IAS Winter School & Workshop on Advanced Concepts in Wave Physics

Coding Metamaterials and Programmable Metamaterials

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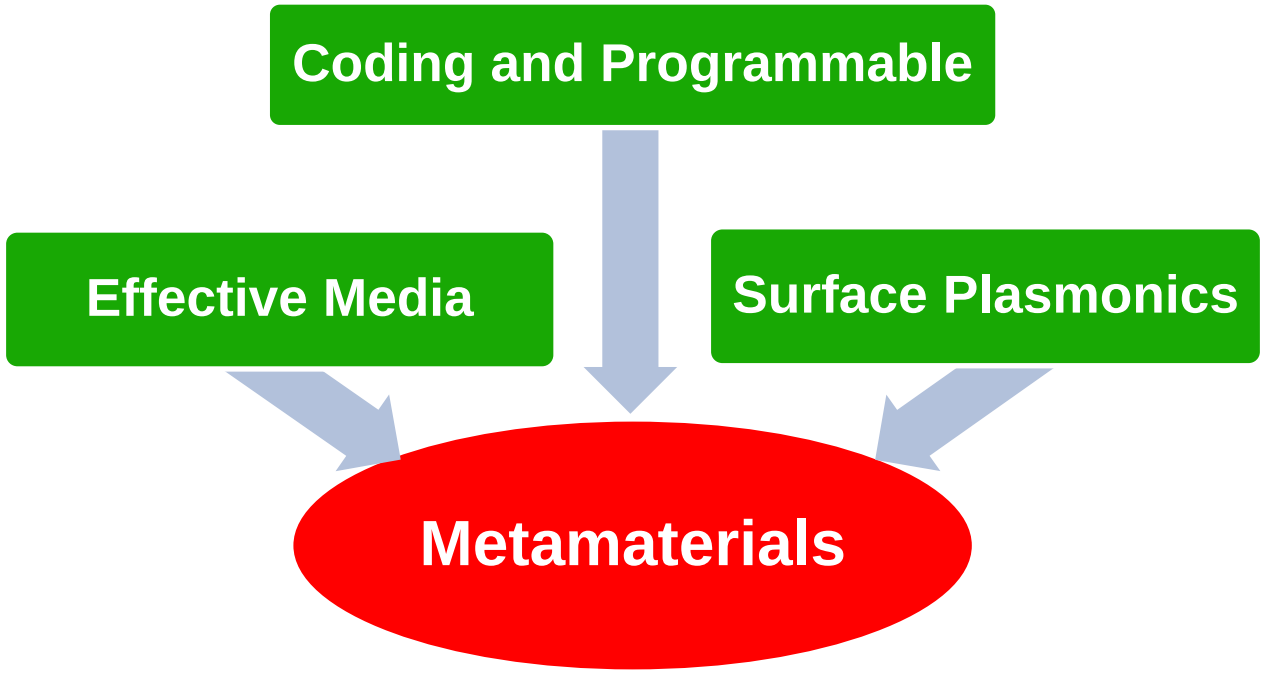
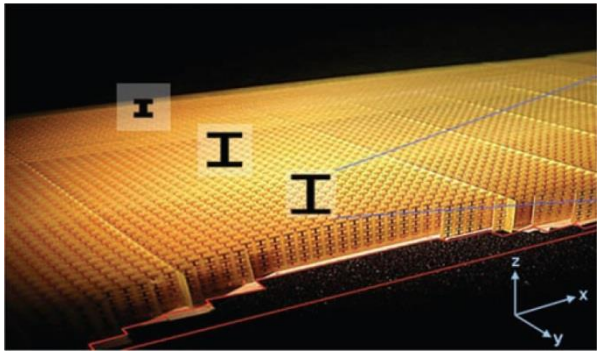
11 January 2016, Hong Kong

Metamaterials

- **Physics Community: New Physics**
- **EE Community: - Follow the Work from Physics**
  - Engineering & Applications
  - New Views from Information Science



Background: Effective Medium



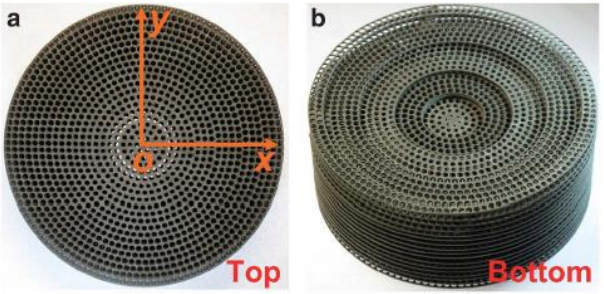
Science, 2009.

Cloaks

New Lenses

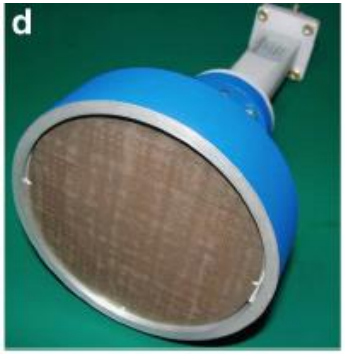
Nat. Comm., Nov. 2010.

New Physics



Nat. Comm., June 2010.

New Applications



JAP, 2011; IEEE TAP,2013.

New J. Phys., June 2010.

EM Black Hole

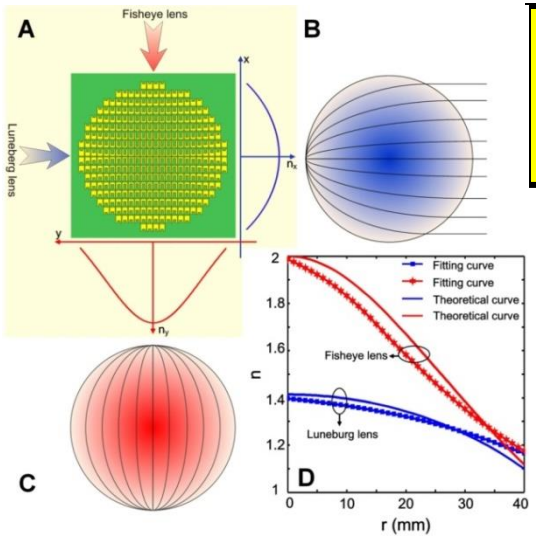
Random Metasurface

Opt. Lett. 2010.

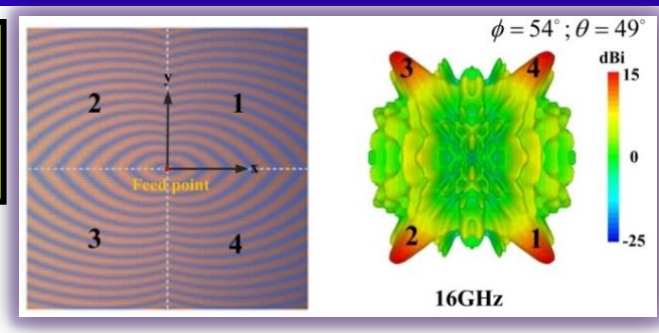
Background: Metasurfaces

Surface Waves

Spatial Waves

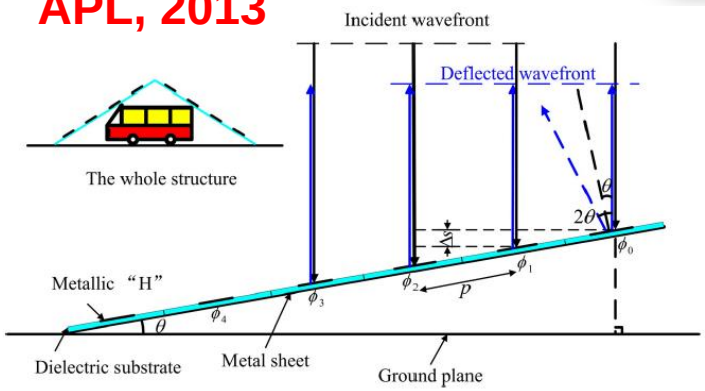


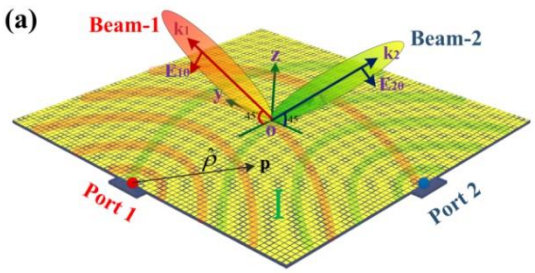
Laser Phot. Rev., 2014.



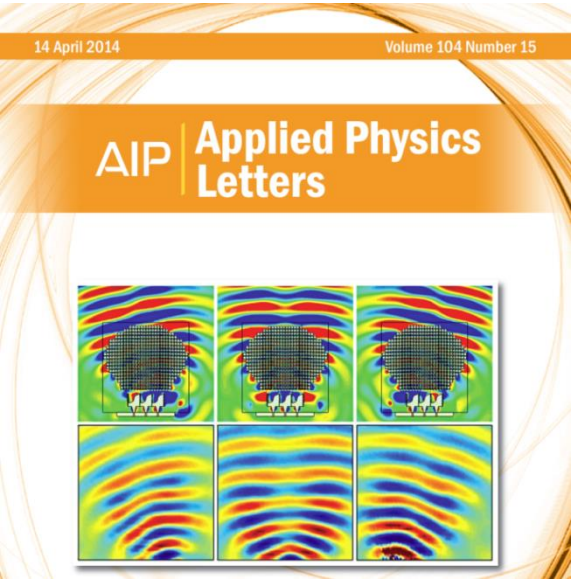
Sci. Rep., 2014.

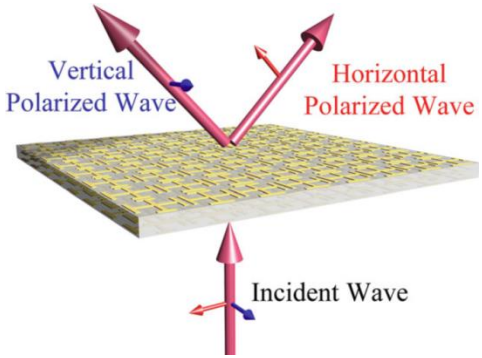
APL, 2013



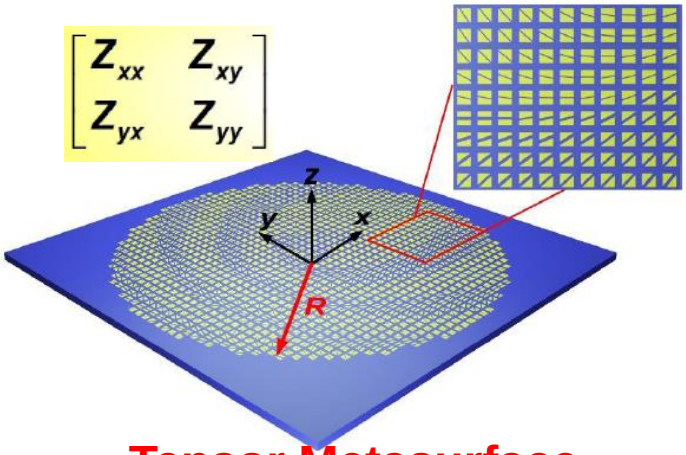


Adv. Fun. Mater., 2015.



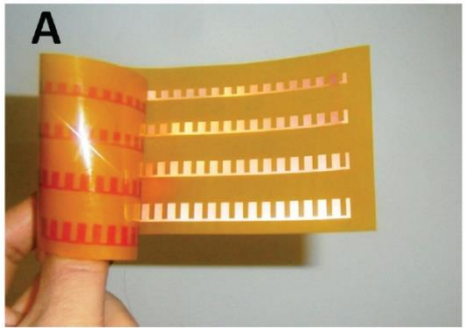


Laser Phot. Rev., 2015



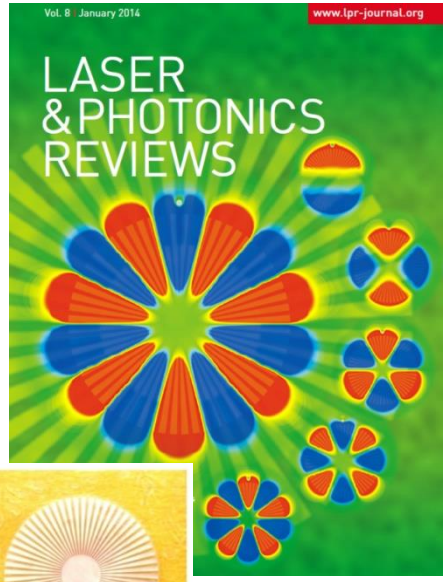
Tensor Metasurface

Background: Surface Plasmonics

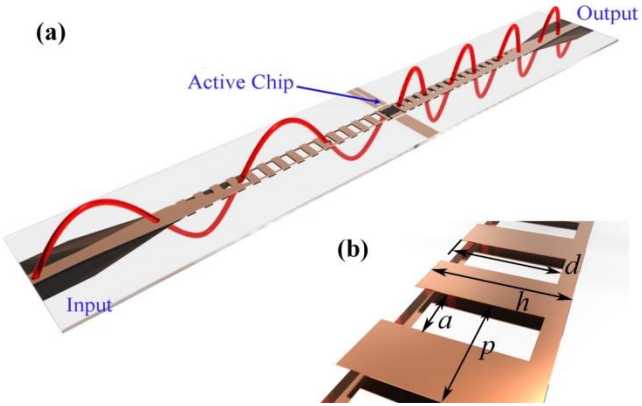


Flexible SPPs

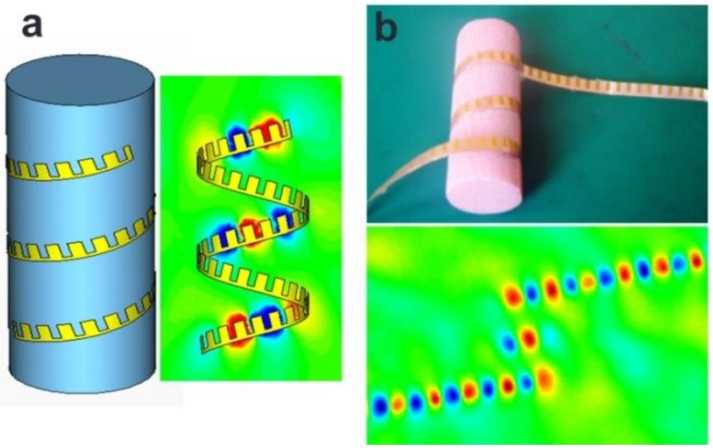
LSPs



PNAS, 2013.



ACS Photonics, 2015.

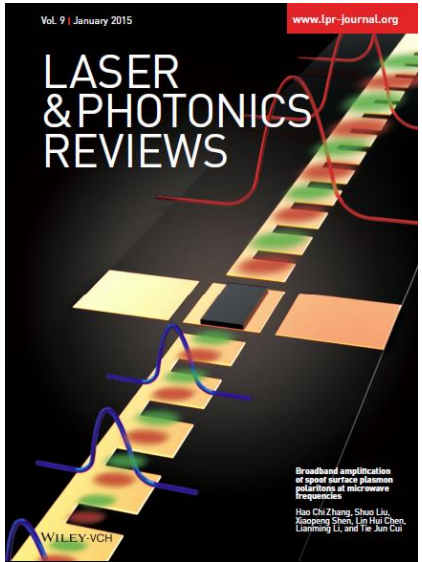


A Lot of Passive Components.

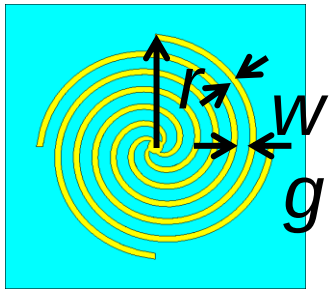
Laser Phot. Rev., 2014.

Sci. Rep., 2015

Active SPP Components:



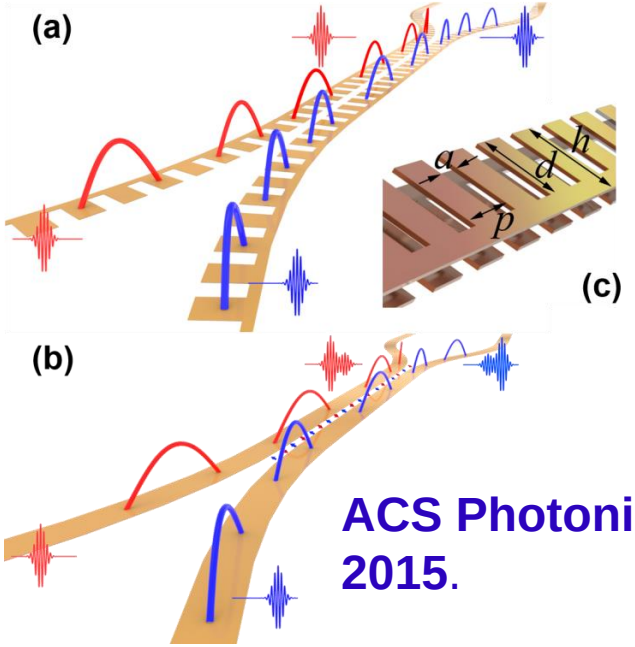
Laser Phot. Rev., 2015



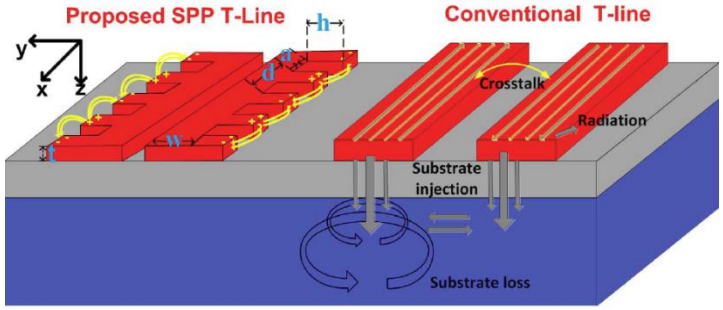
Phys. Rev. X, 2014.

Background: Surface Plasmonics

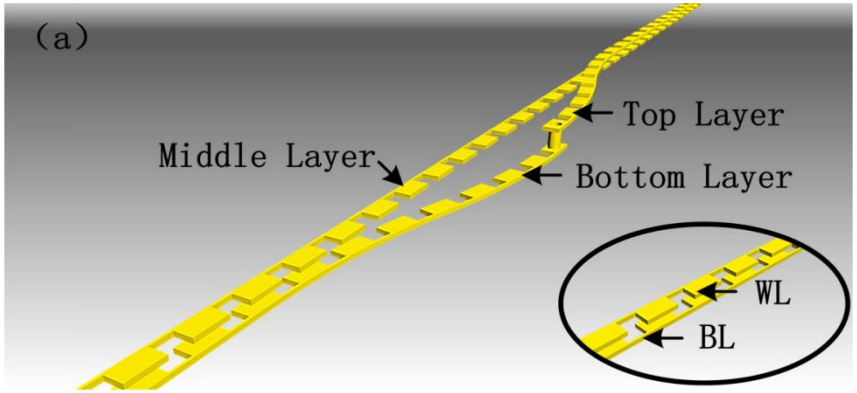
Interference Reduction



ACS Photonics 2015.

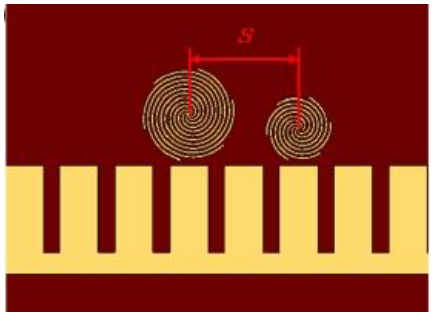


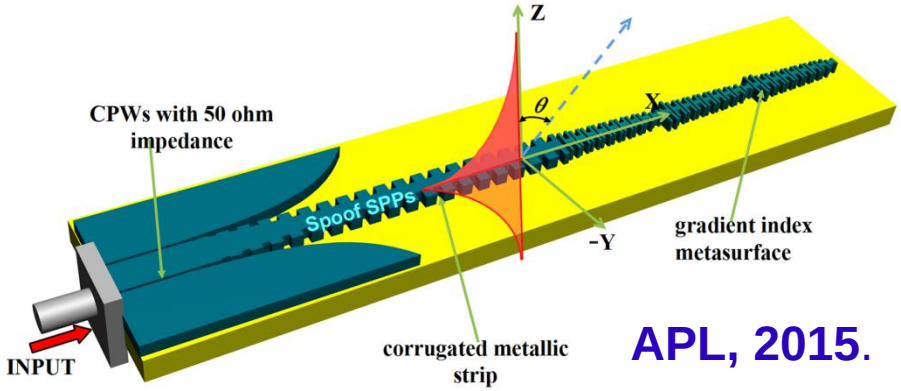
CMOS @ 220-325GHz (NTU+SEU)
Sci. Rep., 2015.



ACS Photonics 2015.

Multi-Layered Circuits





APL, 2015.

Antenna and System

Background: Our Motivation

- To make instant or real-time controls of EM waves by metamaterials
- To realize significantly switchable functionalities using a single metamaterial

Background: A Lessen from Circuit

Circuits

- Analog Circuits: Continuous currents
- Digital Circuits: People use the coding of 0 and 1 to process information.

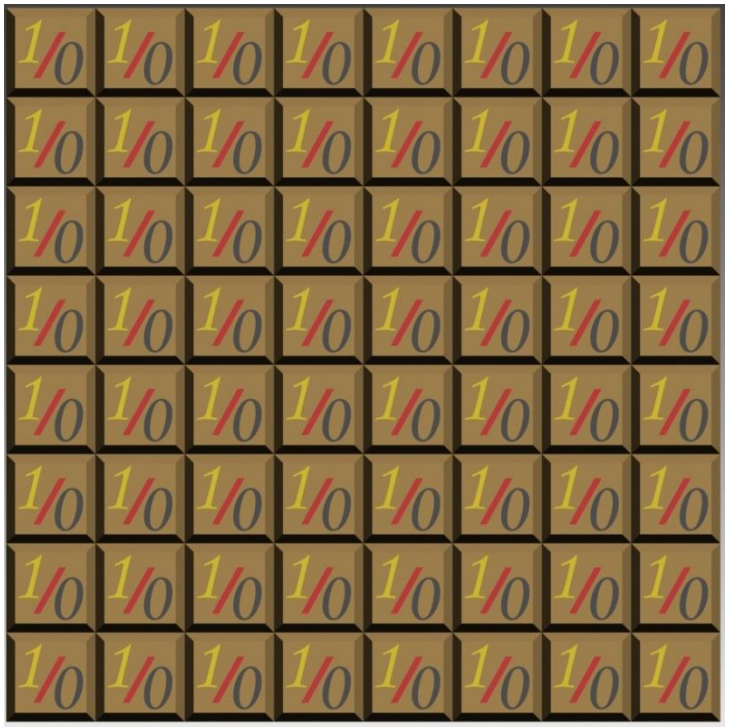
Metamaterials

- The current metamaterials are based on continuous medium parameters, which can be considered as analog metamaterials.

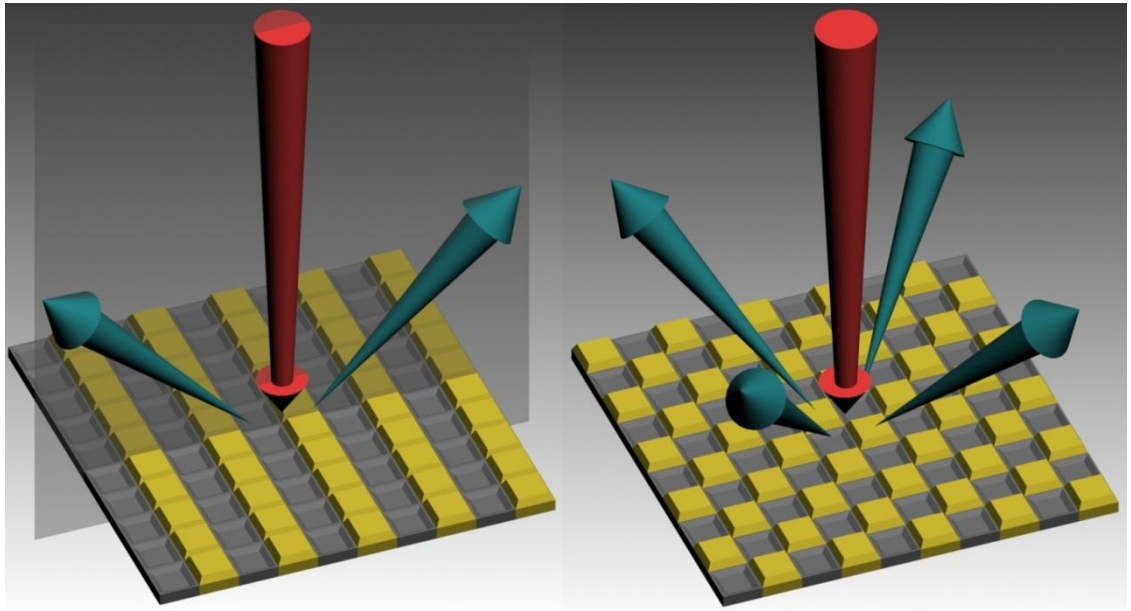
- We propose the concept of coding metamaterial, which can be further extended to programmable metamaterial.

Coding Metamaterials

1-Bit Coding Metamaterials



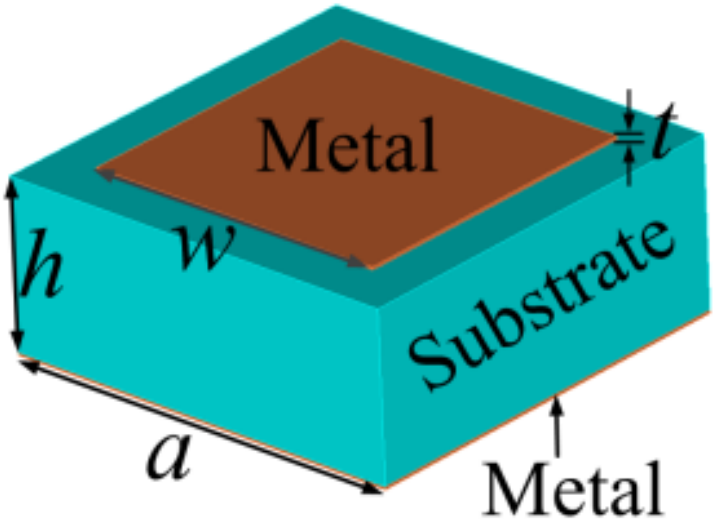
- 0 Unit: 0 Phase
- 1 Unit: 180 Phase



- Control EM waves by changing the coding sequences of 0 and 1 units

Cui et al., Light: Science & Applications 3, e218; 2014

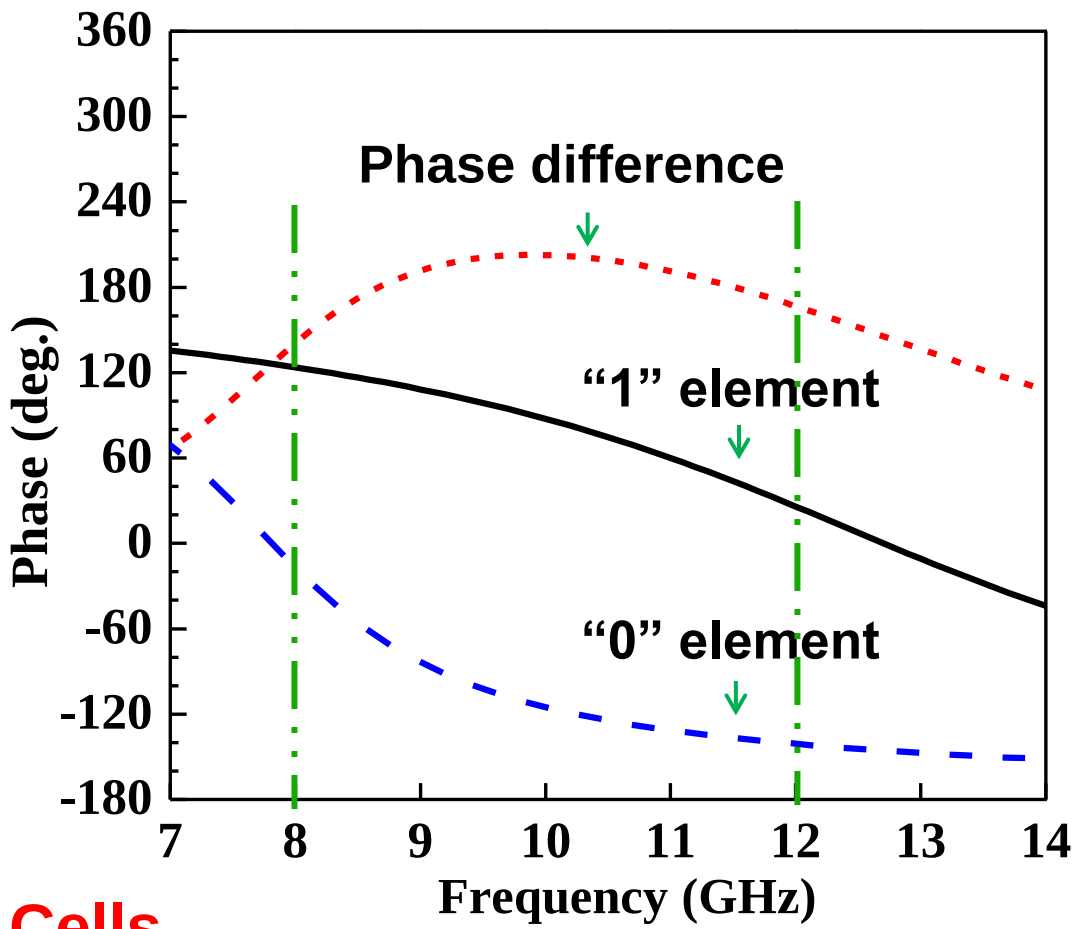
Coding Metamaterials



Basic Element

a = 5 mm, h =1.964 mm,
t = 0.018 mm
w = 4.8 mm: 0 Unit
w = 3.75 mm: 1 Unit

Phase Responses



Realization of 0/1 Unit Cells

Coding Metamaterials

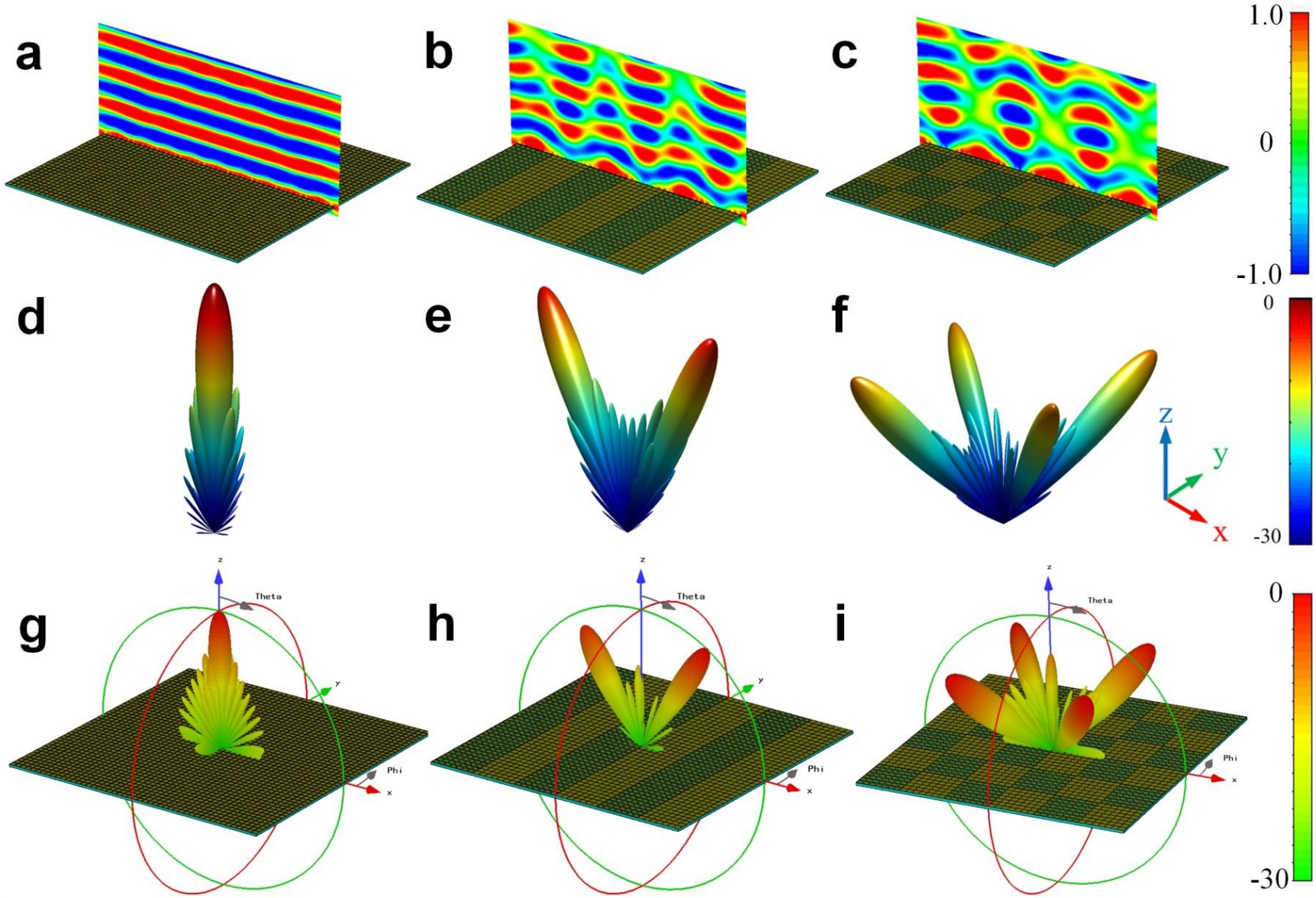
The radiation and scattering patterns can be controlled by coding the 0 and 1 elements:

$$f(\theta,\varphi) = f_e(\theta,\varphi)\sum_{m=1}^{N}\sum_{n=1}^{N}\exp\{-i\{\varphi(m,n)+kD\sin\theta[(m-1/2)\cos\varphi+(n-1/2)\sin\varphi]\}\},$$

$$\mathrm{Dir}(\theta,\varphi) = 4\pi\left|f(\theta,\varphi)\right|^2 / \int_0^{2\pi}\int_0^{\pi/2}\left|f(\theta,\varphi)\right|^2 \sin\theta d\theta d\varphi.$$

Solving the inverse problem, given arbitrary wave patterns, we can design the corresponding coding sequences of 0 and 1 elements.

1-Bit Coding Metamaterials



1-Bit Coding Metamaterials

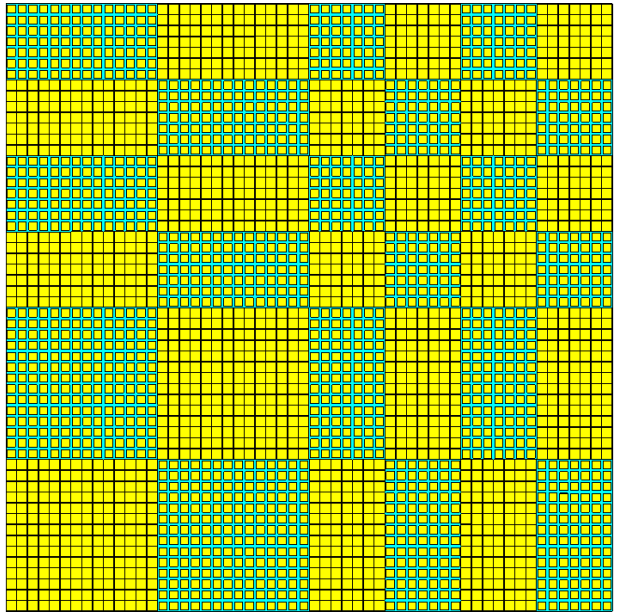
The optimized codes for different lattice numbers *N*

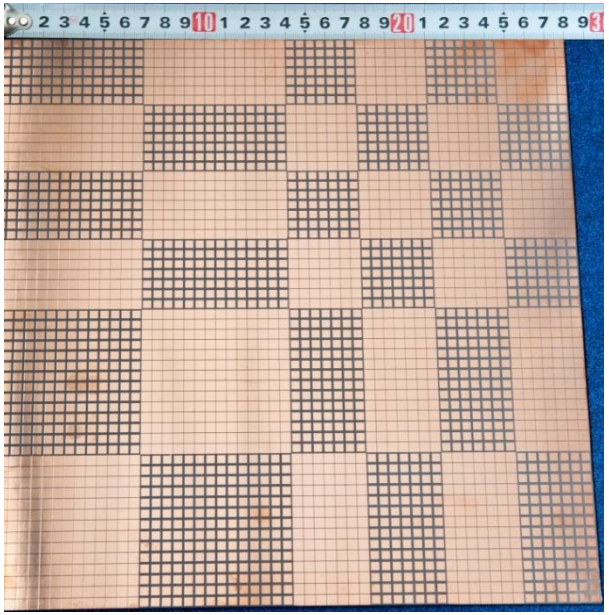
Design Example:

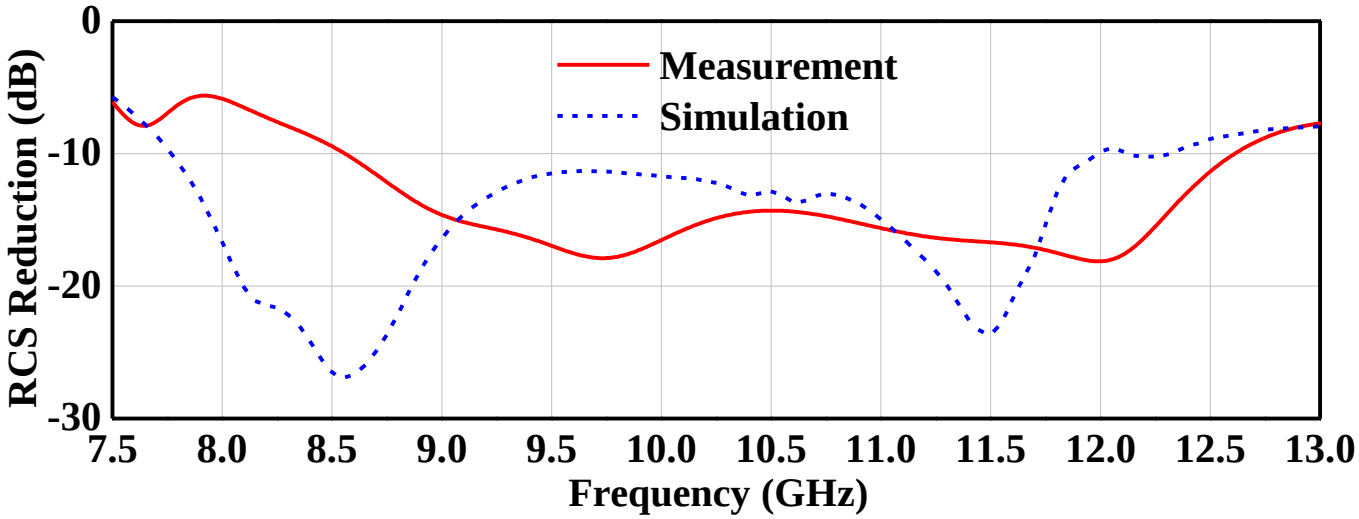
RCS Reduction – A New Strategy of Cloaking

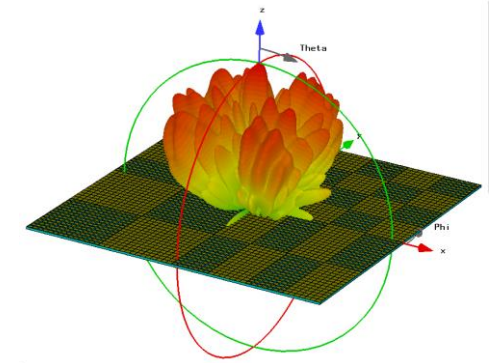
N	Code Sequence	RCS Reduction (dB)
6	001011	-12.08
7	0011010	-14.64
8	00110101	-15.82
10	0001010110	-18.39
12	001001110101	-19.75
14	00111110110101	-21.41
16	0011110110101010	-22.37
20	01000100110000110101	-23.58

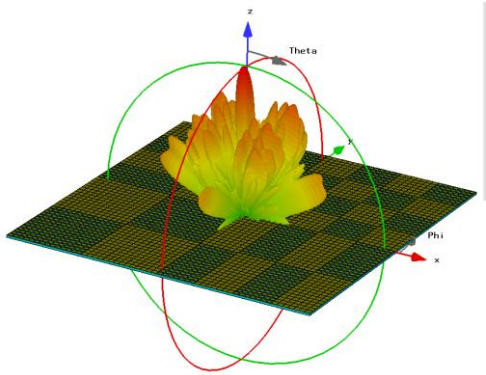
1-Bit Coding Metamaterials

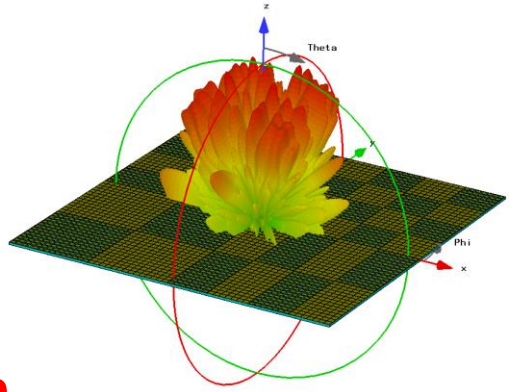






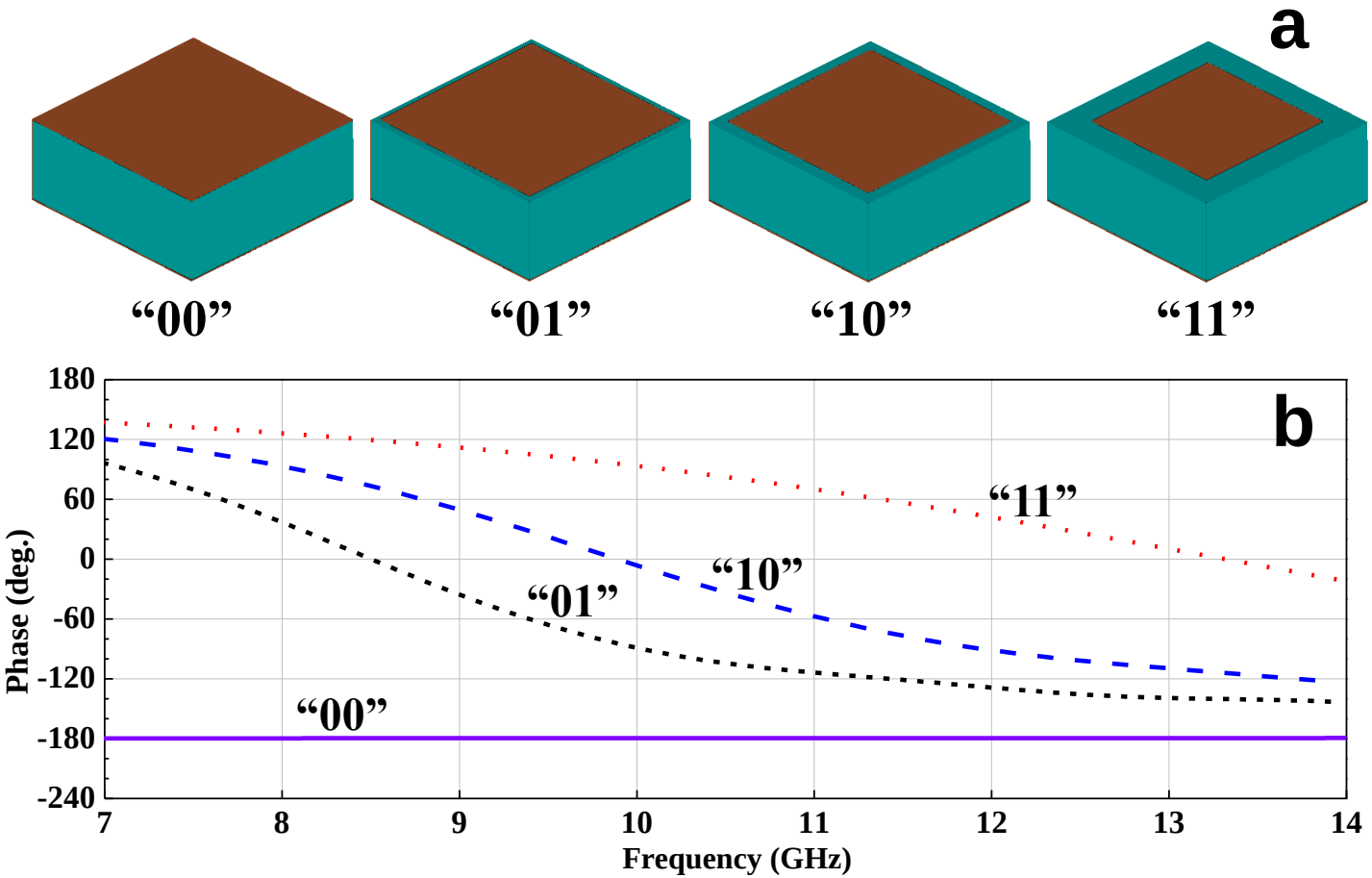






1-Bit Coding Metasurface for RCS Reduction

2-Bit Coding Metamaterials



2-Bit Coding Metamaterial - Four Basic Elements

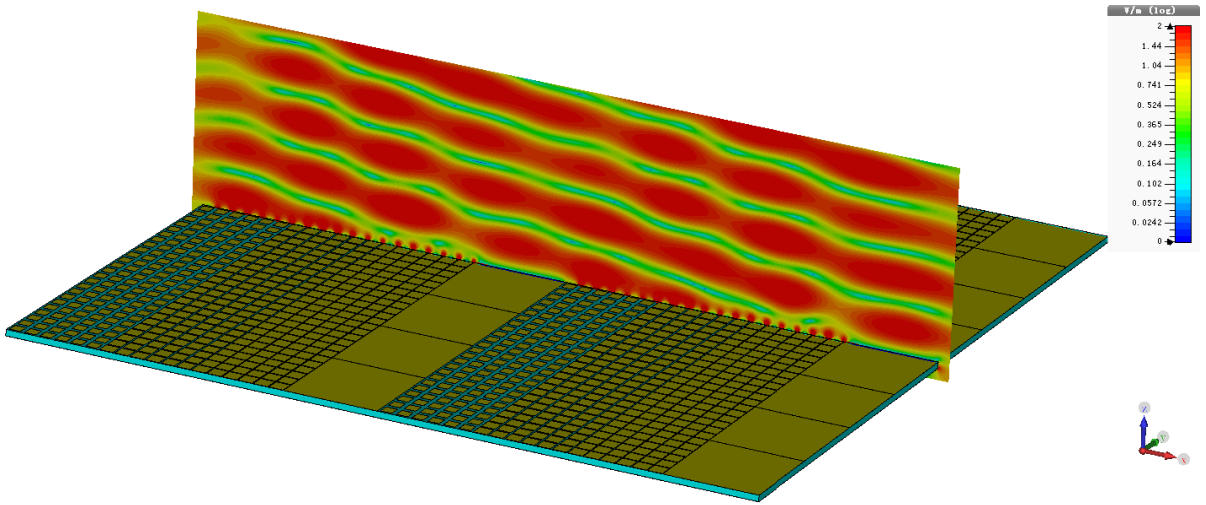
"00" – 0; "01" – 90; "10" – 180; "11" – 270

2-Bit Coding Metamaterials

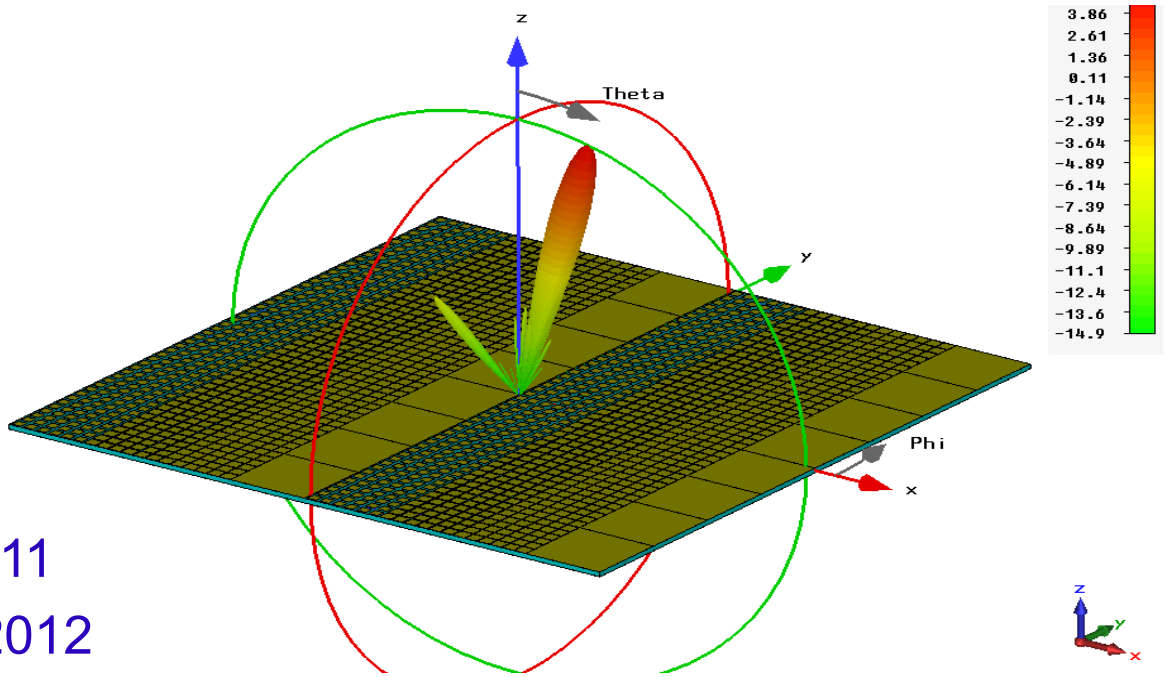
“00”“01”“10”“11”

Sequence:

Gradient Phase



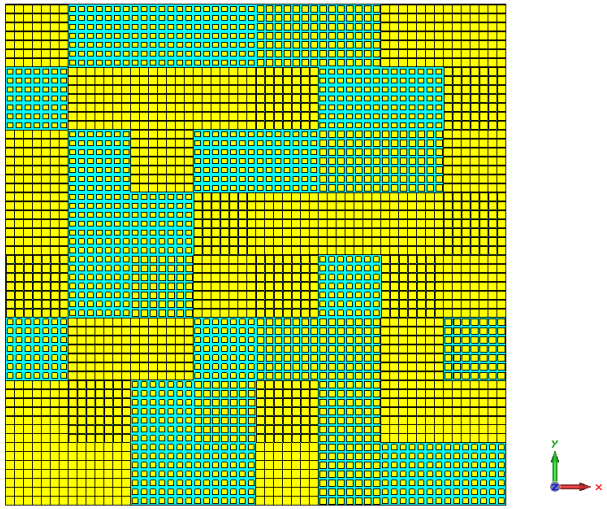
Generalized Snell’s Law

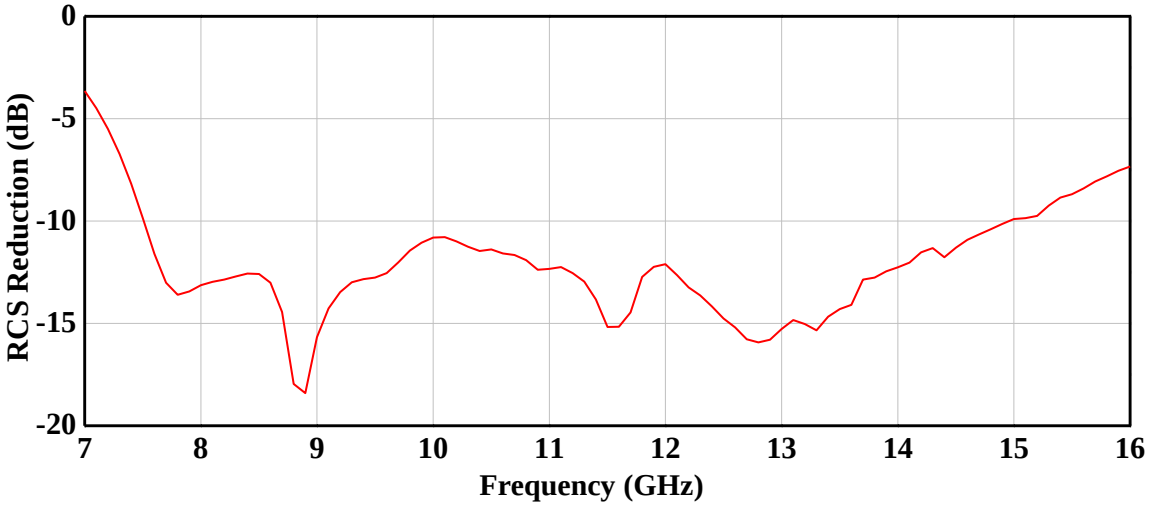


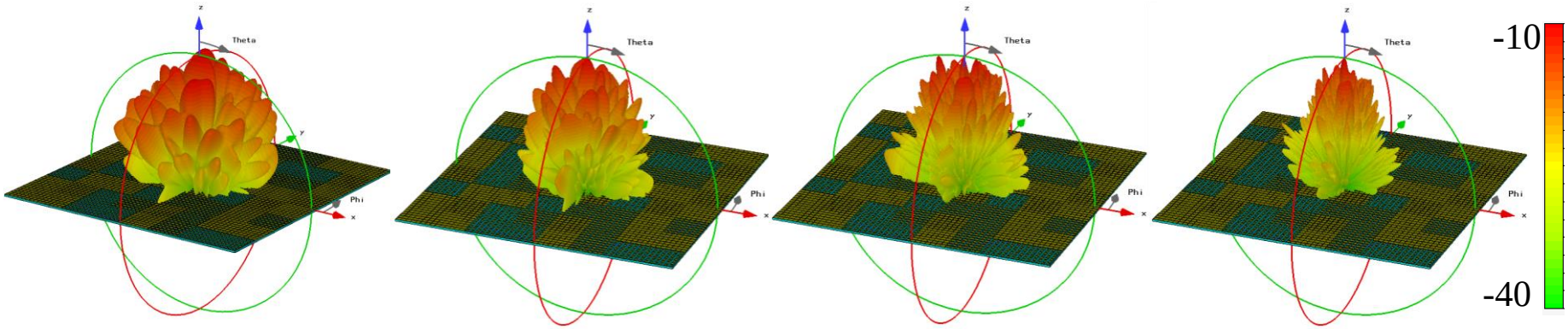
Capaso’ Grp, Science, 2011

Zhou’s Grp, Nat. Mater., 2012

2-Bit Coding Metamaterials







Better performance is observed for RCS reduction using 2-bit coding metamaterial

Digital Metamaterials

- ◆ Coding metamaterials are not our final purpose
- ◆ We aim to realize digital control of coding sequence

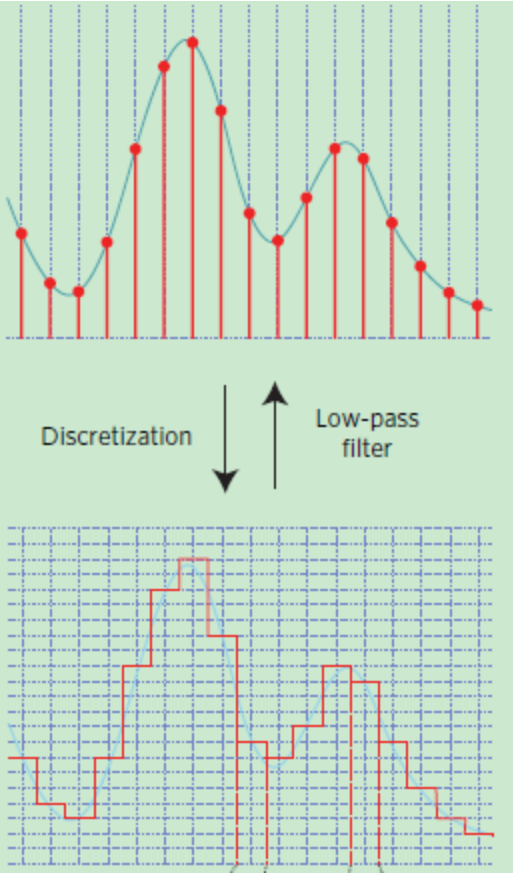
nature materials

ARTICLES

ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NMAT4082

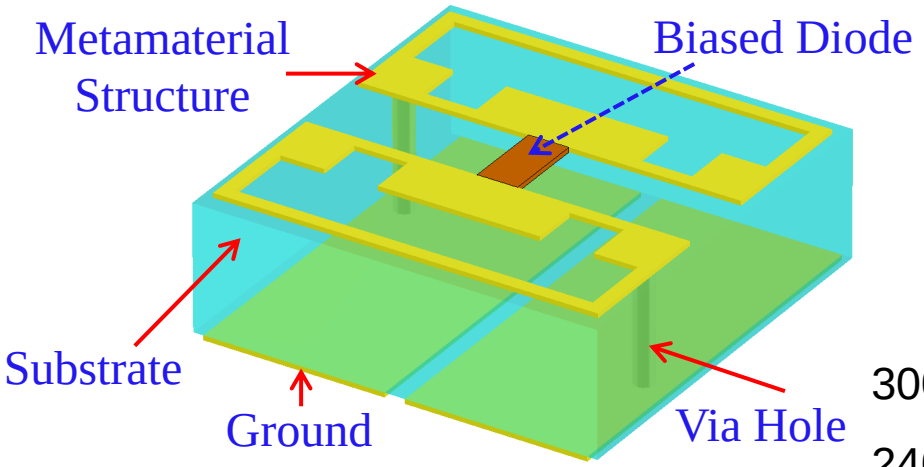
Digital metamaterials

Cristian Della Giovampaola and Nader Engheta*



- ◆ This is a purely theoretical work.
- ◆ The "digital" here in fact means "discrete".
- ◆ Our concept is proposed independently, and has totally different meaning: digitally control

Digital Metamaterials

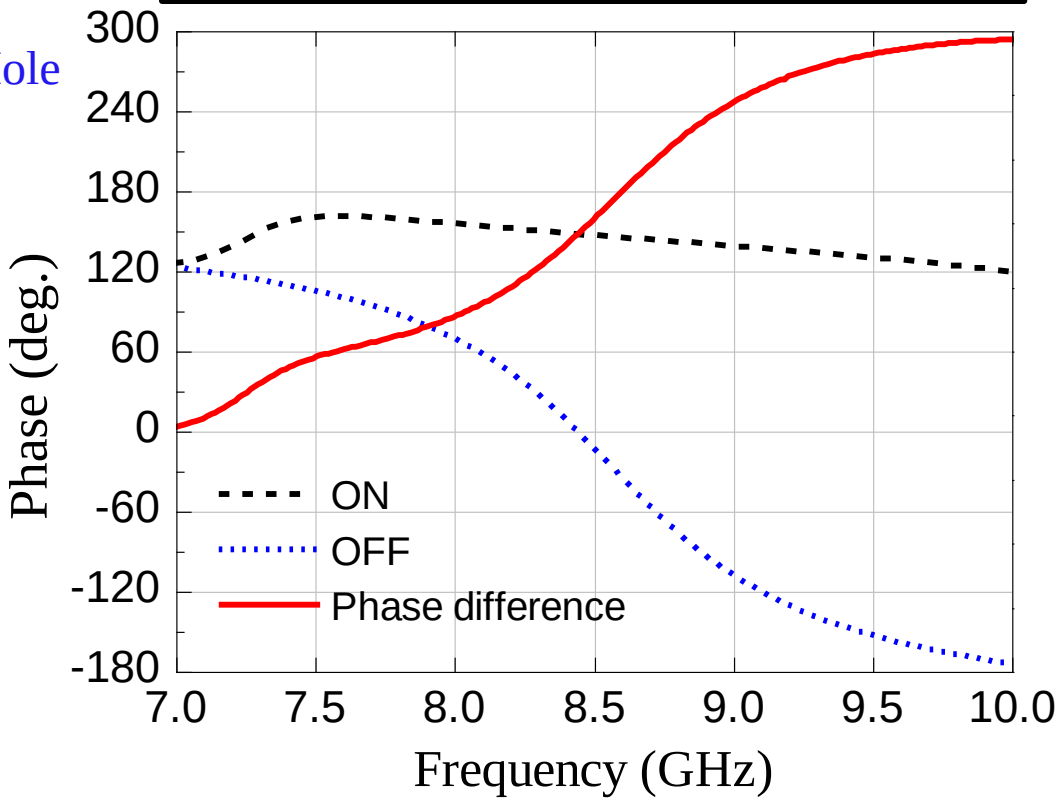


Cui et al., Light: Science & Applications 3, e218; doi:10.1038/lsa.2014.99, 2014

A unique metamaterial particle, which can be either 0 or 1, controlled by the pin diode.

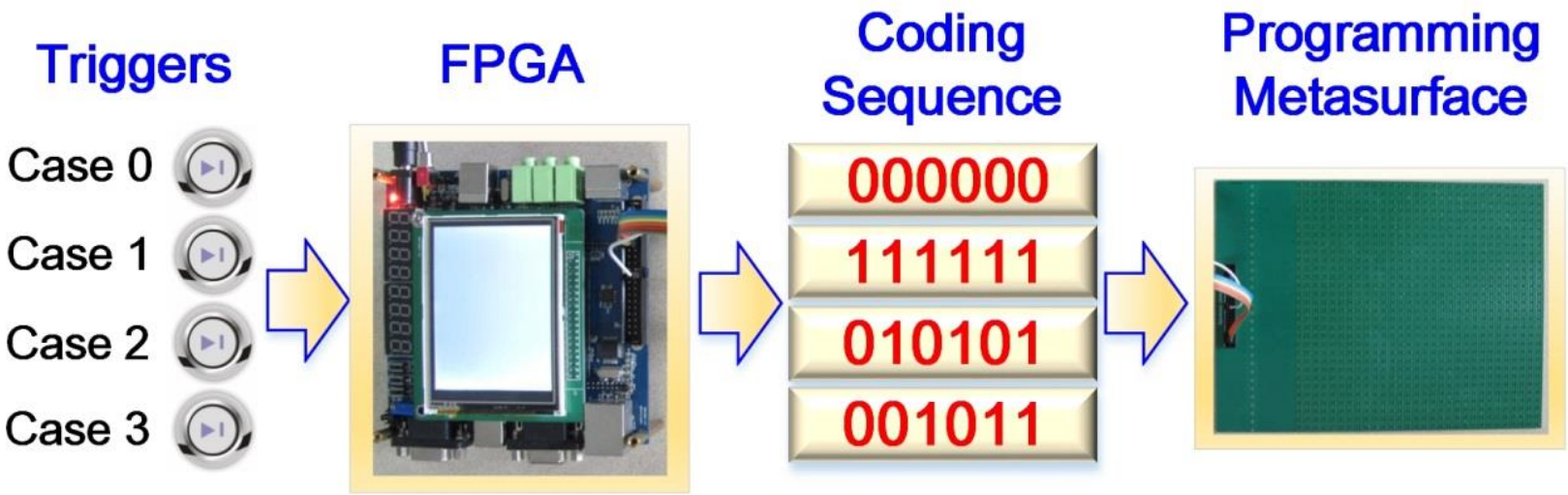
- **We can control the state of each particle as 0 or 1 by giving two different biased voltages.**
- **We can then control the coding sequences of 0 and 1**

The Phase Responses

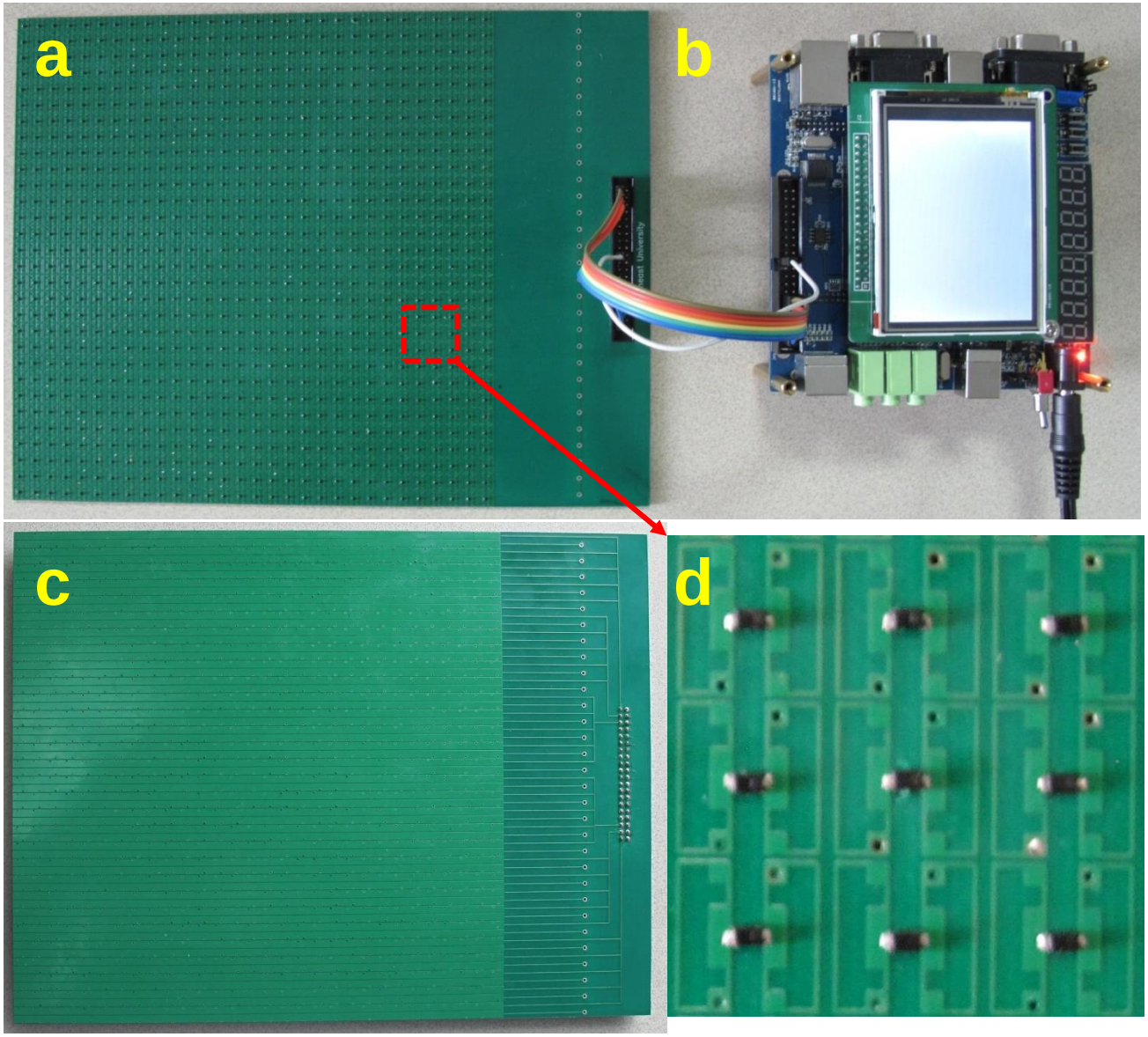


Programmable Metamaterials

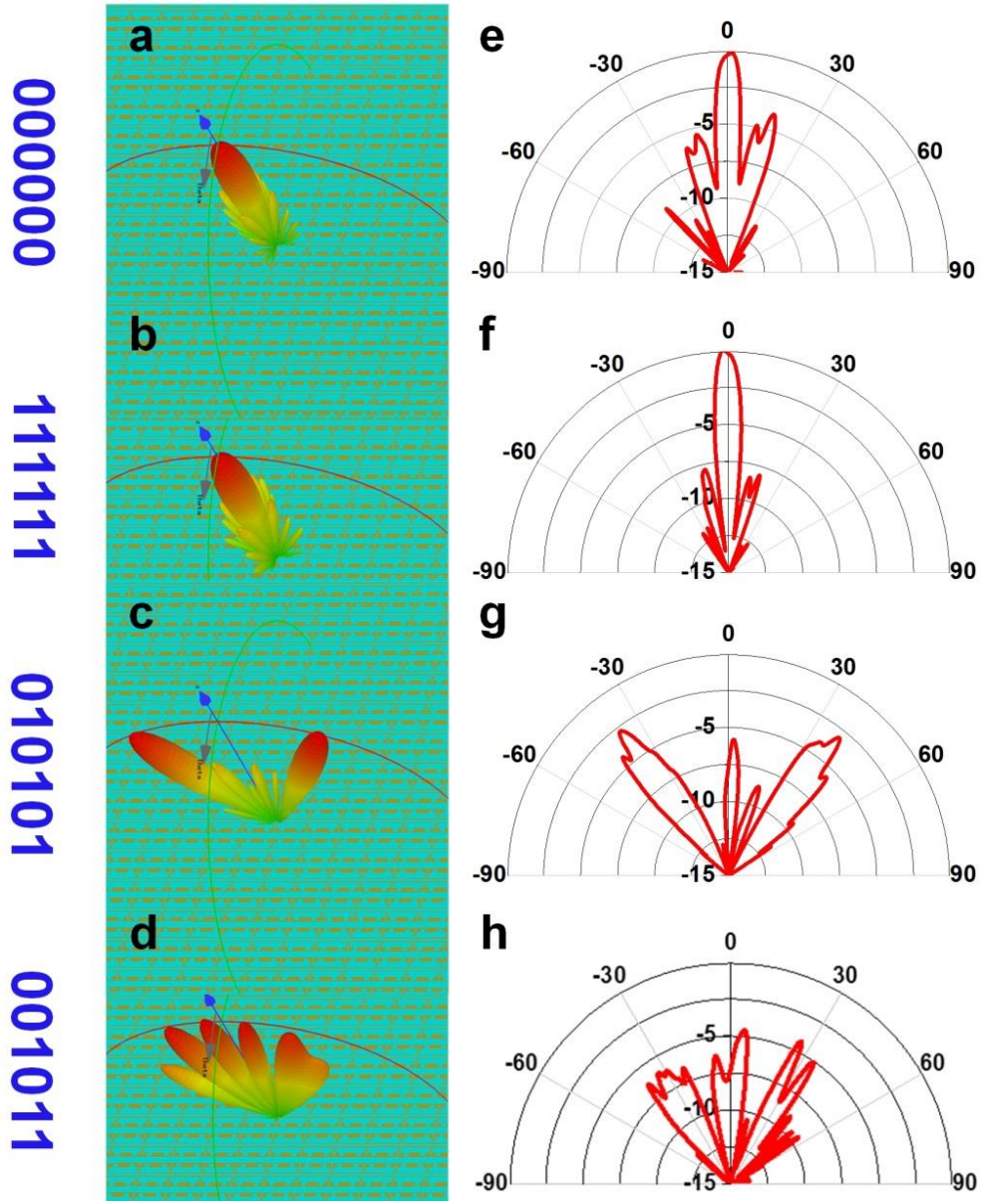
- By using field-programmable gate array (FPGA) hardware, we realize digital control over the digital metamaterial.
- We can write a program consisting of many cases onto FPGA, which is used to control many functionalities in real-time: **Programmable Metamaterial**.



Programmable Metamaterials



Experimental Validation

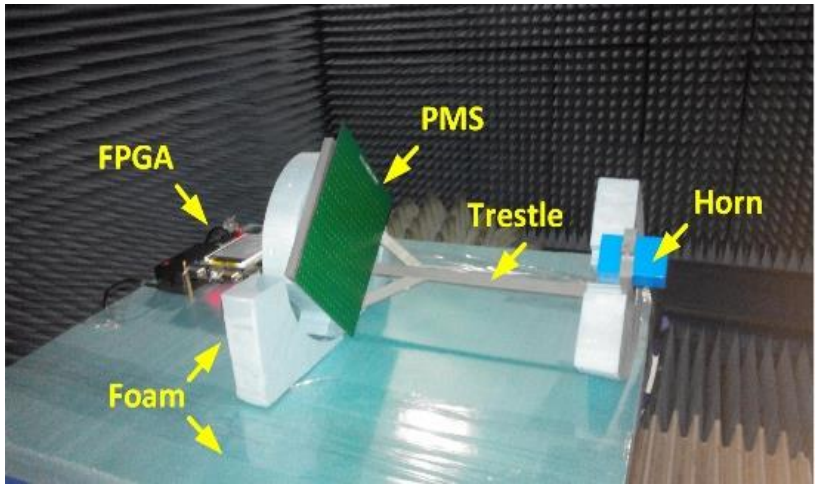


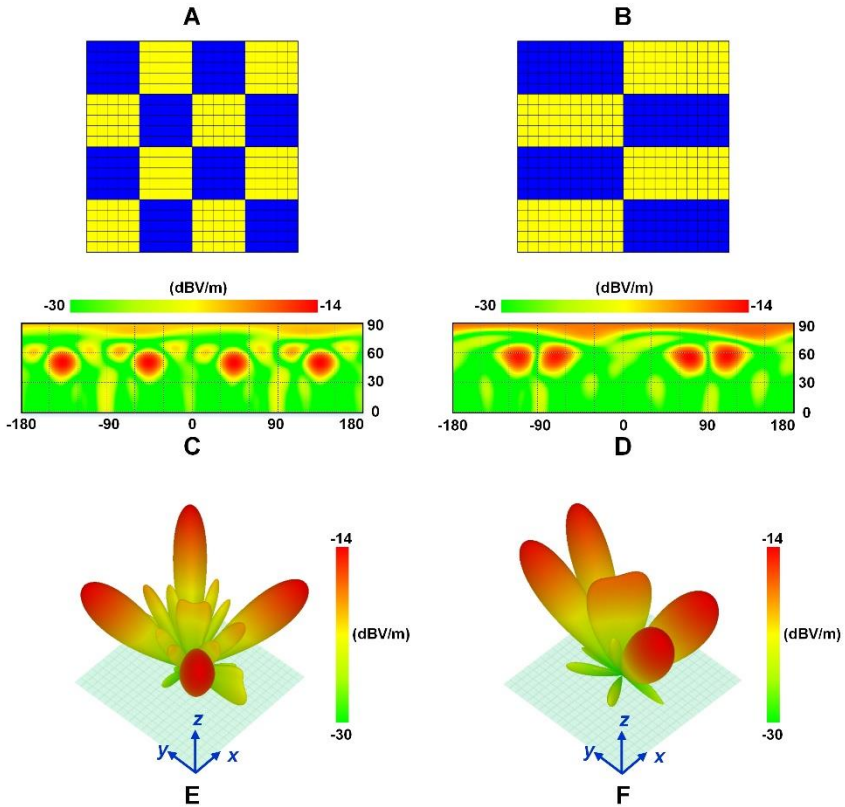
- **A Simple Example:**
- **Six-Code Sequence**
- **Many functionalities can be realized by a single metamaterial, which are switched in real time, and computer controllable.**

Cui et al., Light: Science & Applications 3, e218; 2014

New-Concept Radar

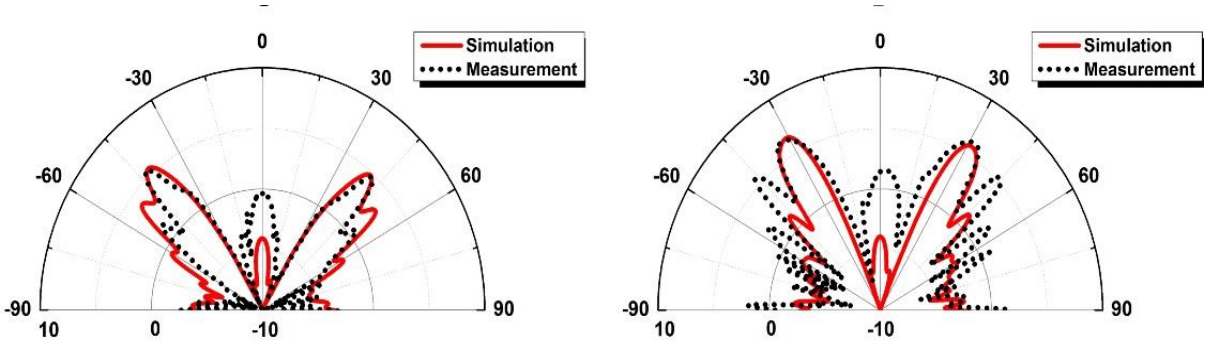
2D Programmable Metasurface





New-Concept Radar:

- Single Beam
- Multiple Beams
- Beam Scanning
- RCS Reduction



Wan et al., Sci. Rep., 2015

New Imaging System

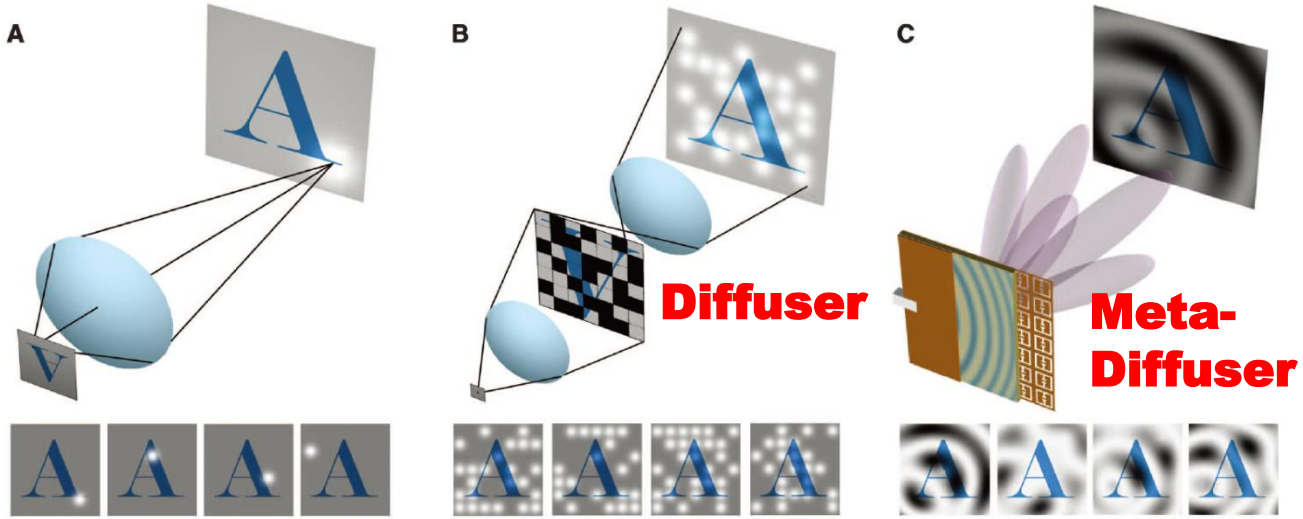
Radar Imaging: Phase Array; Mechanical Scanning (SAR)

Single-Radar Imaging

Science AAAS

Metamaterial Apertures for Computational Imaging
John Hunt *et al.*
Science **339**, 310 (2013);
DOI: 10.1126/science.1230054

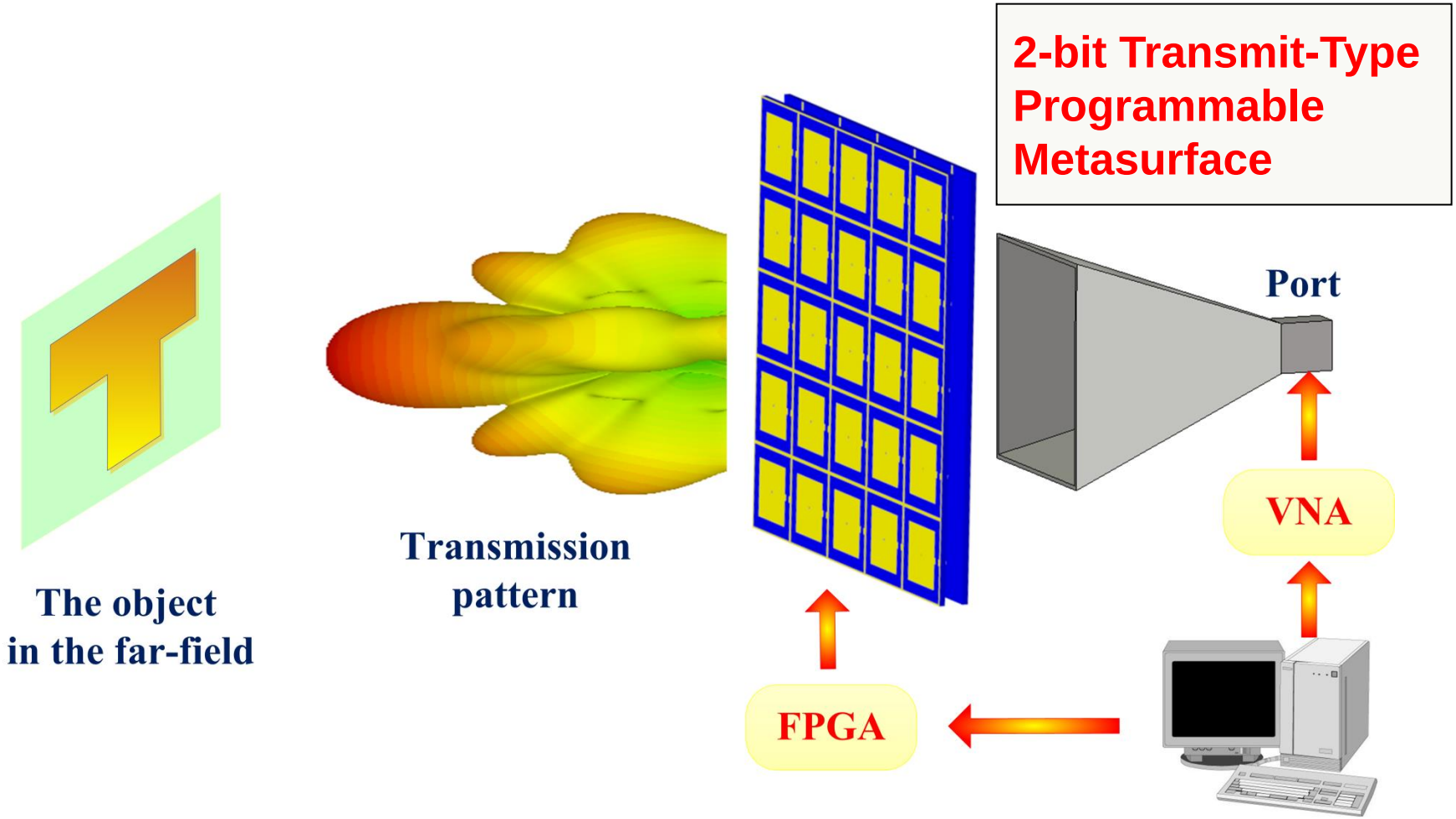
- **Diffusion Metasurface**
- **Frequency Diversity**
- **Object Dispersion**



Cummer's Grp: Acoustic, PNAS 2015

Padilla's Grp: THz, Nat. Phot. 2014

New Imaging System



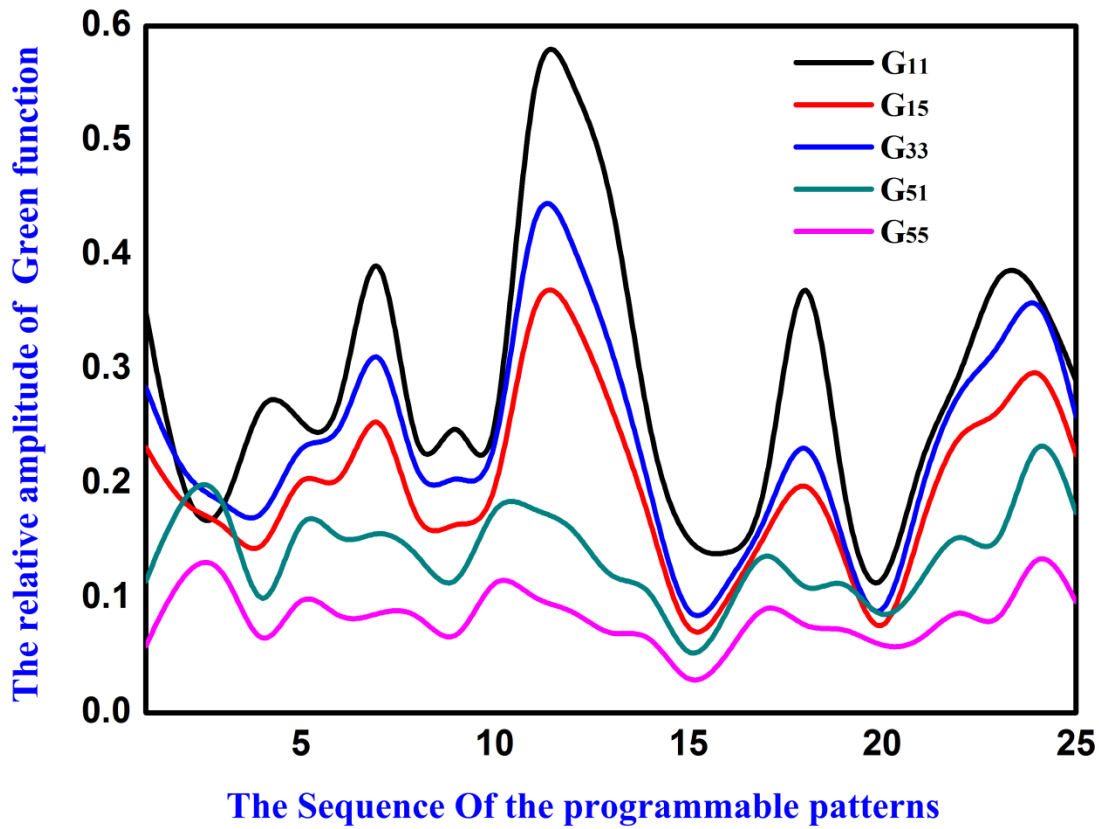
Single-Radar and Single-Frequency Imaging System

Li et al., Sci. Rep., 2015

New Imaging System

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1N} \\ G_{21} & G_{22} & & \\ & & \ddots & \\ G_{N1} & & & G_{NN} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_N \end{bmatrix}$$

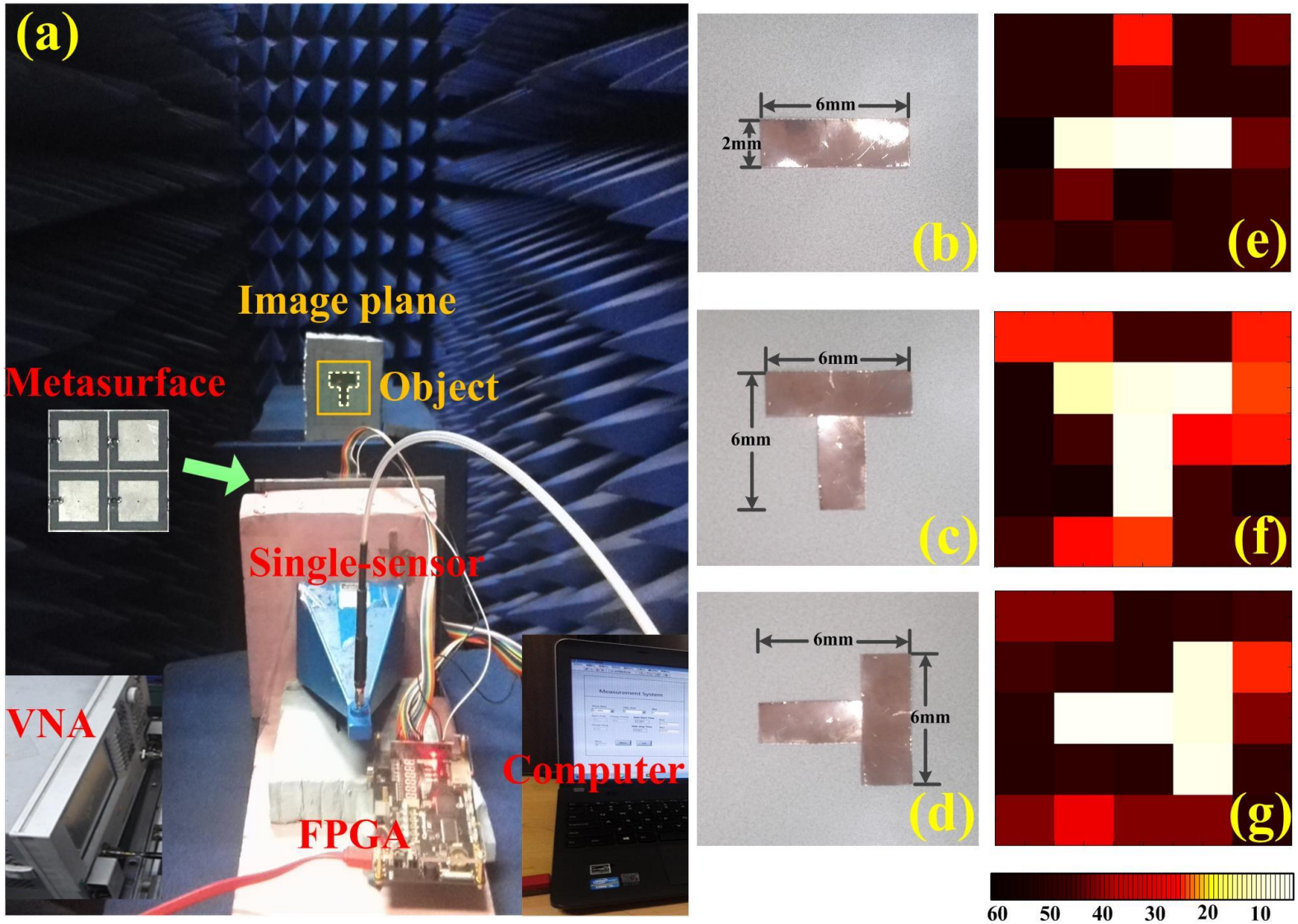
Inverse-Scattering Theory



Generalized System Response Matrix

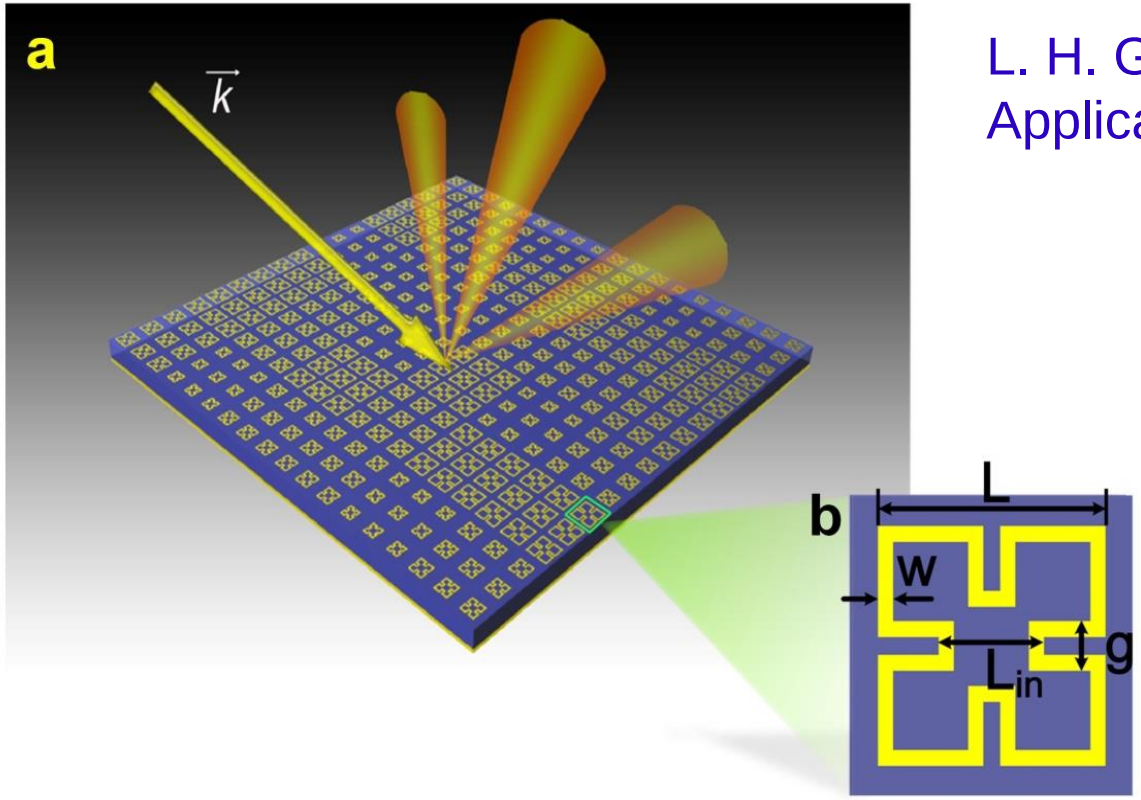
Li et al., Sci. Rep., 2015

New Imaging System



Li et al., Sci. Rep., 2015

Terahertz Coding Metasurfaces

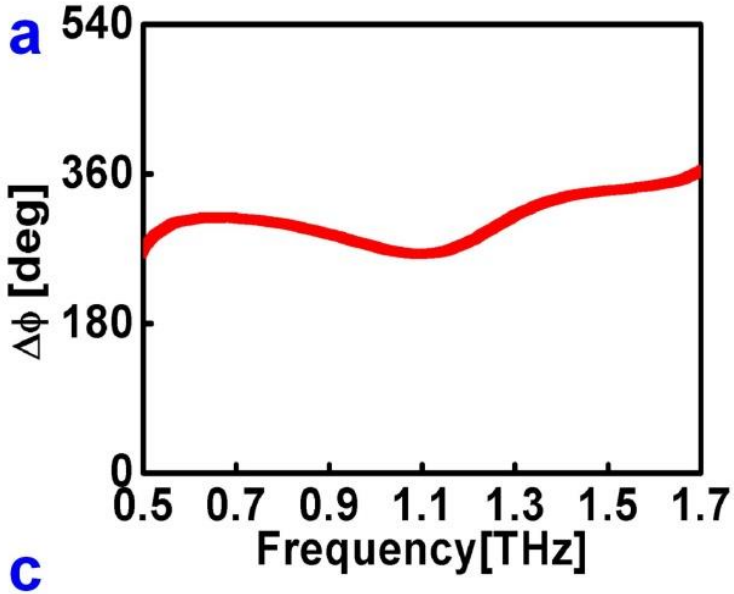


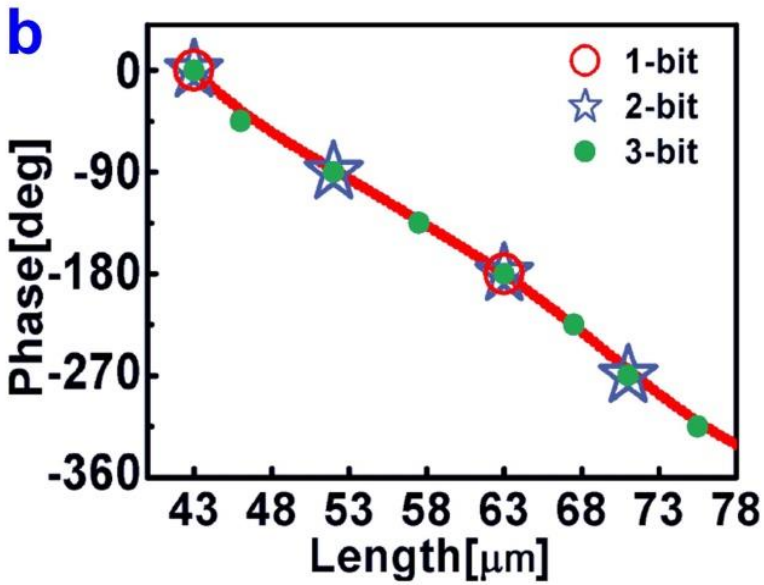
L. H. Gao *et* al., Light: Science & Applications 4, e324 (2015)

- **A novel coding particle: Minkowski fractal structure**
- **1-bit, 2-bit, and 3-bit coding particles can be realized using the Minkowski loops with different scales**

Design of Coding Particles

Designs of the Minkowski coding particles

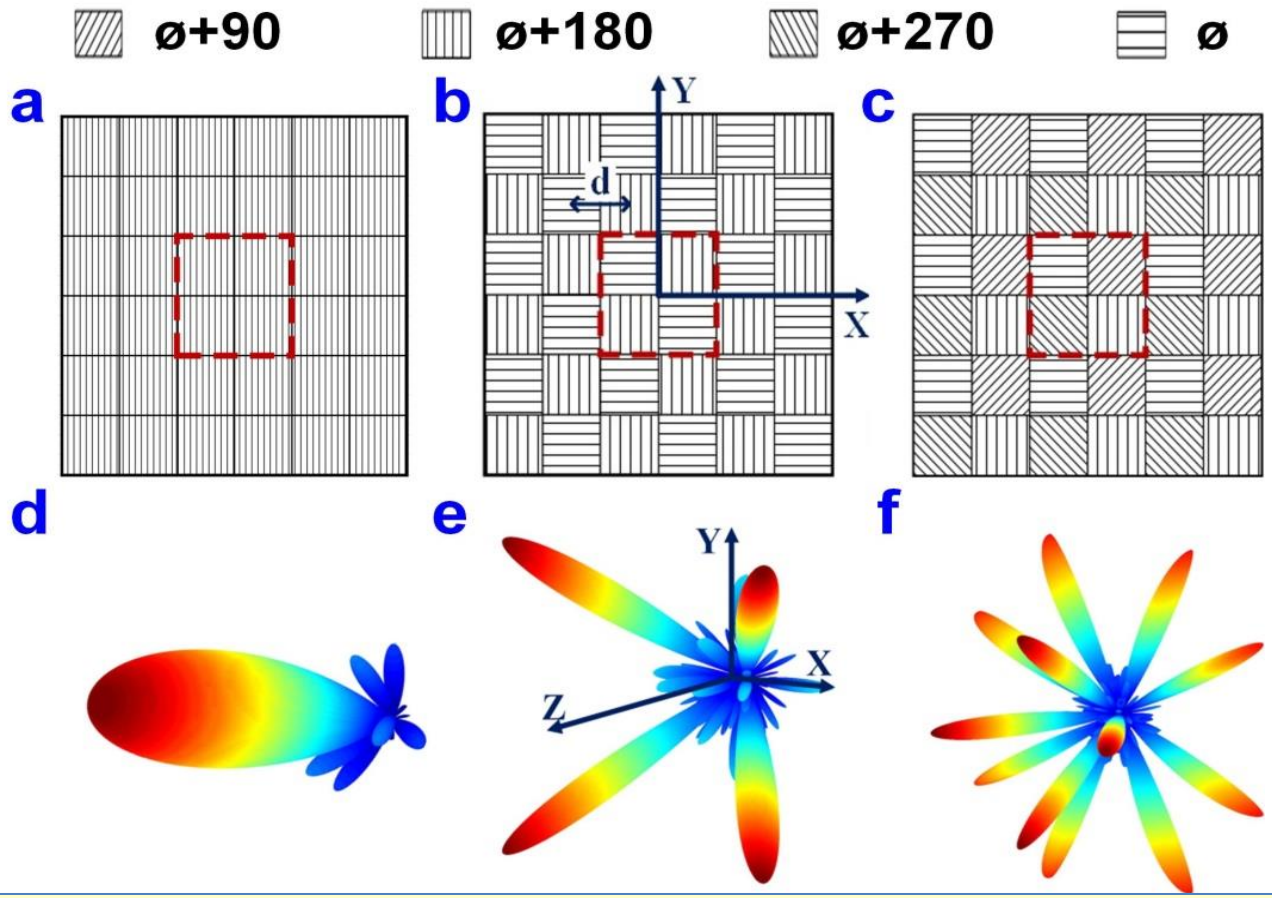




c

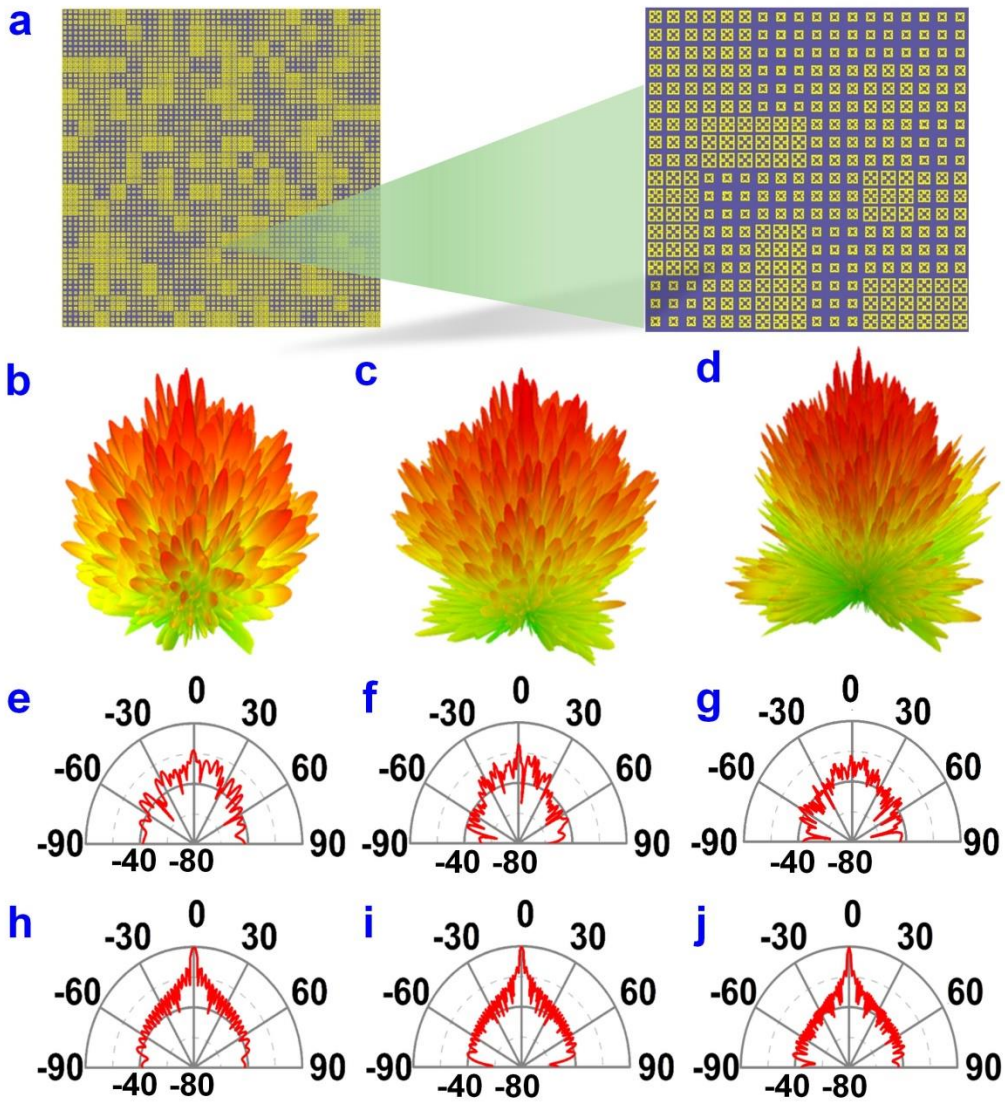
Shape & Phase / Multi-bit	0	-45	-90	-135	-180	-225	-270	-315
1-bit	0				1			
2-bit	00		01		10		11	
3-bit	000	001	010	011	100	101	110	111

Abnormal THz Reflections



The scattering features of periodic arrangements of coding particles. (a) The 1-bit coding with all “1” elements. **(b)** The 1-bit coding with the chess-board “0” and “1” distribution. **(c)** The 2-bit coding with the periodic “00”“01”/“11”“10” distribution. **(d-f)** The simulated scattering patterns of the 1-bit and 2-bit coding sequences.

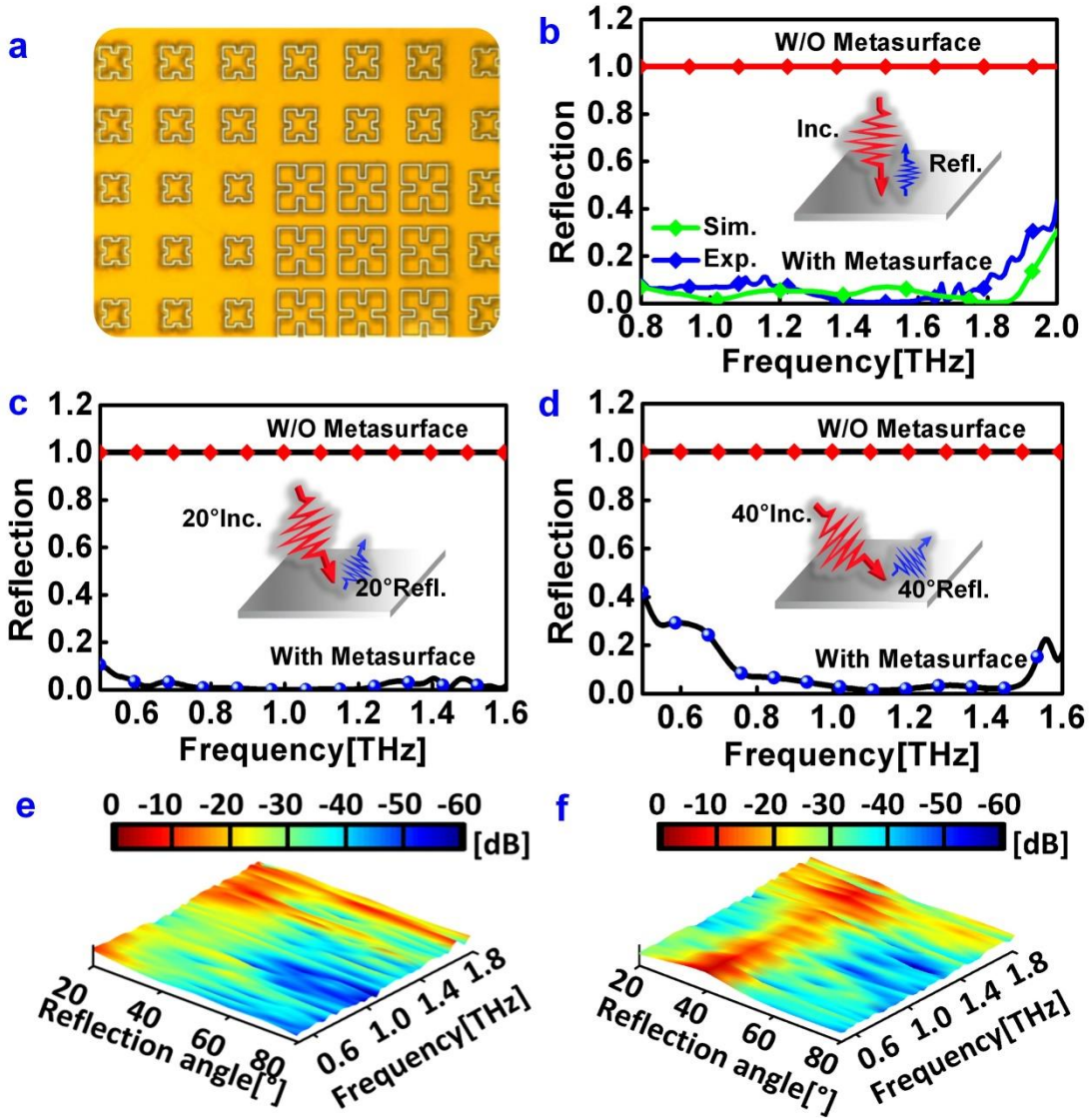
Terahertz Diffusions



The coding distribution on a large area (7.56*7.56 mm^2), which contains 7056 coding particles constructed by the Minkowski loops.

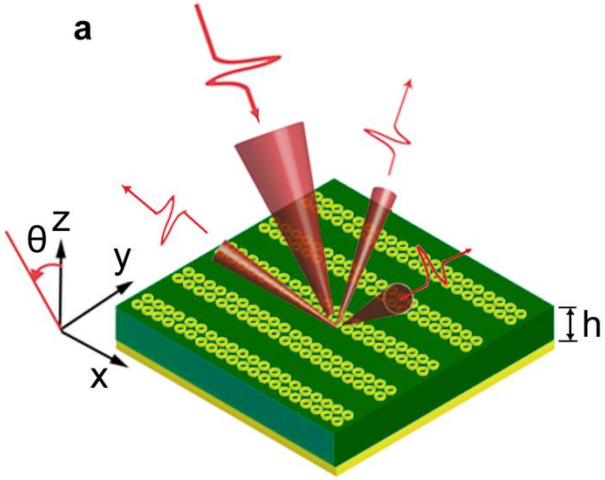
Numerical simulation results of a 2-bit diffusion coding metasurface

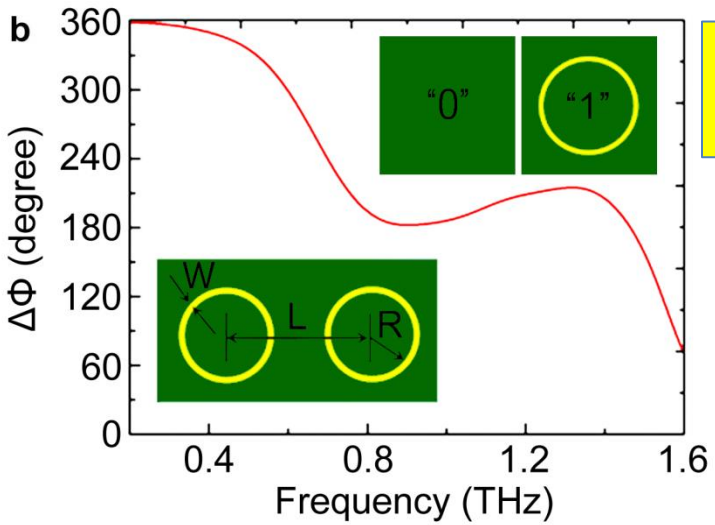
Measured Results



The fabricated sample and measurement results. (a) Part of fabricated sample of the 2-bit diffusion coding metasurface. **(b)** The measured and simulated backward scattering coefficients of the 2-bit coding metasurface under the normal incidence. **(c,d)** The measured scattering coefficients in the specular directions of the 2-bit coding metasurface under the oblique incidences of 20 and 40 degrees, respectively. **(e,f)** The measured scattering coefficients in wide angles from 20 to 80 degrees of the 2-bit coding metasurface under the oblique incidences of 20 and 40 degrees, respectively.

Conformal THz Coding Metasurfaces

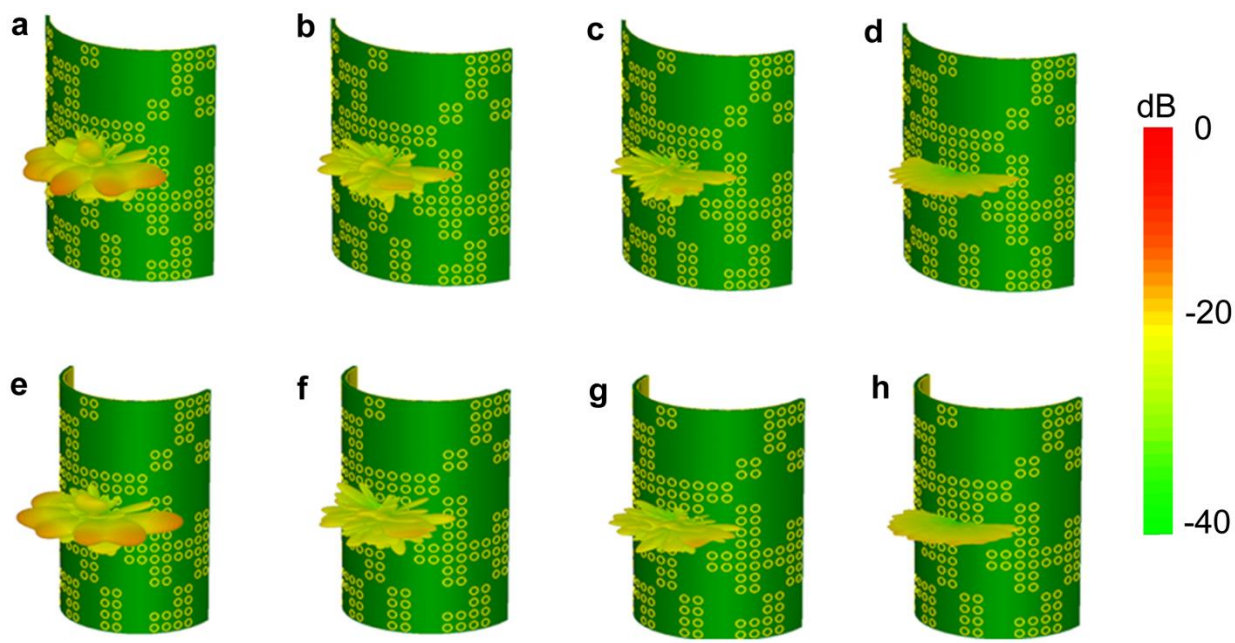




Liang et al., Advanced Optical Materials, 2015.

New Designs

Broad Band, Flexible and Conformal



Prof. Biaobing Jin
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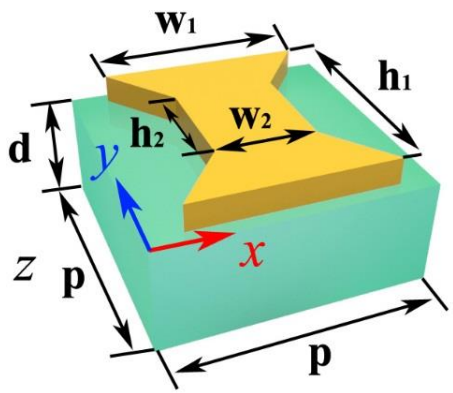
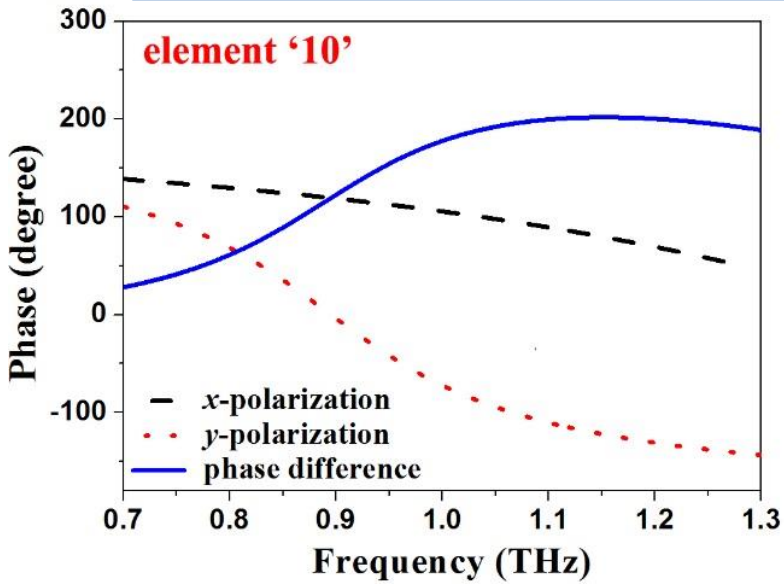
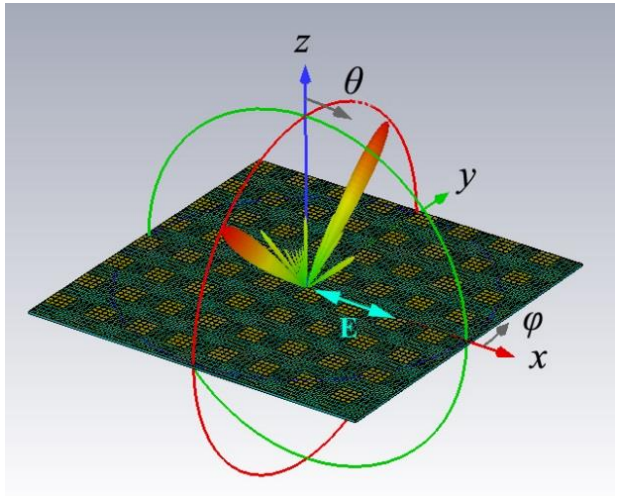
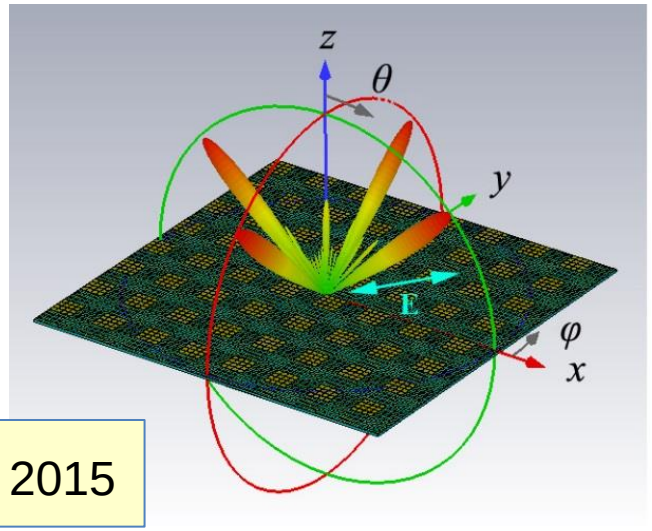
Anisotropic Coding Metasurfaces

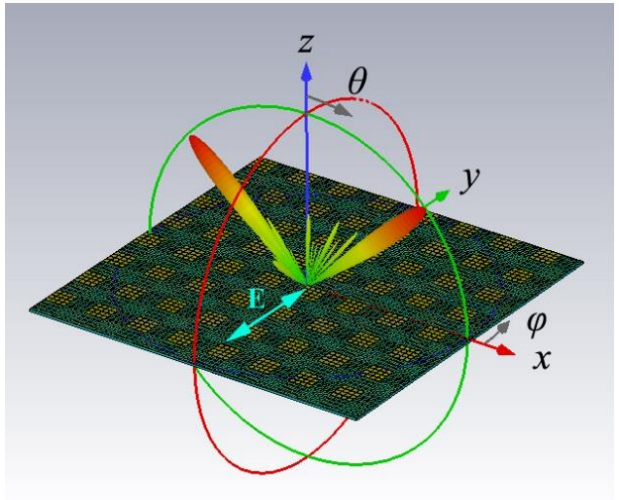
Polarization Controlled Functionalities





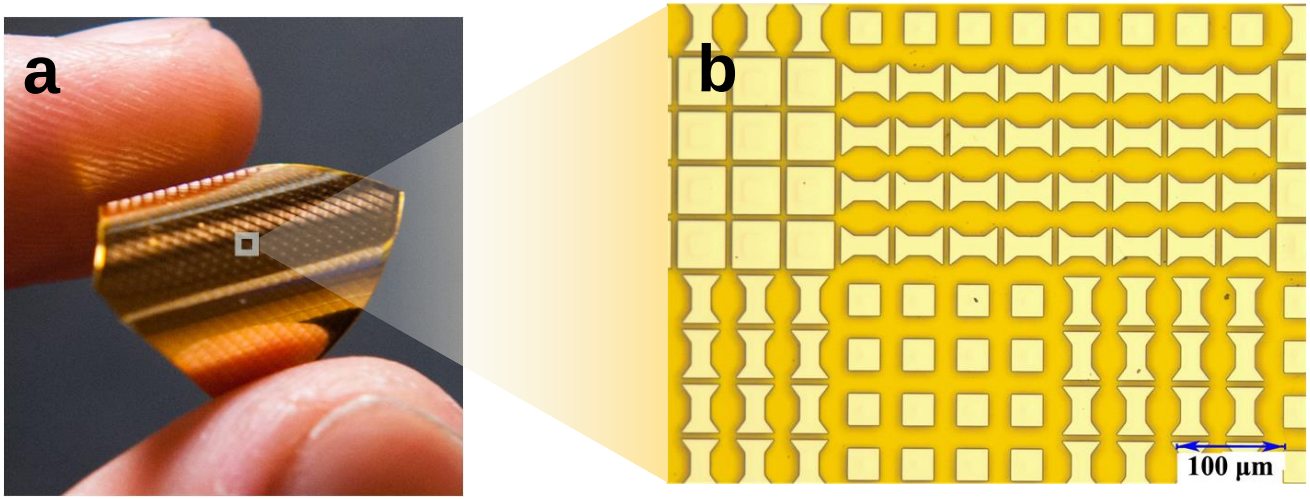


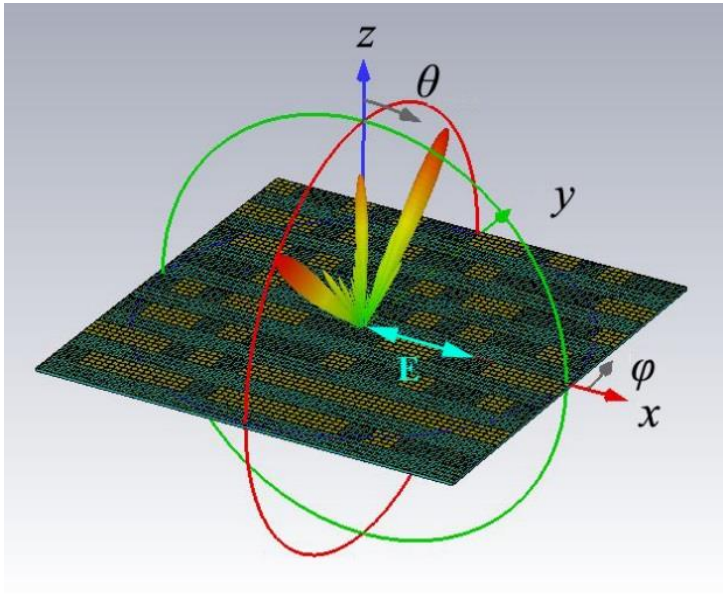


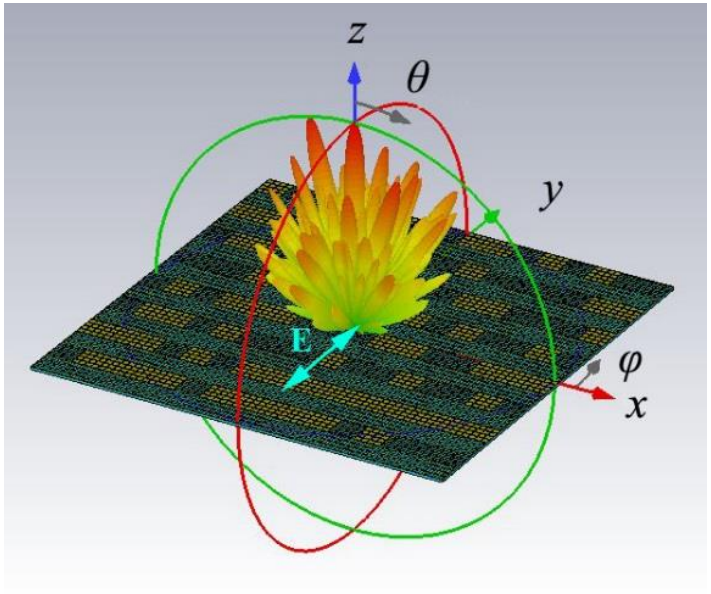


Liu et al., Light: Sci. Appl., 2015

Anisotropic Coding Metasurfaces

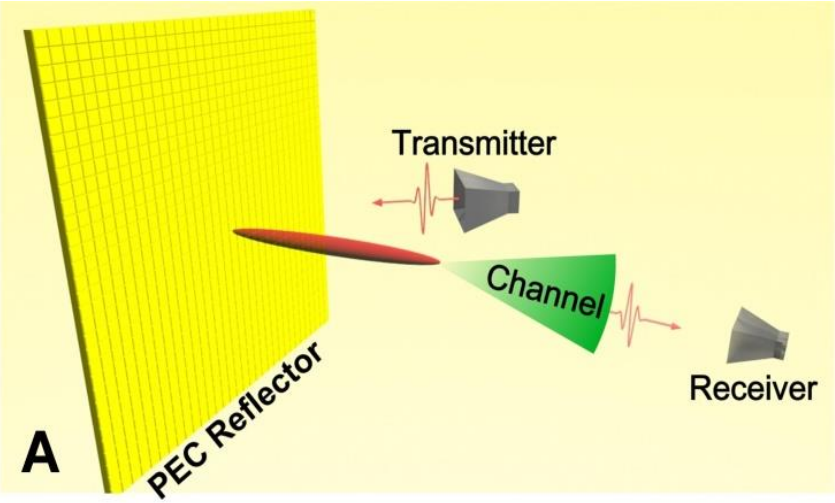


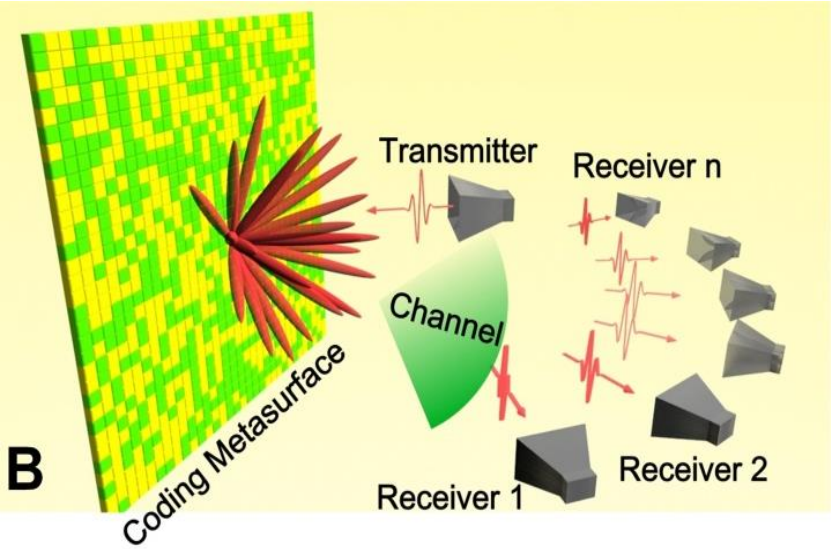


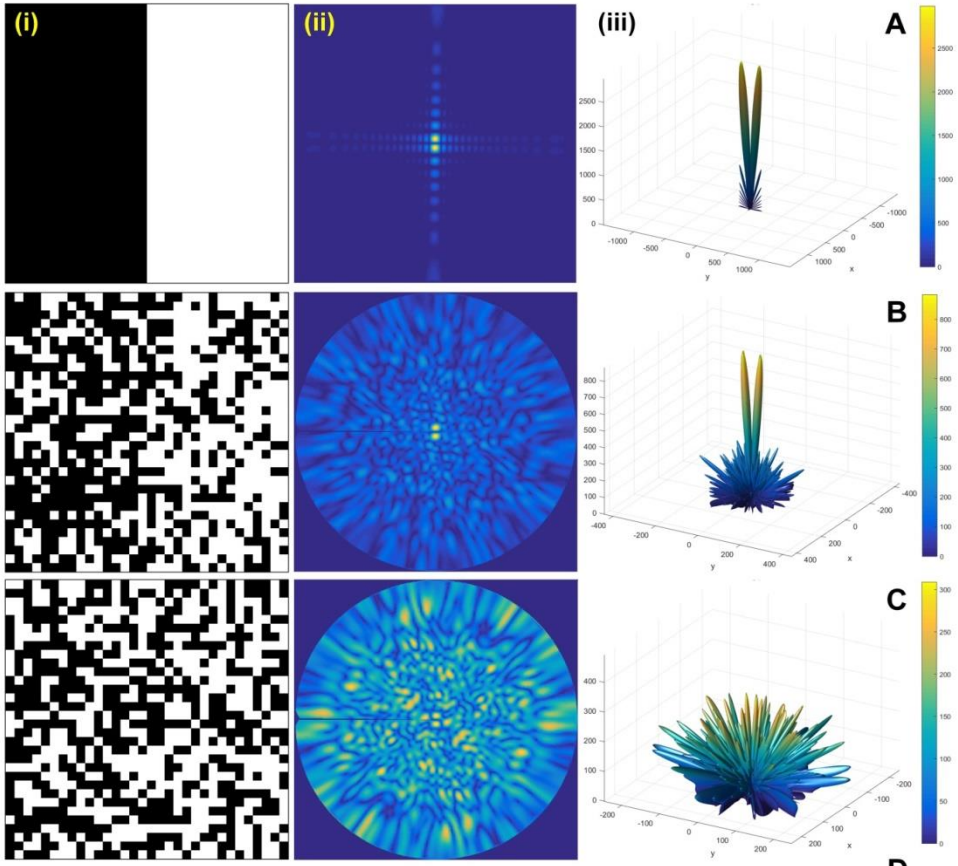


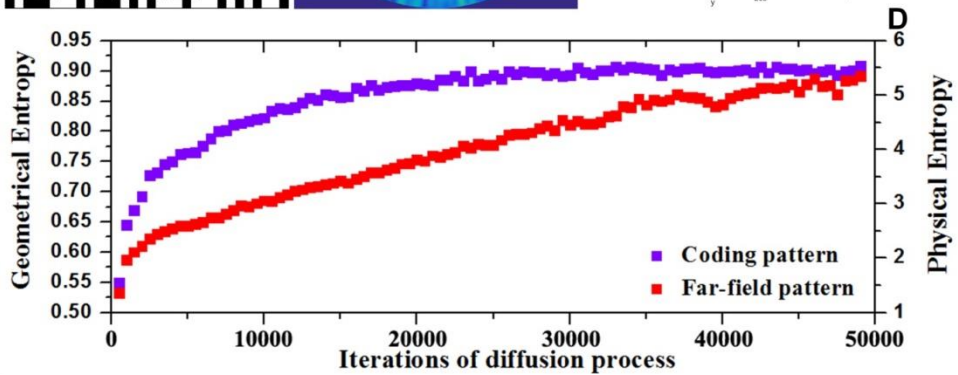
More Flexible Controlled Functions ……

Coding Metasurface and Entropy









Cui and Liu, unpublished, 2015

Acknowledgments

- Prof. David Smith, Duke University
- Prof. Francisco J. Garcia-Vidal
  Universidad Autonoma de Madrid, Spain
- Prof. Yu Luo & Hao Yu, NTU, Singapore
- Prof. Sir John Pendry, Prof. Stefan Maier
  Dr. Antonio Fernandez-Domínguez
  Imperial College London, UK
- My Colleagues and Students: Q. Cheng, H. F. Ma, W. X. Jiang, X. Shen, W. X. Tang, D. Bao Y. B. Li, S. Liu, H. C. Zhang, J. Y. Li