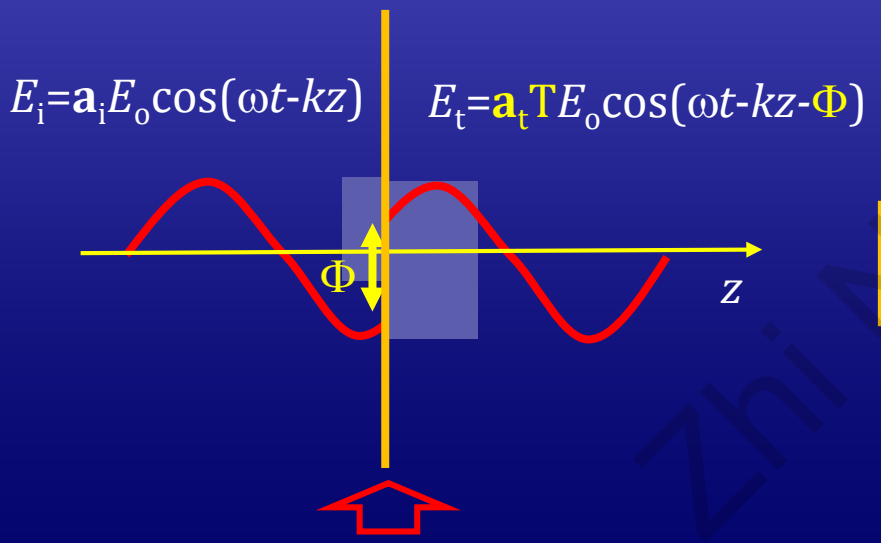


Zhi Ning Chen NUS

Metasurface:
Two-dimensional arrays of polarizable unit cells

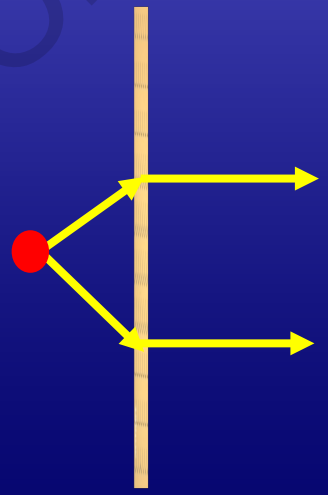
Abrupt discontinuities over electrically short distance for

1. Wavefront shaping
2. Amplitude, phase and polarization
3. Electric and magnetic field coupling



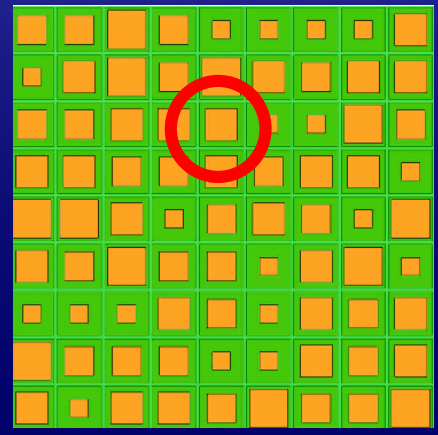
metasurface

Example: **planar lens**



Related to

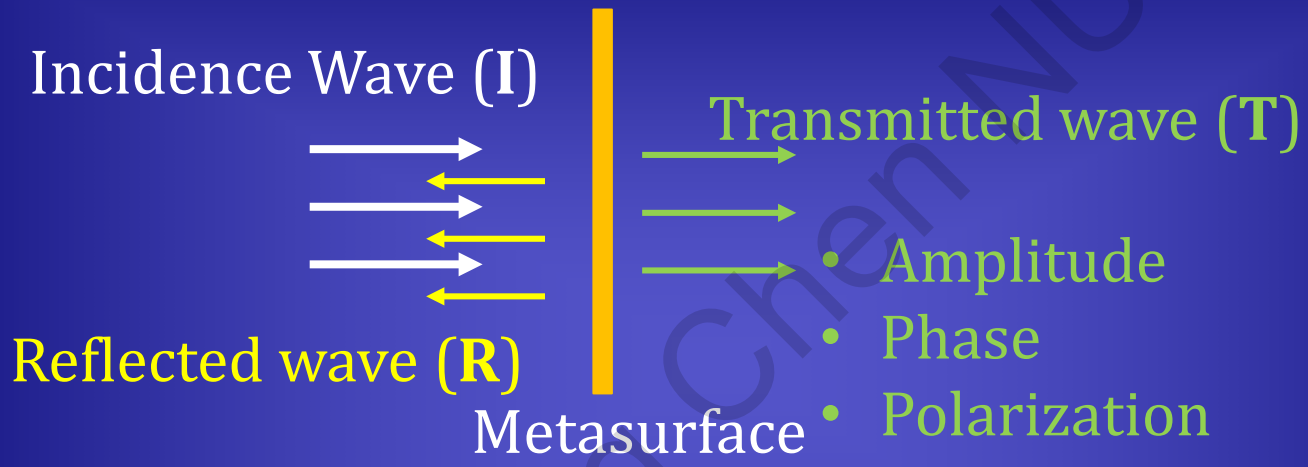
- **transmit-array**
- **reflect-array**



Zhi Ning Chen, NUS

Modeling of Metasurface with Normal Incidence Waves

$P_I = P_T + P_R + P_L$ Lossy (**L**)

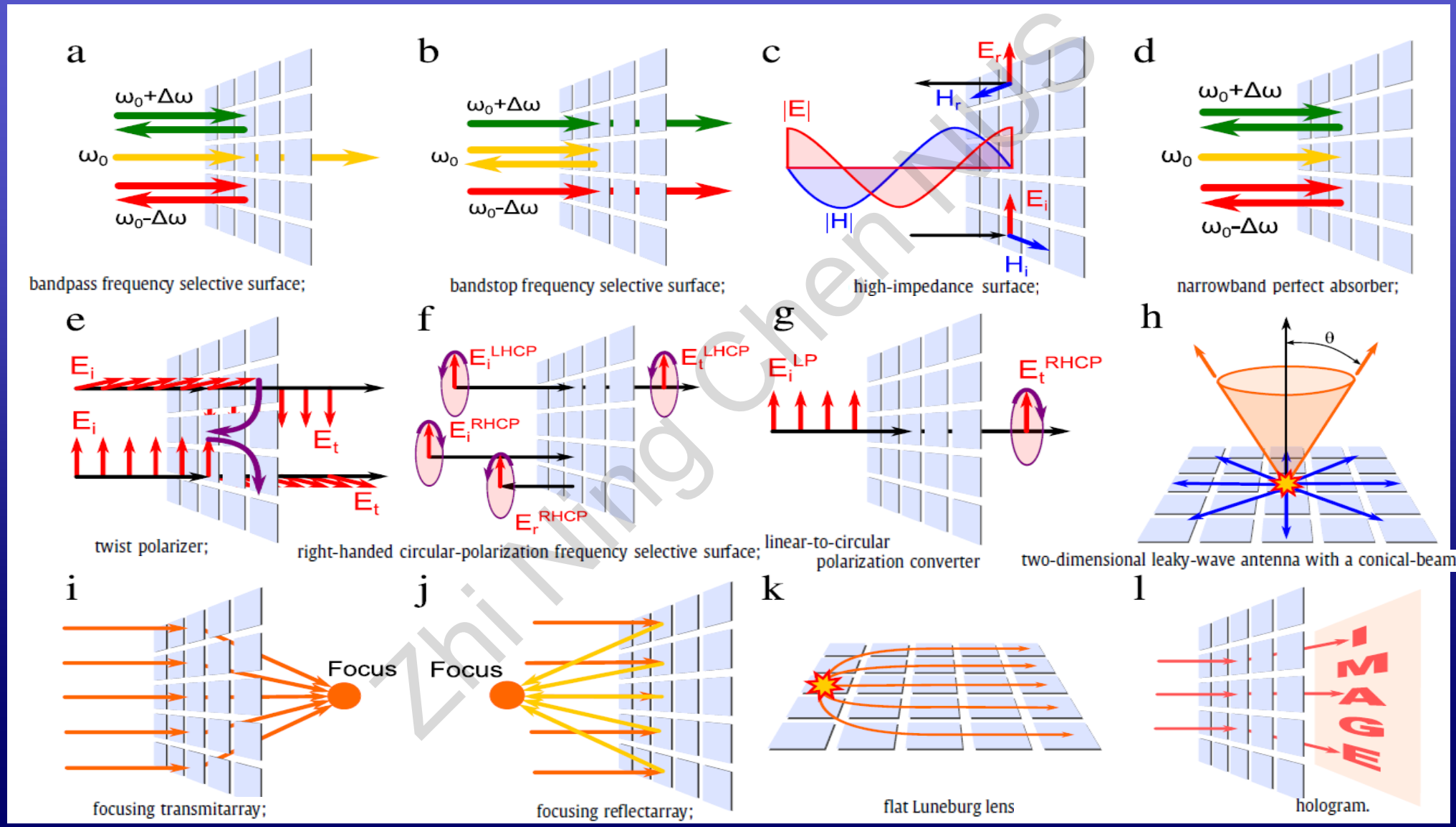


- Amplitude
- Phase
- Polarization

Easy to
- Design
- Model
- Fabricate
- Test
- Install

Zhi Ning Chen NUS

Functionalities of Metasurafces



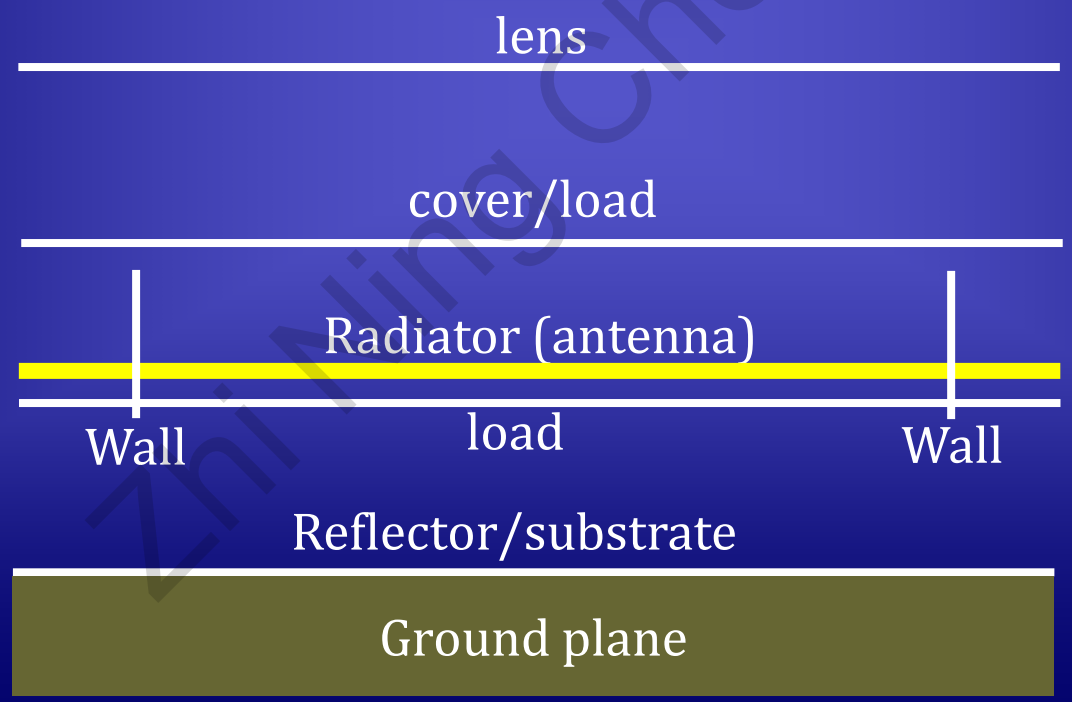
Zhi Ning Chen NUS

Stanislav B. et al., Metasurfaces: From microwaves to visible, Physics Report, Volume 634, Pages 1-72 (24 May 2016)

Microwave Metasurface Antennas: **Metantennas**

Complex Impedance Surfaces to control phase, amplitude and polarization of wave propagating thru and reflected by the metasurface

- artificial magnetic conductors (AMC)
- electromagnetic bandgap (EBG) surfaces
- High/zero/anisotropic metadielectric



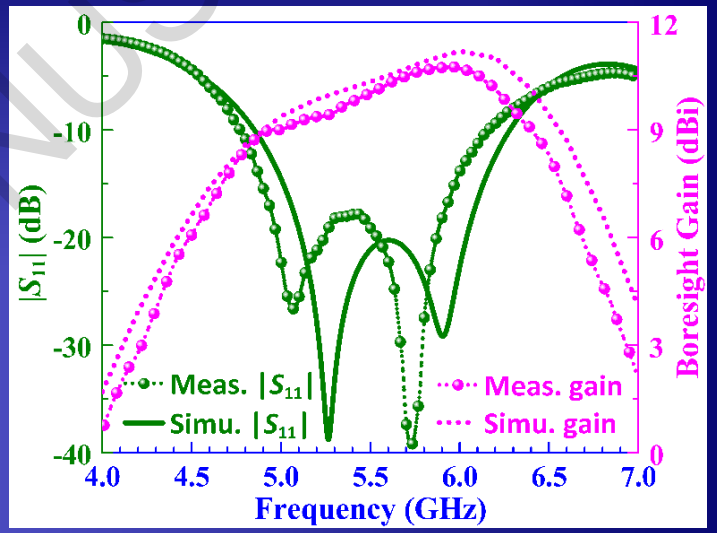
Metantennas

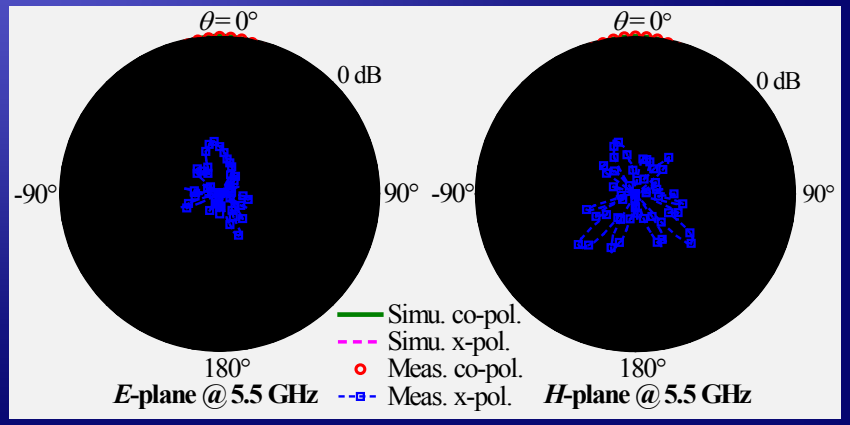
Zhi Ning Chen NUS

Metantennas: **Radiator for Low-profile Broadband**

Multiple Dipole Antennas with Improved Radiation Performance

In 2014



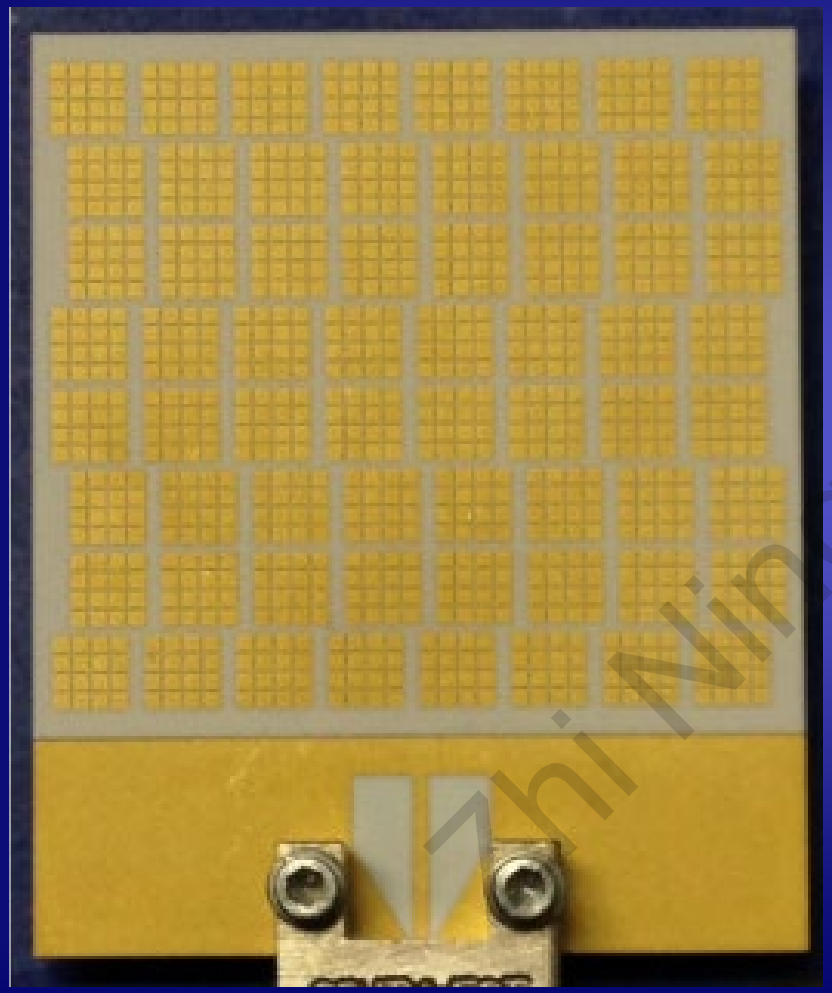


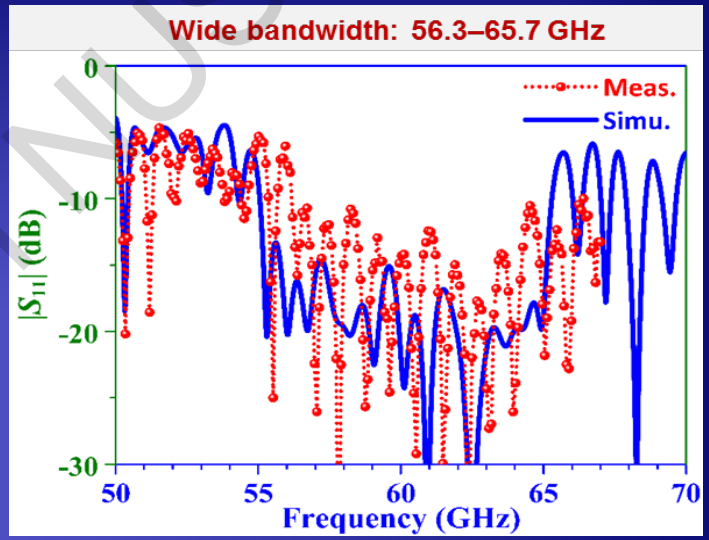
Zhi Ning Chen NUS

W Liu, Z N Chen, X Qing, "Metamaterial-based low-profile broadband mushroom antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1165–1172, Mar. 2014.

Metantennas: **Radiator for Low-profile Broadband**

Multiple Dipole Antennas with Improved Radiation Performance





Bandwidth	**57-65 GHz, 13%**
Gain Boresight	**22-24 dBi**
Impedance	50 Ω
Return loss	10 dB
Beamwidth	8° in *E*-plane, **8° in *H*-plane**
Polarization	Linear
Substrate	LTCC, Ferro A6M
Dimension	**0.7×43.8×35.4 mm³**

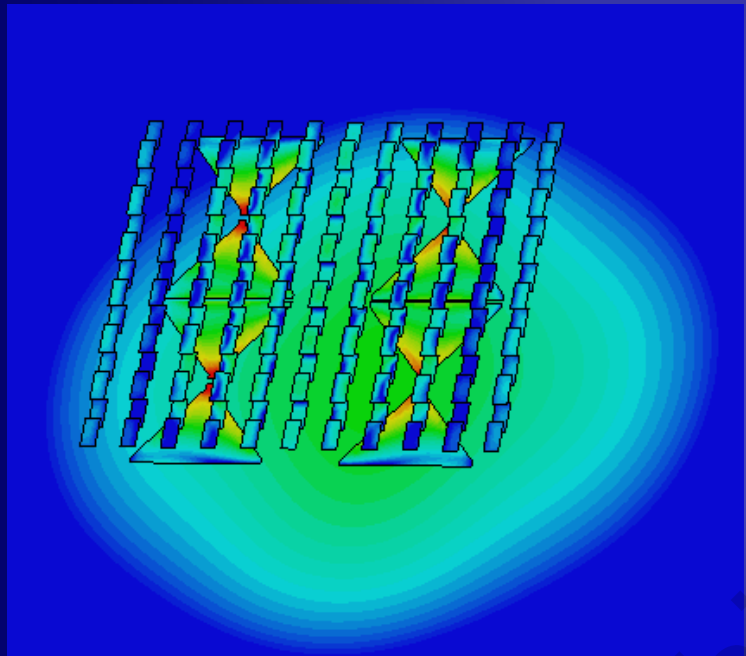
Zhi Ning Chen NUS

W Liu, Z N Chen, X Qing, "Metamaterial-based low-profile broadband mushroom antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1165–1172, Mar. 2014.

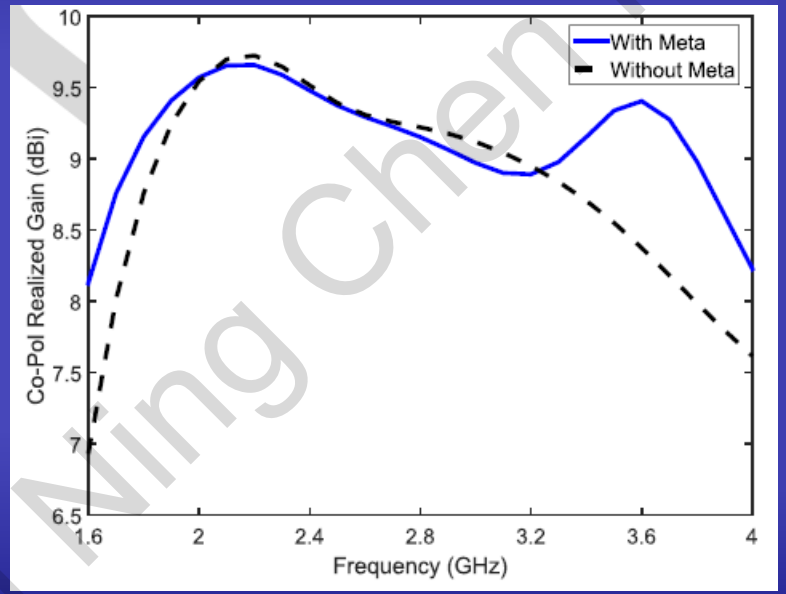
Metantennas: **Cover for High-order Mode Suppression**

Compact Dipole Array backed by Metasurface **Using CMA**

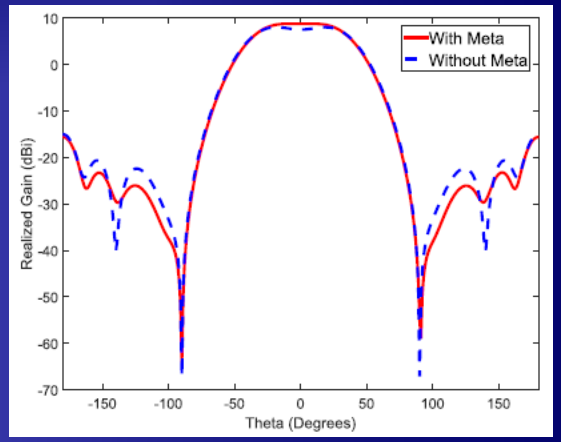
In 2017



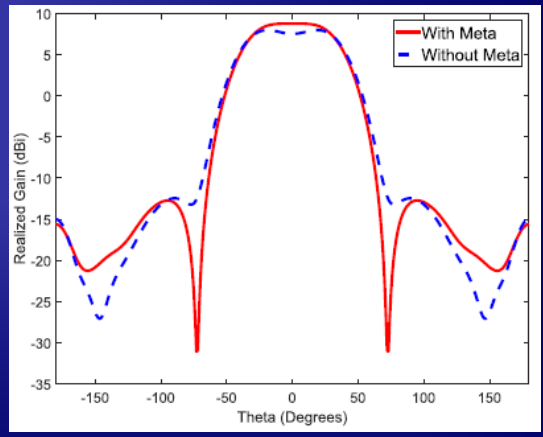
Dipole array with MTS



Broadside Gain



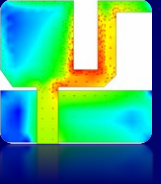
Broadside gain pattern for φ = 0° cut @2GHz



Broadside gain pattern for φ = 90° cut @2GHz

Zhi Ning Chen NUS

A. A. Salih, Z. N. Chen, and K. Mouthaan, Characteristic Mode Analysis and Metasurface- Based Suppression of Higher Order Modes of a 2×2 Closely Spaced Phased Array, IEEE Trans Antennas Propagation, Vol 65, No. 3, March 2017, pp. 1141 - 1150



MetAntennas +Characteristic Mode Analysis

Why

- Multiple complicated operating modes in metasurface antennas

What

- Release operating modes for understanding, selection and control

Challenges

- Characterization of MTSs with finite unit cells under near-field excitation

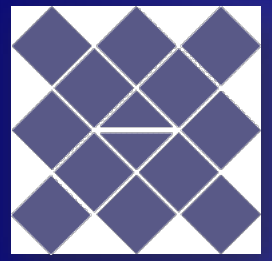
For what

- Wide bandwidth, dual-band, polarization, pattern diversity, pattern control, etc

Zhi Ning Chen NUS

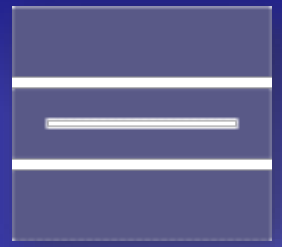
Recent Progress of MTS+CMA since 2017

Slot-fed



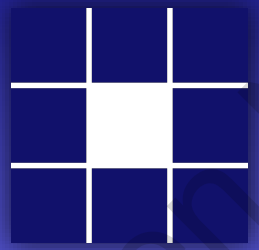
F. H. Lin
TAP, 2017

Probe-fed



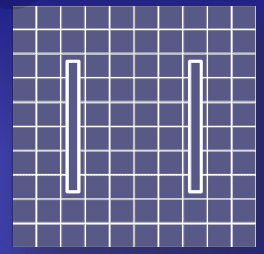
F. H. Lin
APCAP, 2017

Dipole-fed



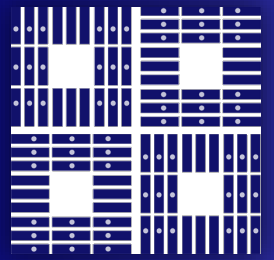
F. H. Lin
TAP, 2018

Coplanar fed



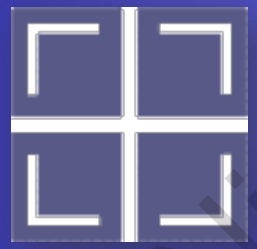
F. H. Lin
TAP, 2018

MIMO / dual-pol



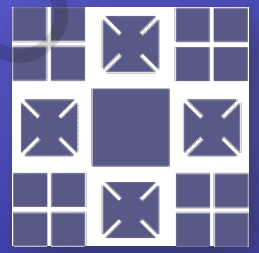
F. H. Lin
TAP, 2018

Dual-band



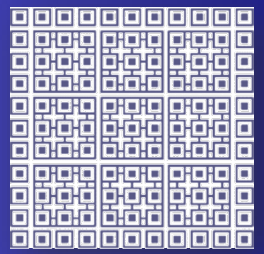
T. Li
APWC, 2018

Dual-band



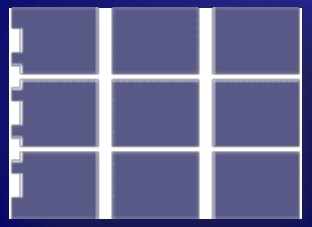
T. Li
TAP, 2018

sub6G + mmW



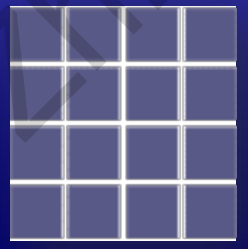
T. Li
TAP, 2018

End-fire



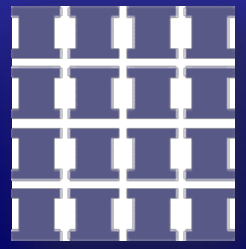
T. Li
TAP, 2018

Omni-directional



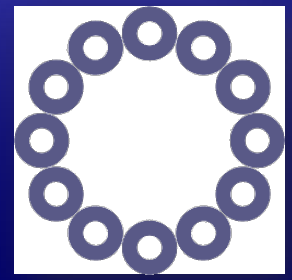
X. Yang
AWPL, 2018

CP radiation



C. Zhao
IEEE
Access, 2018

High-gain lens



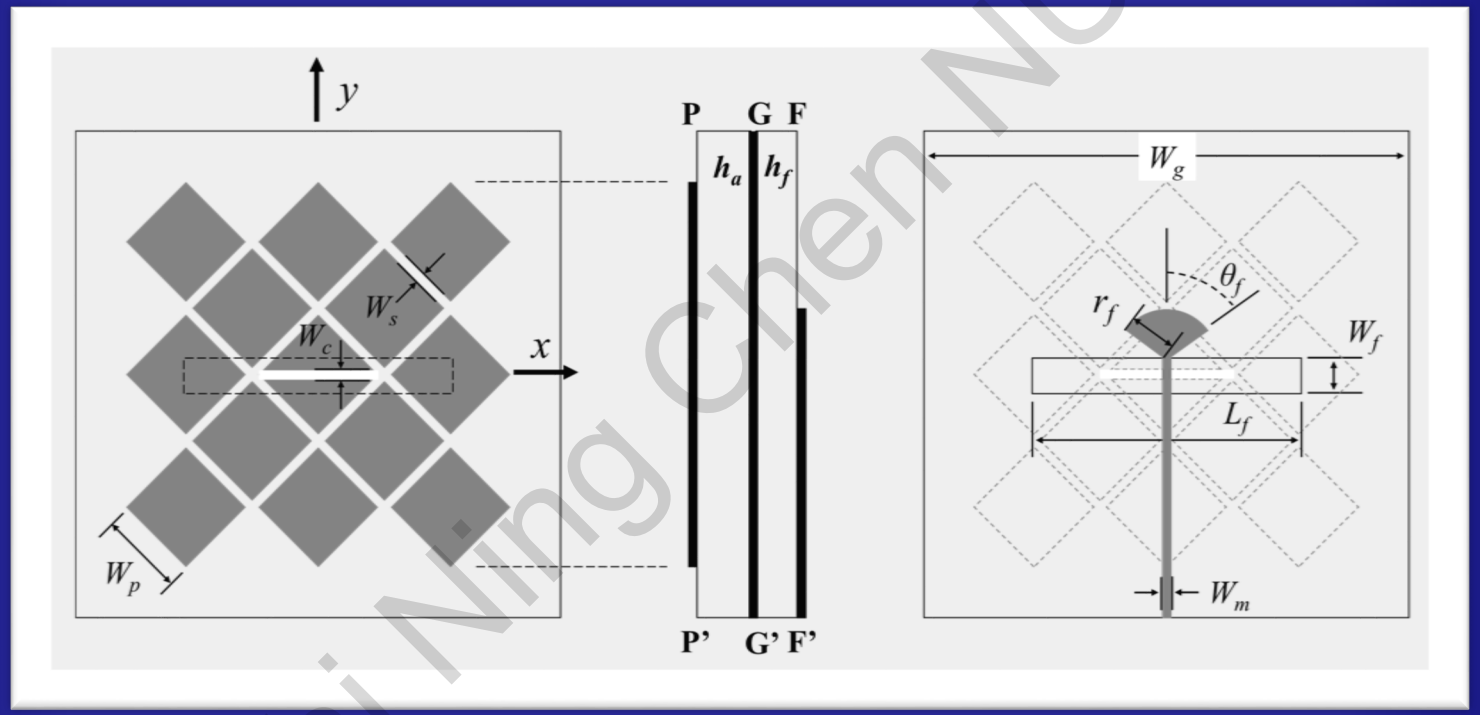
S. Daniel
IJAP, 2018

Zhi Ning Chen NUS

Low-profile Wideband MTS Antennas Using CMA

In 2017

Slot-fed MTS antenna@5GHz bands



1. First time CMA for MTS
2. For high performance: low-profile + wideband

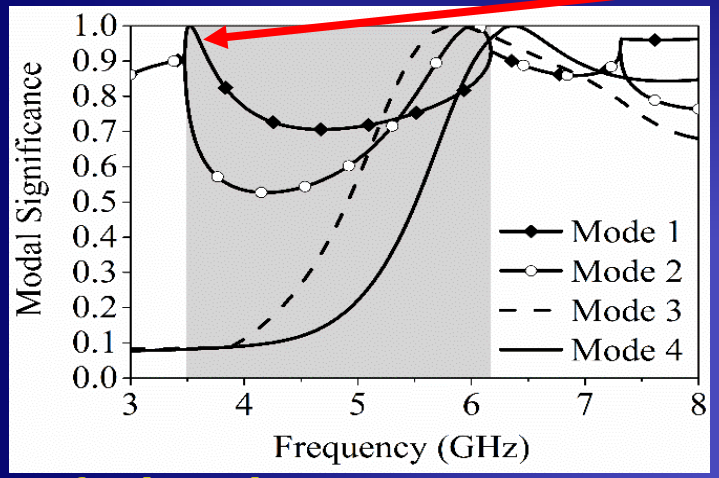
Zhi Ning Chen NUS

F. H. Lin and Z. N. Chen, *IEEE Trans AP*, 65(4), pp. 1706–1713, Apr. 2017

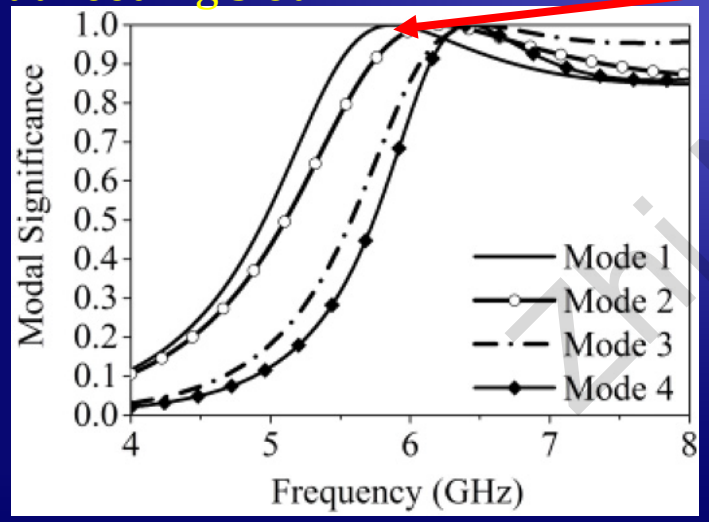
Low-profile Wideband MTS Antennas

Modal significances

with feeding slot

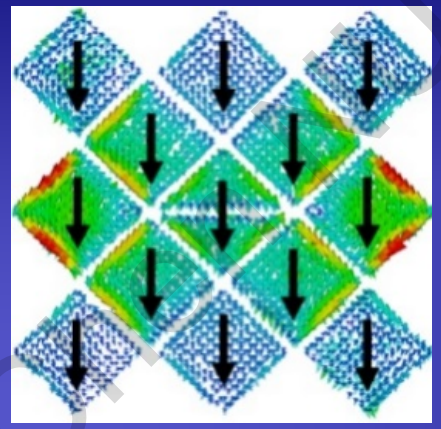


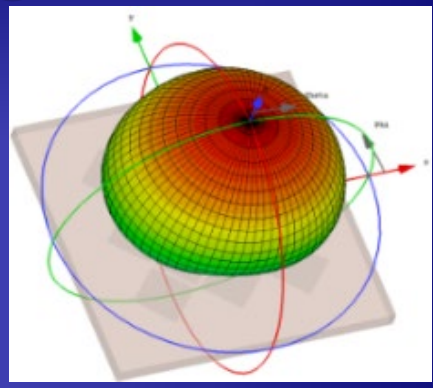
Without feeding slot



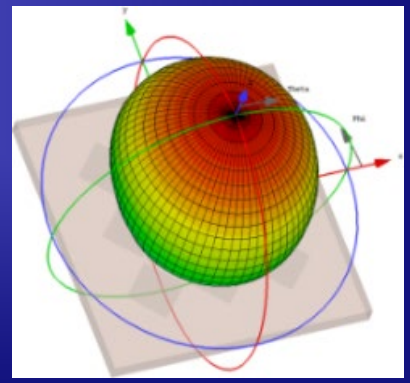
Operating Modes

slot mode by feeding slot@3.5GHz





Q-TM_{30} mode @5.9GHz



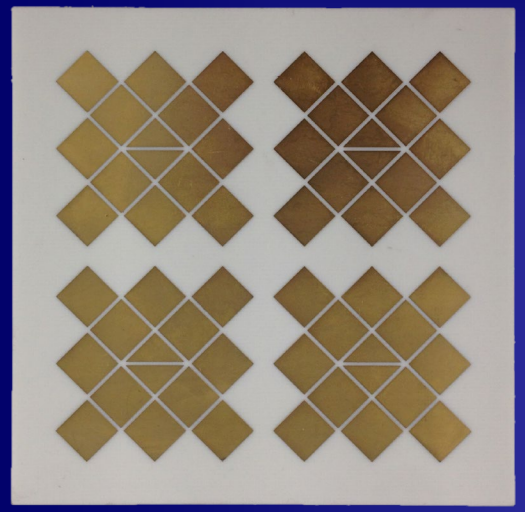
1 New physics: abnormal TM_{03} mode

2 High performance: low-profile + wideband

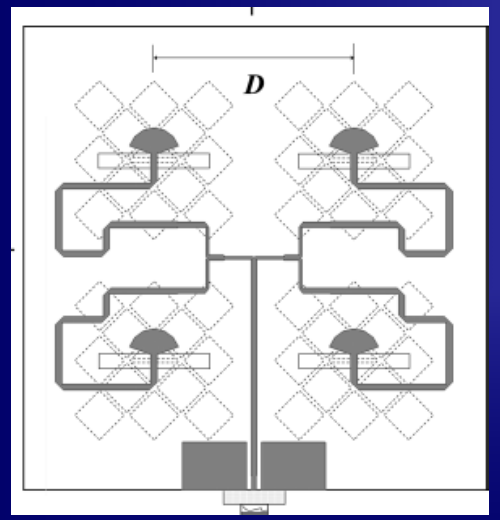
F. H. Lin and Z. N. Chen, *IEEE Trans AP*, 65(4), pp. 1706–1713, Apr. 2017

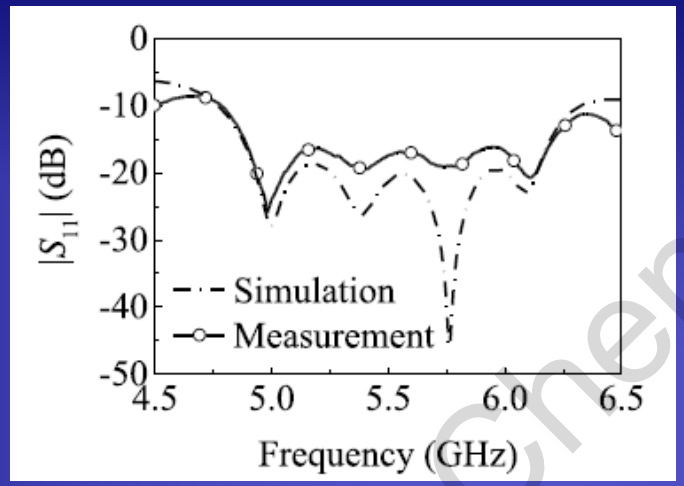
Zhi Ning Chen

Low-profile Wideband MTS Antennas Using CMA

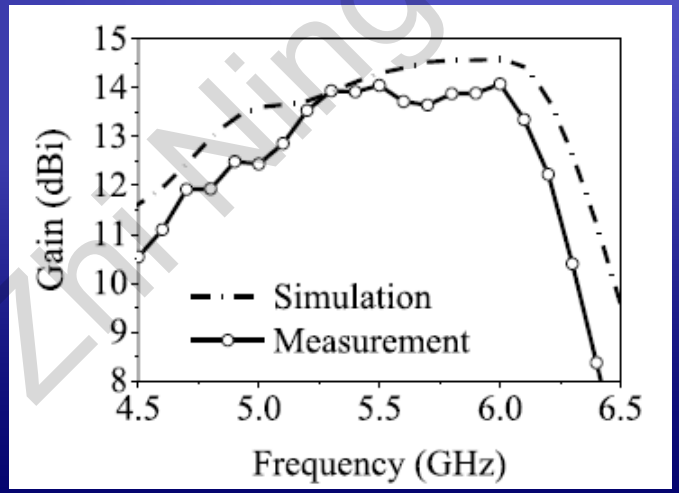


$0.7\times0.7\times0.06\ \lambda_L$

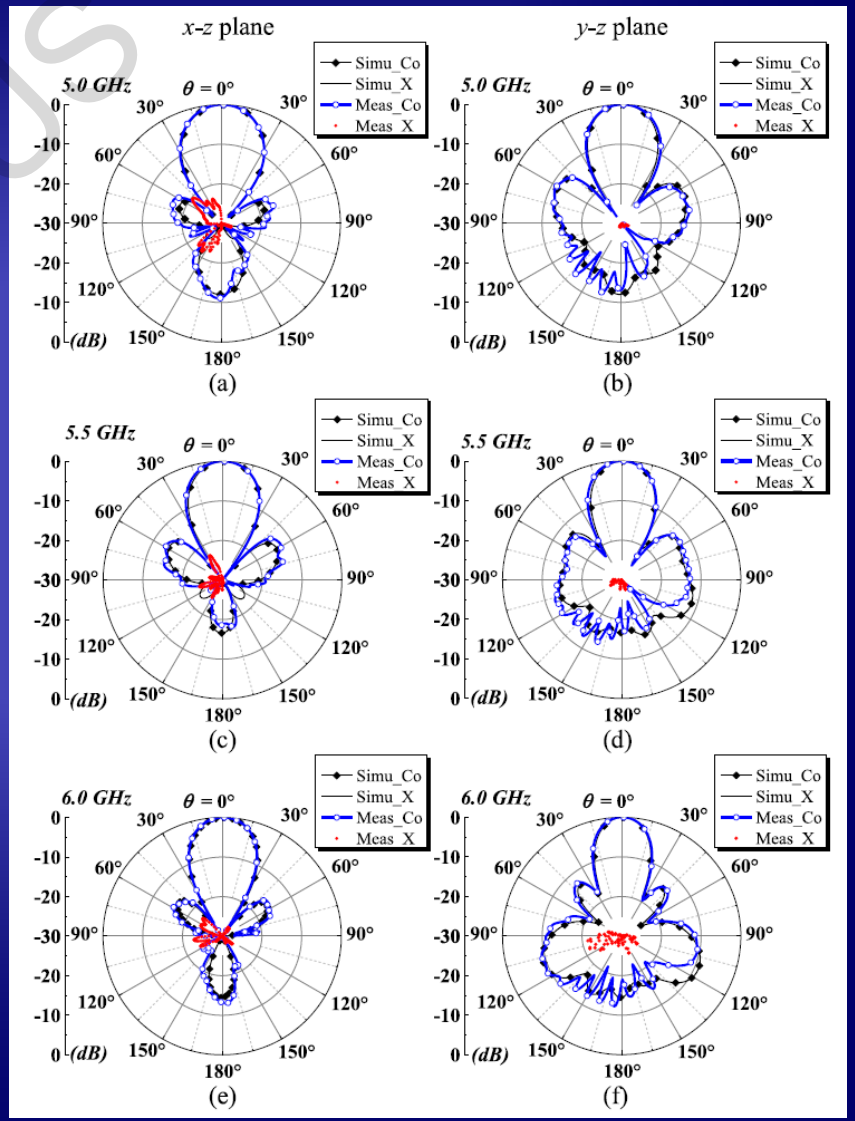




Bandwidth 31%



H-plane E-plane



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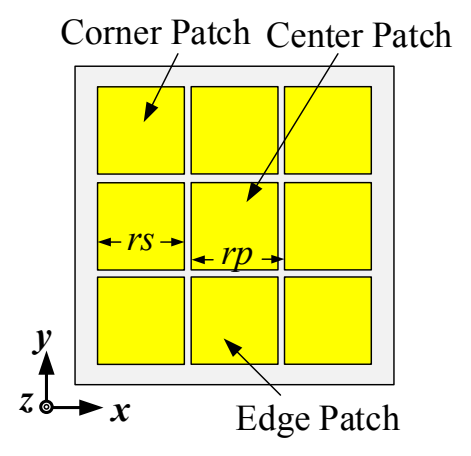
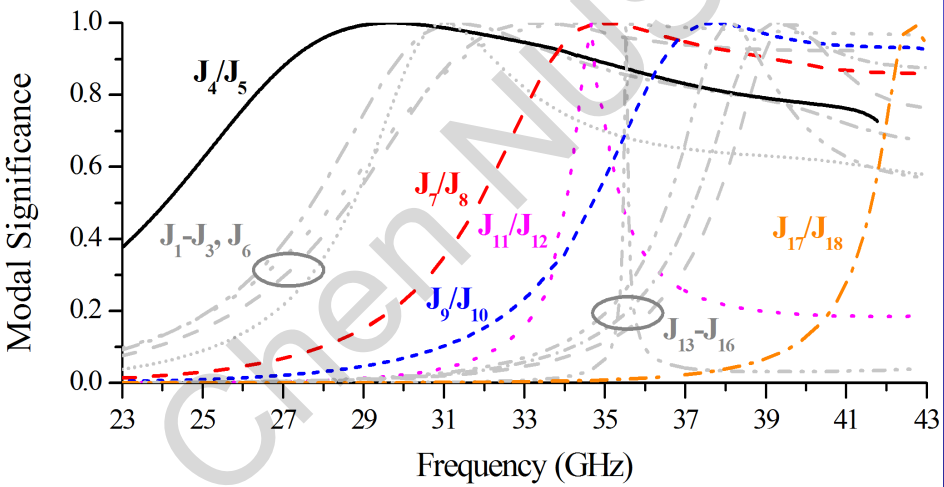
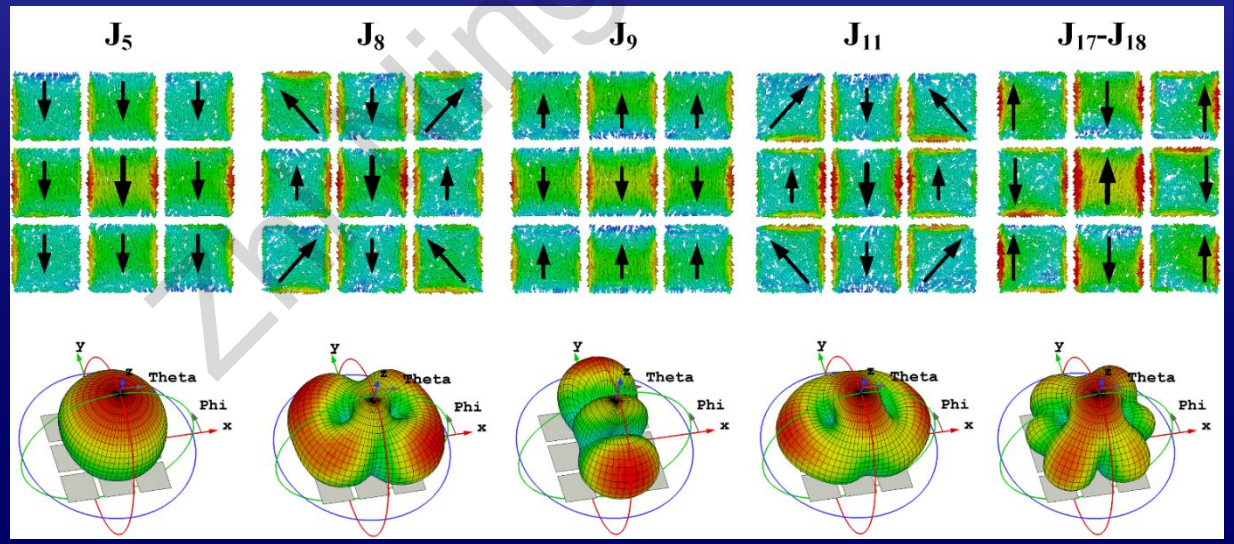
F. H. Lin and Z. N. Chen, *IEEE Trans AP*, 65(4), pp. 1706–1713, Apr. 2017

5G Dual-Band Metasurface Antenna: CMA

Evolution of the Metasurface – Conventional Uniform 3×3 Patches







Band 1: 24.25-29.5 GHz

Band 2: 37-43.5 GHz

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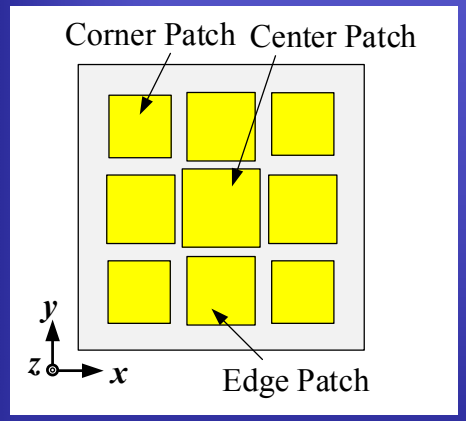
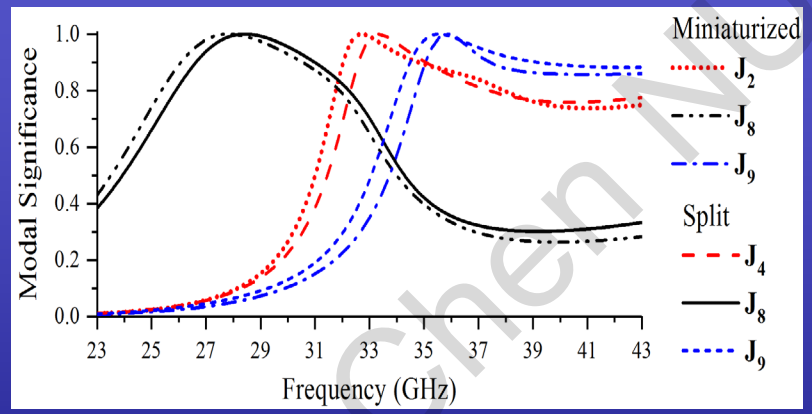
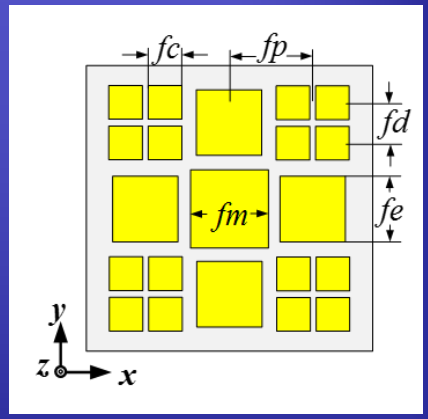
5G Dual-Band Metasurface Antenna: CMA

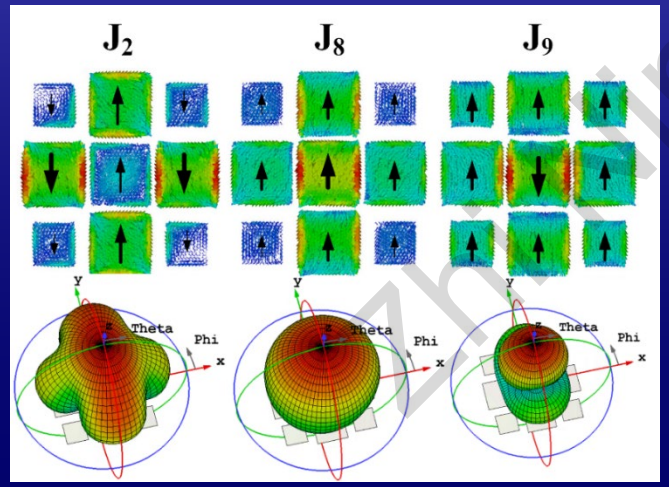
Modified Metasurface of 3×3 Patches by CMA

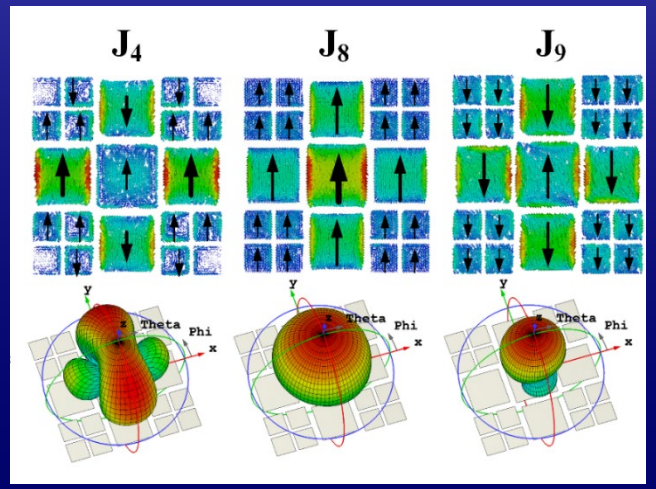






Move Modes J_2 out of the band but include J_4 in





Modes J_2 and J_4 distort the radiation patterns @ Band 2

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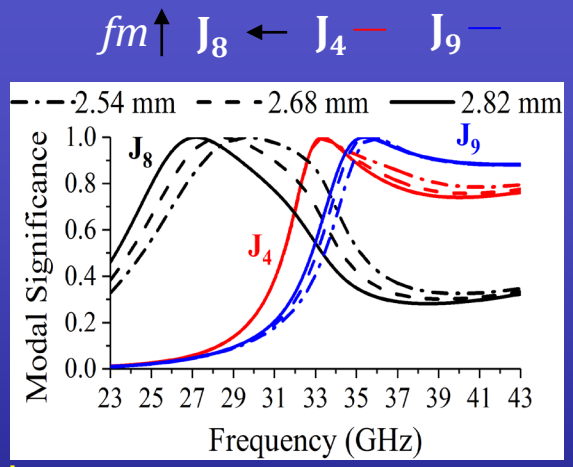
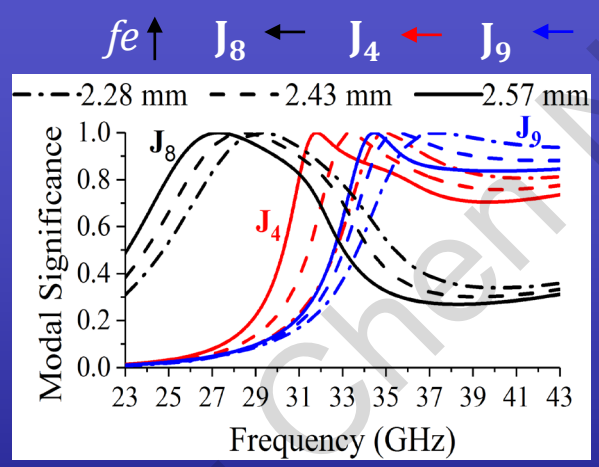
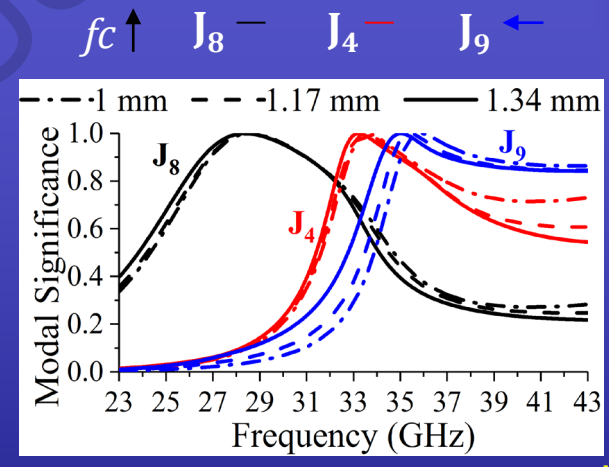
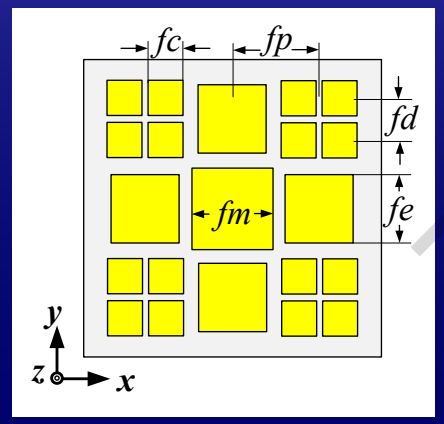
5G Dual-Band Metasurface Antenna: **Mode Control**

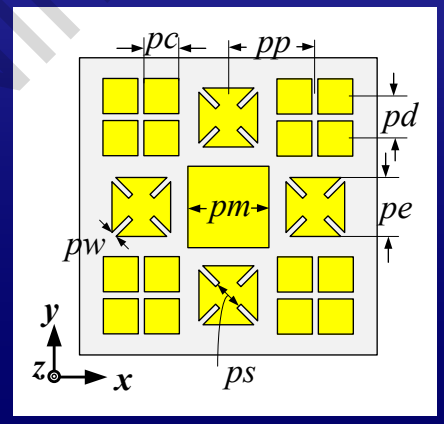
Independent Control of Selected Modes

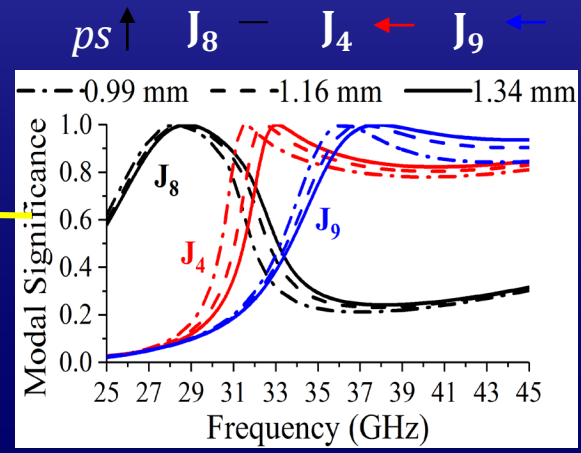












Selected Modes J_4, J_8 and J_9

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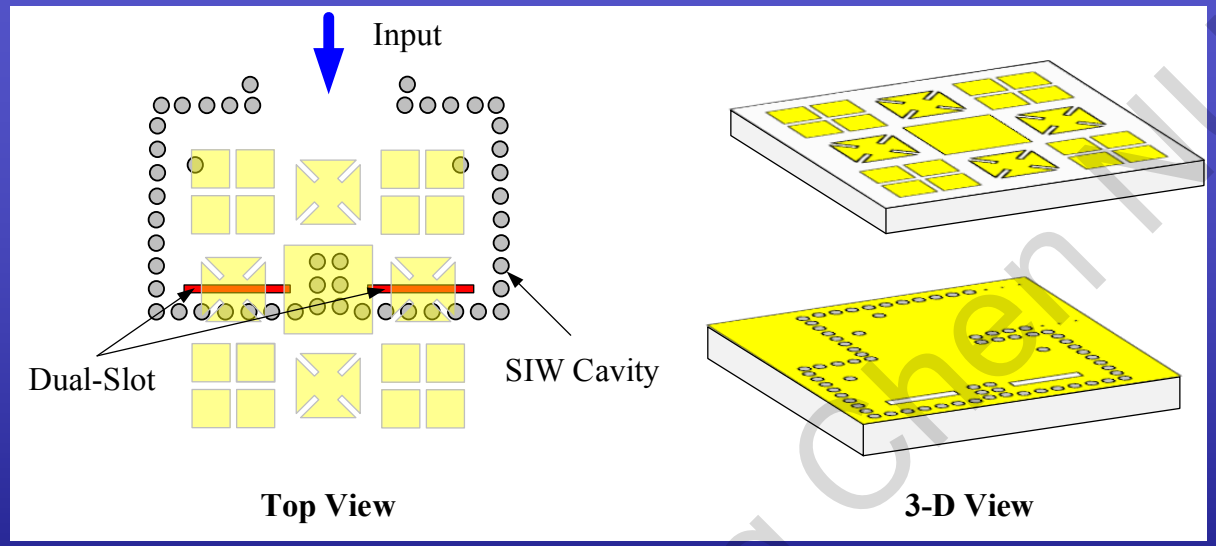
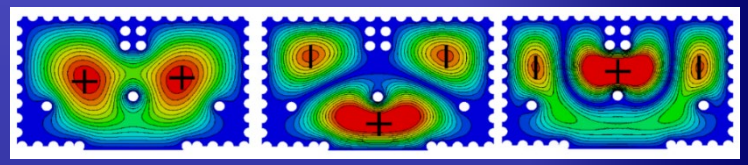
5G Dual-Band Metasurface Antenna: **Design**

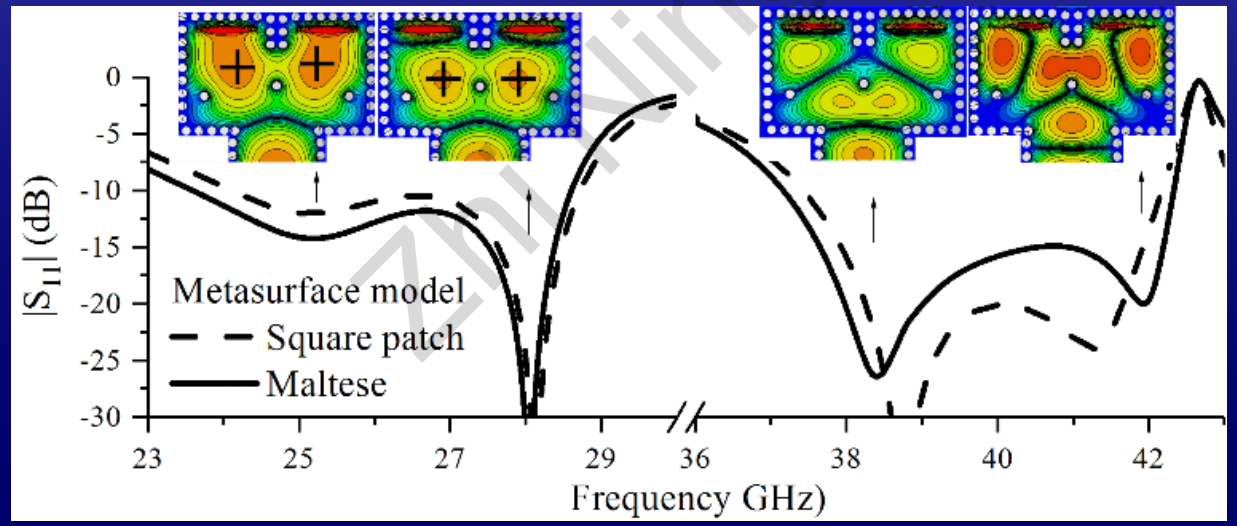
Feeding Structure – SIW-Fed Dual-Slot



Cavity Modes



25.4 GHz 35.4 GHz 41.8 GHz



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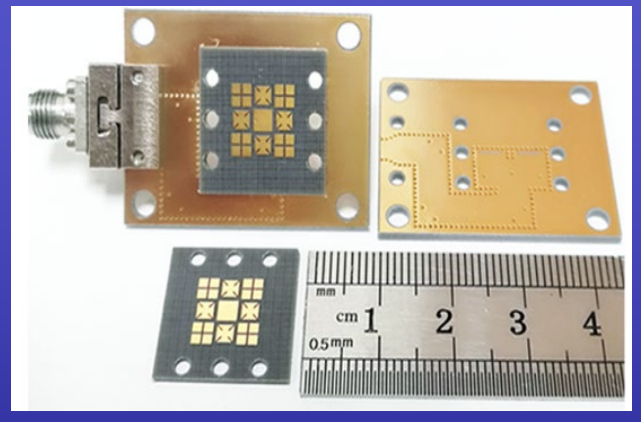
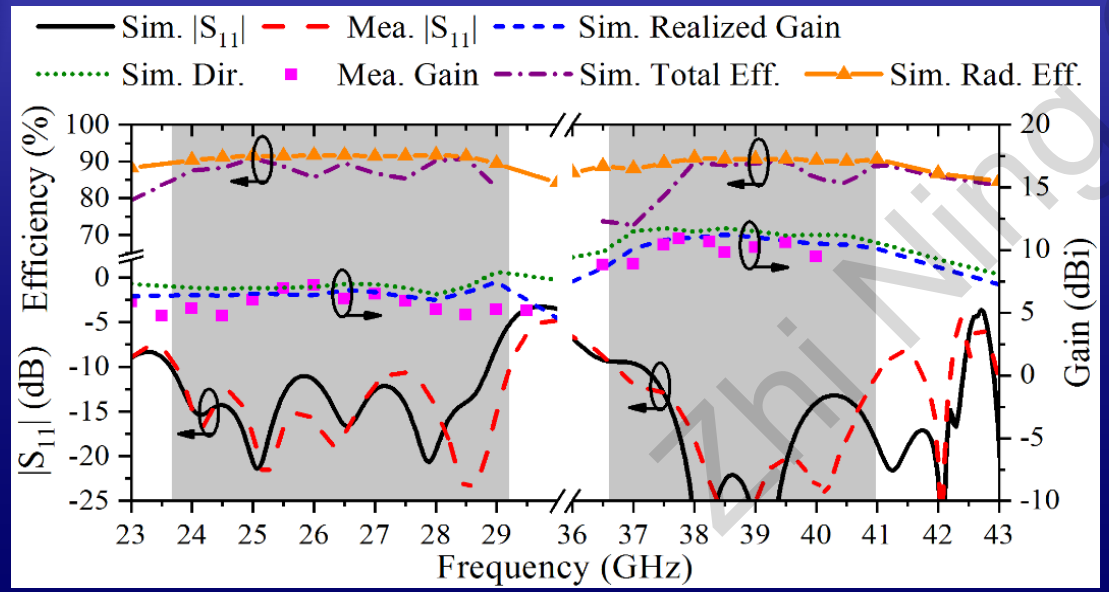
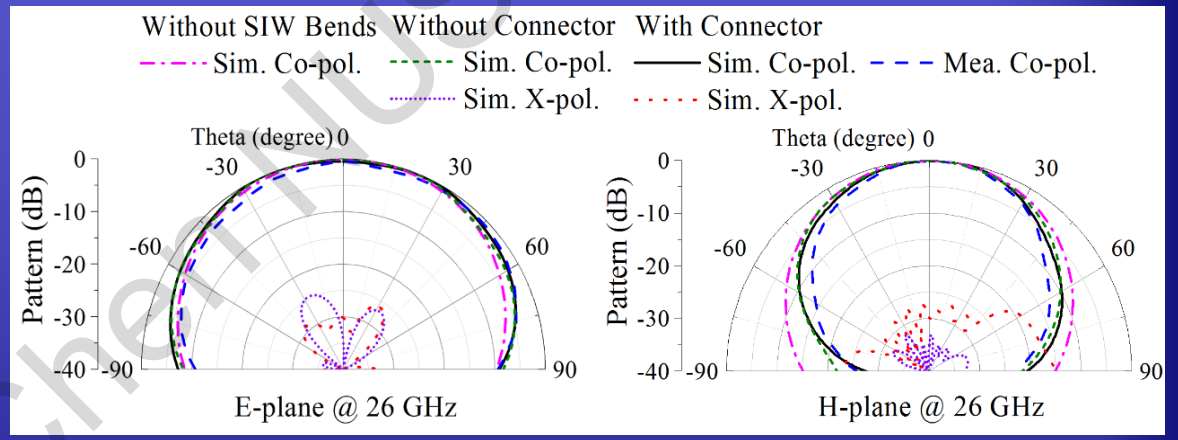
5G Dual-Band Metasurface Antenna: **Performance**

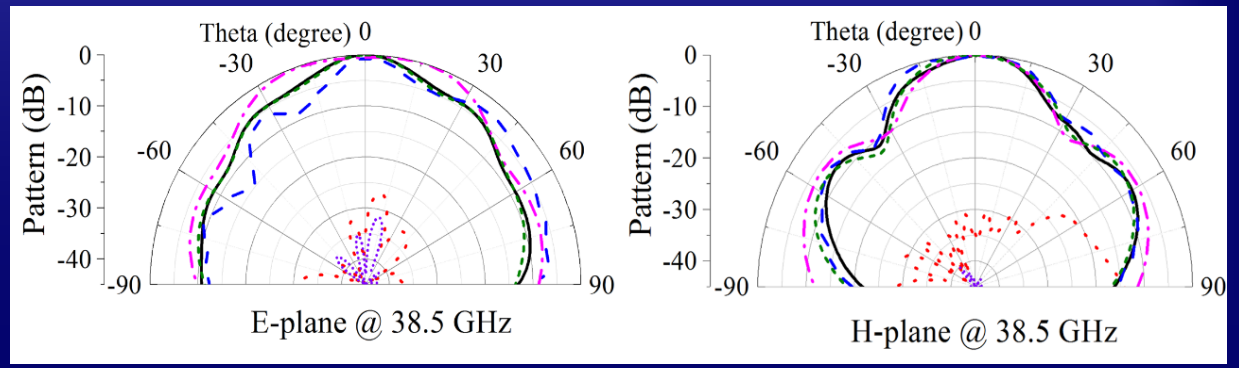
Simulations and Measurements





23.7-29.2 GHz (20.7%)
36.7-41.1 GHz (11.3%)





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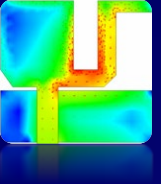

Conclusion

Metasurface+antennas→metantenna+CMA→super-antennas

PHYSICS

1. **A new perspective**: CMA of truncated MTSs and impedance sheet
2. **New insights:** finite-sized MTSs ~ multi-mode resonator
3. **New concepts:** local / global resonant MTSs (4 methods to control f_r)

ENGINEERING

4. **New framework:** powerful and systematic for analysis, design and optimize MTS antennas, arrays, multi-antenna systems
5. **New designs:** MTS antennas of significantly improved performance
6. **Simple techniques:** for challenging mode excitation, synthesis, and manipulation.

APPLICATION

7. **Industry value**: low-profile antennas, bandwidth enhancement, wideband antenna decoupling, pattern diversity, problem shooting etc.

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Relevant Publications of Metasurface – I

1. T. Li and Z. N. Chen, "Wideband substrate integrated waveguide (SIW)-fed end-fire metasurface antenna array," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 7032–7040, Dec. 2018.
2. T. Li and Z. N. Chen, "Metasurface-based shared-aperture 5G S-/K-band antenna using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 6742–6750, Dec. 2018.
3. T. Li and Z. N. Chen, "A dual-band metasurface antenna using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 66, no. 10, pp. 5620–5624, Jul. 2018.
4. F. H. Lin and Z. N. Chen, "Truncated impedance-sheet model for low-profile broadband nonresonant-cell metasurface antennas using characteristic mode analysis," *IEEE Trans. Antennas. Propag.*, vol. 66, no. 10, pp. 5043-5051, Jul. 2018.
5. T. Li and Z. N. Chen, "Control of beam direction for substrate-integrated waveguide slot array antenna using metasurface," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2862–2869, Jun. 2018.
6. F. H. Lin and Z. N. Chen, "A method of suppressing higher-order modes for improving radiation performance of metasurface multiport antennas using characteristic mode analysis," *IEEE Trans. Antennas. Propag.*, vol. 66, no4., pp. 1894-1902, Apr. 2018. (ESI Highly Cited)
7. S. S. S. Nasser, W. Liu, Z. N. Chen, "Wide bandwidth and enhanced gain of a low-profile dipole antenna achieved by integrated suspended metasurface," *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1540–1544, Mar. 2018.
8. W. E. I. Liu, Z. N. Chen, X. Qing, J. Shi, F. H. Lin, "Miniaturized wideband metasurface antennas," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 7345–7349, Dec. 2017.
9. F. H. Lin and Z. N. Chen, "Low-profile wideband metasurface antennas using characteristic mode analysis," *IEEE Trans. Antennas. Propag.*, vol. 65, no. 4, pp. 1706-1713, Apr. 2017. (CST University Publication Award 2017, ESI Highly Cited Paper)
10. W. Liu, Z. N. Chen, X. Qing, "Metamaterial-based low-profile broadband aperture coupled grid-slotted patch antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 3244–3248, Jul. 2015.
11. W. Liu, Z. N. Chen, X. Qing, "60-GHz thin broadband high-gain LTCC metamaterial-mushroom antenna array," *IEEE Trans. Antennas Propag.*, vol. 62, no. 9, pp. 4592–4601, Sep. 2014. (CST University Publication Award 2015)
12. W. Liu, Z. N. Chen, X. Qing, "Metamaterial-based low-profile broadband mushroom antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1165–1172, Mar. 2014.

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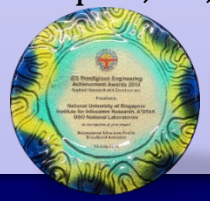
Relevant Publications of Metasurface – II

1. W. E. I. Liu, Z. N. Chen, and X. Qing, "Wideband cavity backed metasurface antenna under multi-mode resonance," *Int. Symp. Antennas Propag. (ISAP)*, Busan, South Korea, Oct 23–26, 2018, pp. 1–2.
2. T. Li and Z. N. Chen, "Design of dual-band metasurface antenna array using characteristic mode analysis (CMA) for 5G millimeter-wave applications," *Proc. IEEE Antennas Propag. Wireless Commun. (APWC)*, Cartagena des Indias, Colombia, pp. 721–724, Sep. 2018.
3. T. Li and Z. N. Chen, "Design of dual-band metasurface antenna," *Proc. IEEE Int. Workshop on Antenna Tech. (iWAT)*, Nanjing, China, pp. 1–3, 2018. . (Best Poster Paper Award)
4. F. H. Lin and Z. N. Chen, "Probe-Fed Broadband Low-Profile Metasurface Antennas using Characteristic Mode Analysis", *2017 IEEE 6th Aisa-Pacific Conf. Antennas Propagt. (APCAP 2017)*, Xi'an, China, Oct. 2017, pp. 664–666.
5. W. E. I. Liu, Z. N. Chen, X. Qing, "Compact, wideband and circularly polarized metasurface-based phased array at Ka-band," *IEEE-APS Tropical Conf. Antennas Propag. Wirel. Comm. (APWC)*, Verona, Italy, Sept. 11–15, 2017, pp. 17–21.
6. T. Li and Z. N. Chen, "Miniaturized metasurface unit cell for microwave metalens antennas," *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Verona, Italy, pp. 980–983, Sep. 2017.
7. W. Liu, Z. N. Chen, X. Qing, "Mode analysis and experimental verification of shorting-wall loaded mushroom antenna," *Asia-Pacific Microw. Conf. (APMC)*, New Delhi, India, Dec. 5–9, 2016, pp. 1–4.
8. W. Liu, Z. N. Chen, X. Qing, "Miniaturized broadband metasurface antenna using stepped impedance resonators," *IEEE Asia-Pacific Conf. Antennas Propag. (APCAP)*, Kaohsiung, Taiwan, Jul. 26–29, 2016, pp. 365–366.
9. F. H. Lin and Z. N. Chen, "A Metamaterial-Based Broadband Circularly Polarized Aperture-Fed Grid-slotted Patch Antenna", *2015 IEEE 4th Asia-Pacific Conf. on Antennas Propag. (APCAP 2015)*, Kuta, Indonesia, Jun. 2015, pp. 353–354. (Student Paper Award)
10. W. Liu, X. Qing, Z. N. Chen, "Metamaterial-based wideband shorting-wall loaded mushroom array antenna," *European Conf. Antennas Propag. (EuCAP)*, Lisbon, Portugal, Apr. 12–17, 2015, pp. 1–4.
11. W. Liu, Z. N. Chen, X. Qing, "Stripline aperture coupled metamaterial mushroom antenna with increased front-to-back ratio," *IEEE Int. Symp. Antennas Propag. (APS/URSI)*, Memphis, TN, USA, Jul. 6–12, 2014, pp. 444–445.



The Institution of Engineers Singapore (IES) Prestigious Engineering Achievement Awards 2014

for Applied Research and Development of "Metamaterial ultra-low-profile broadband antennas" by teams from National University of Singapore and Institute for Infocomm Research, Singapore.

https://www.ies.org.sg/ccms.r?pageid=10113&TenID=IES

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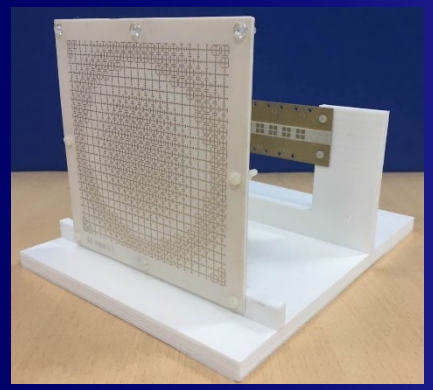
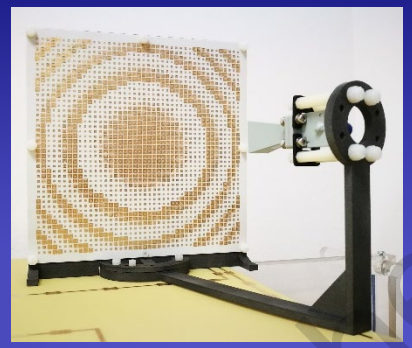
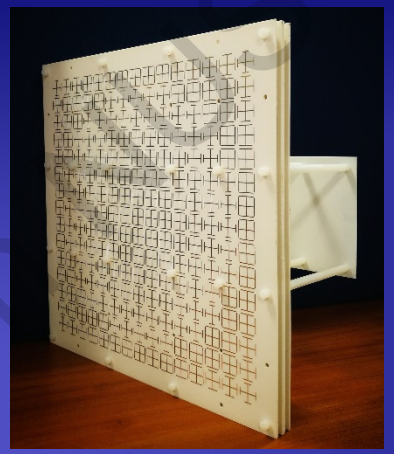
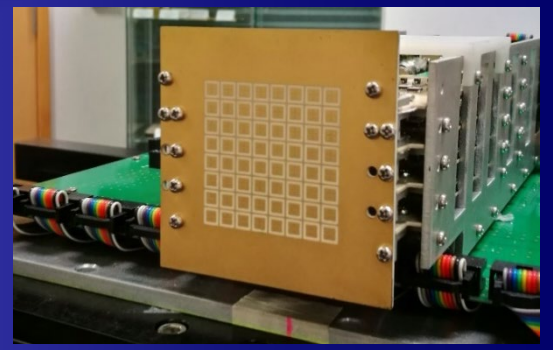
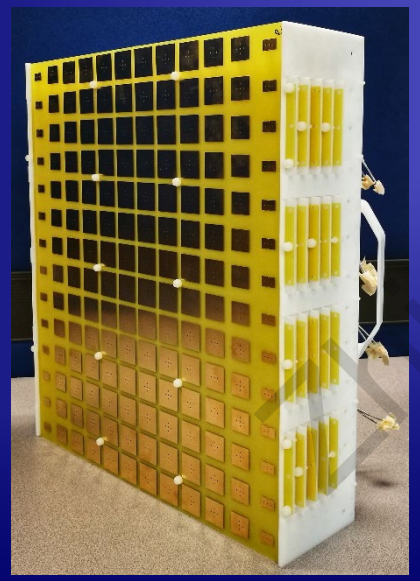
Selected Recent Designs





Li Ning Chen

Marina Forum:

EM*etamaterials *from Microwave to Lightwave

on 1-4 September 2019, Singapore

IEEE International Symposium of Antennas and Propagation Society (IEEE AP-S'2021) in July 2021, Singapore

Handbook of Antenna Technologies

Editor-in-Chief: **Zhi Ning Chen** et al

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