Metamaterial – From Effective Material to Real-Time Information Processing System

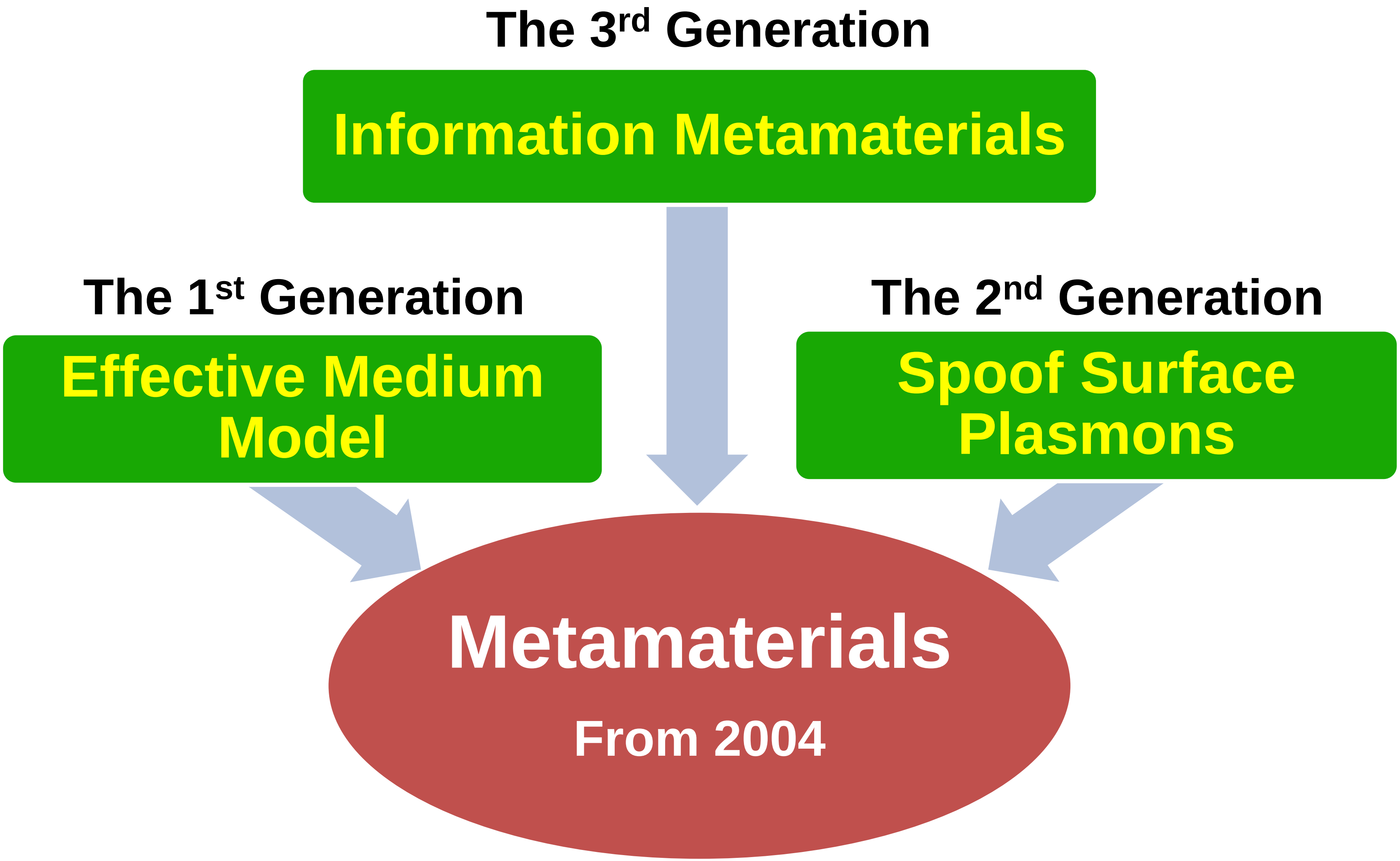
Tie Jun Cui

State Key Laboratory of Millimeter Waves

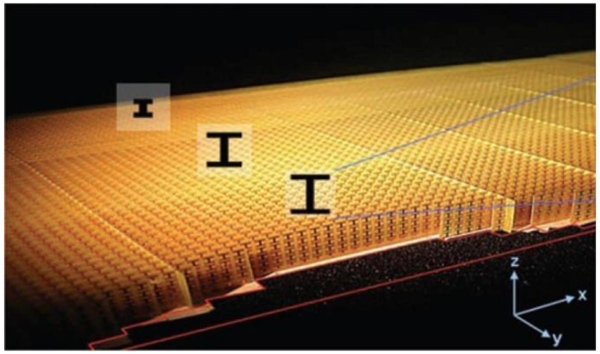
Southeast University, Nanjing 210096

Meta-Optics and Metamaterials, IBS, Daejeon, Korea

Background: META@SEU

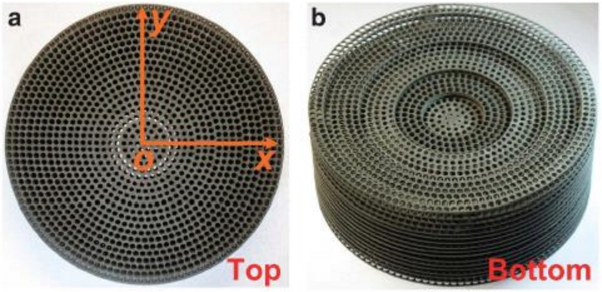


The 1st Generation: Effective-Medium Metamaterials



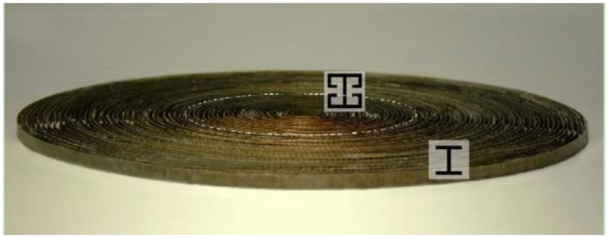
Cloaking

Science, 2009.



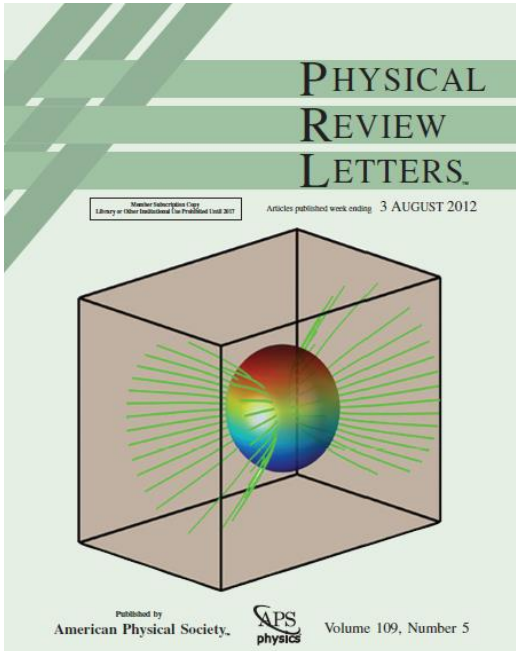
Nat. Comm., June 2010.

EM Black Hole



New J. Phys., June 2010.

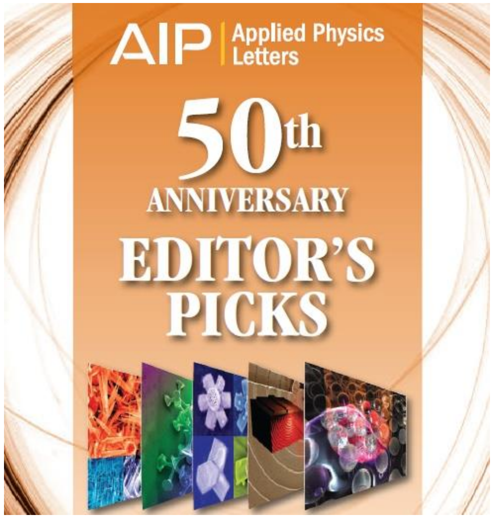
New Physics and Experimental Verification



PRL 109, 2012

PRL 111, 2013

Illusion Optics



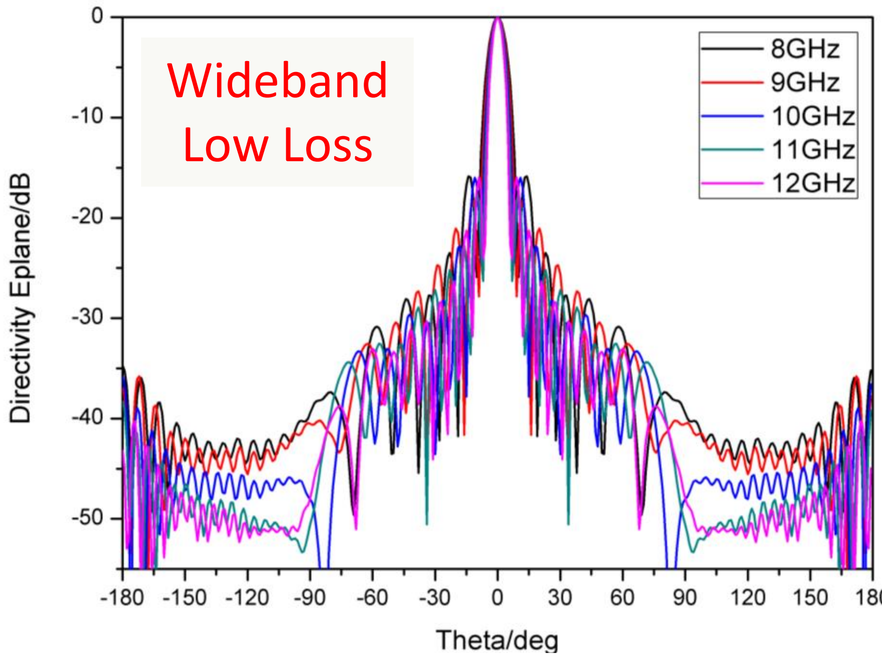
APL 50th Anniversary

One of 50 among 20000+

The 1st Generation: Effective-Medium Metamaterials

Meta Lens

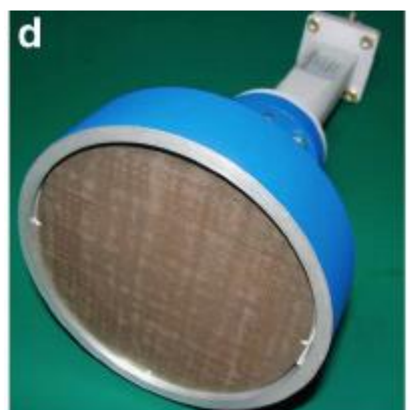
Nat. Comm., Nov. 2010



X Band

High Gain

Enhanced by 3-6dB under the same aperture



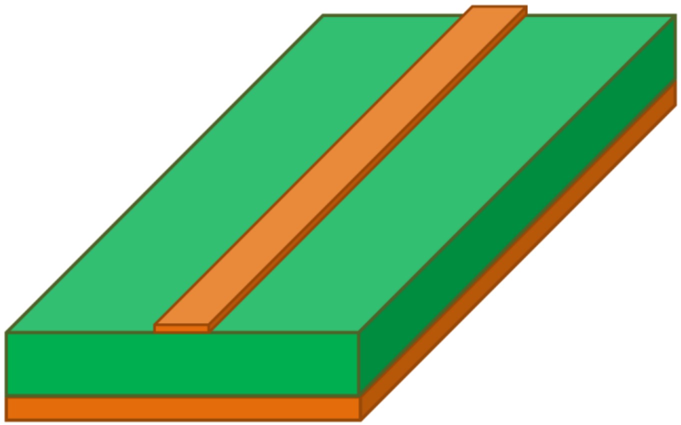
Diffuse Metasurface

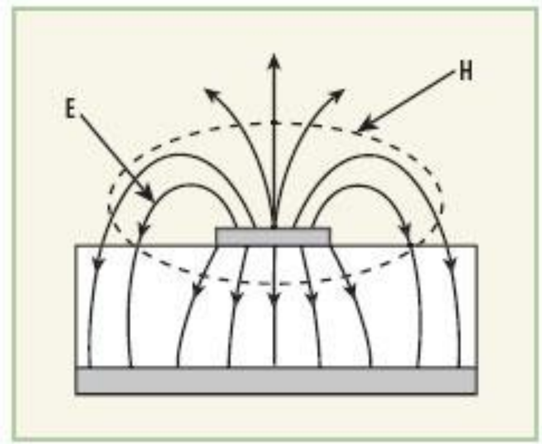
J. Appl. Phys., 2011

Opt. Lett. 2010

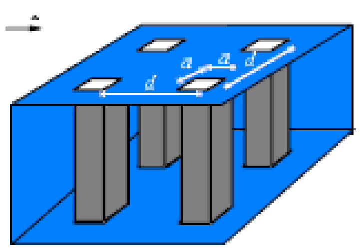
The 2nd Generation: Plasmonic Metamaterials

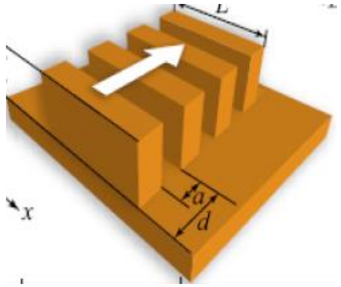
Microwave Technology: TL (Passive) + Semiconductor (Active)





- **Traditional Microwave Transmission Line: Spatial Modes**
- **Non-Conformal; Strong Cross Talks - Signal-Integrity Problems**

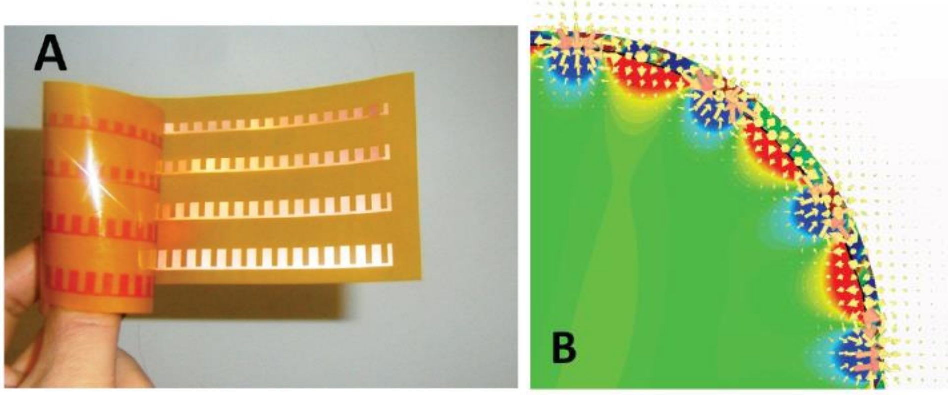




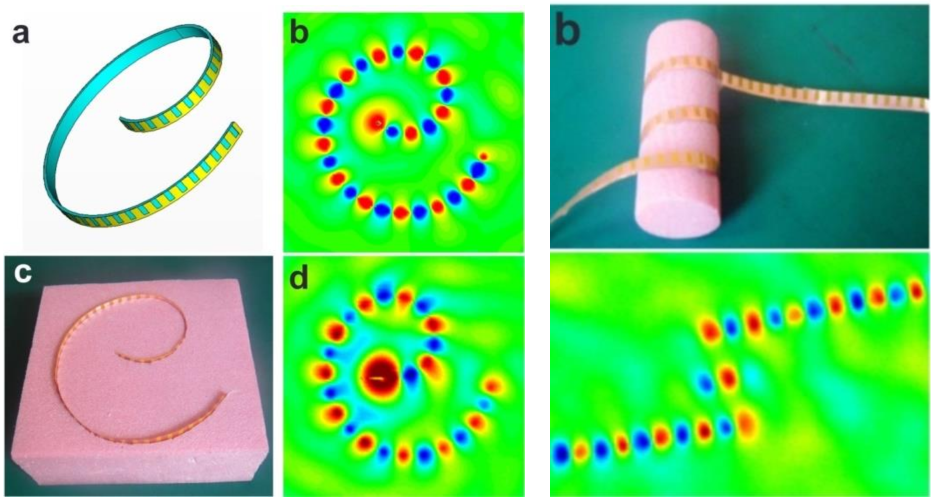
Pendry *et* al. , *Science* 305, 847 (2004)

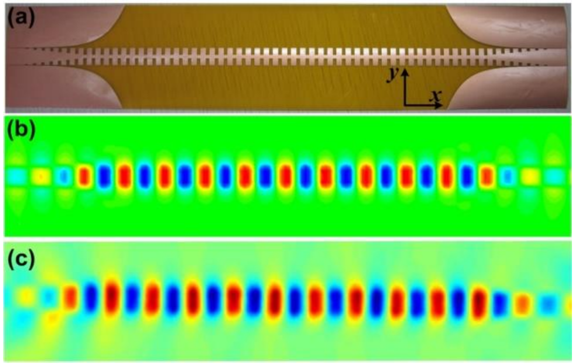
The 2nd Generation: Plasmonic Metamaterials

Ultrathin SPP TL in Microwave



PNAS, 2013 (ESI Top 1%)





Laser Phot. Rev. 8, 146, 2014（ESI Top 1%）

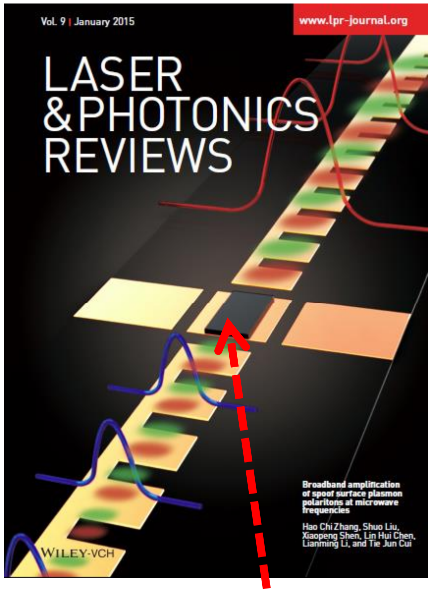
Smooth Conversion Between SPP and Traditional TLs

- **A Series SPP Passive Devices (Filters, Resonators, Couplers)**

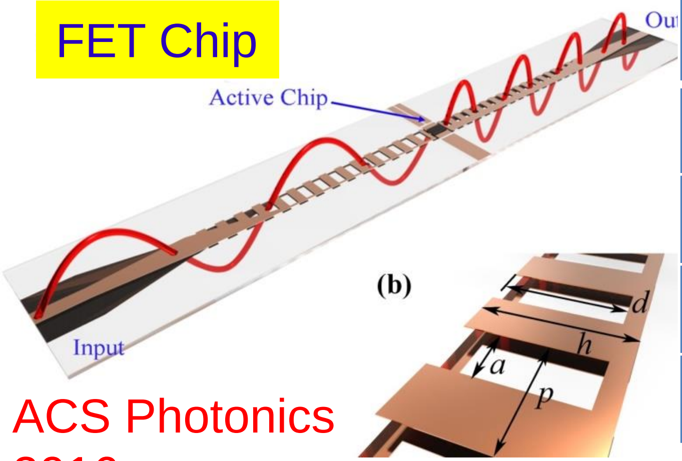
Ultrathin, Conformal, Bendable: Wearable Devices

The 2nd Generation: Plasmonic Metamaterials

Take advantages in microwave: Active SPP Devices



FET Chip



ACS Photonics 2016

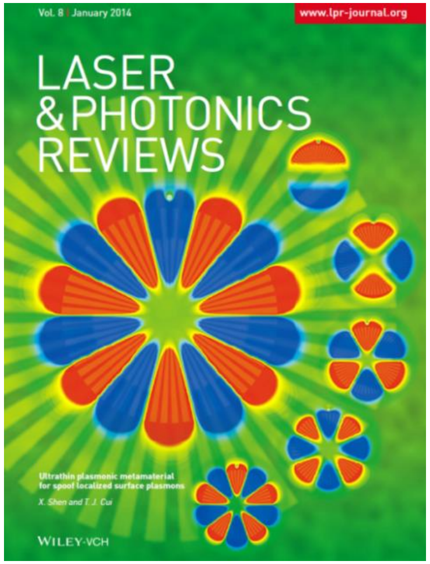
f	1st	2nd	3rd
5 GHz	-15.0	11.1	-3.6
6 GHz	-17.0	10.0	-6.2
8 GHz	-5.0	10.6	-30.0
10 GHz	-8.6	10.2	-55.0

Amplifier Chip

SPP wave is amplified by 20dB in broadband

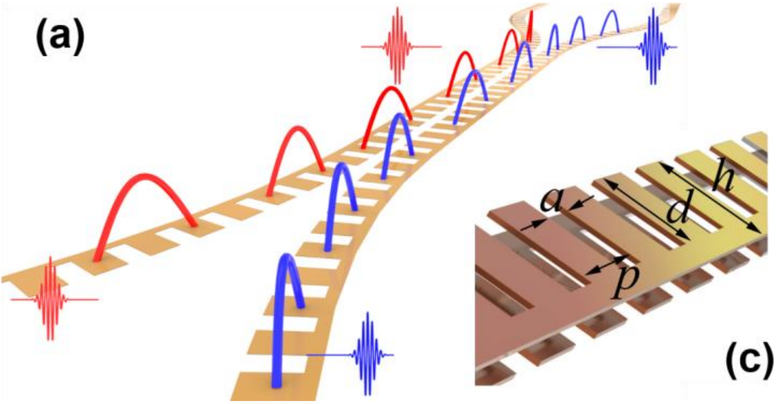
Ultrathin LSPs

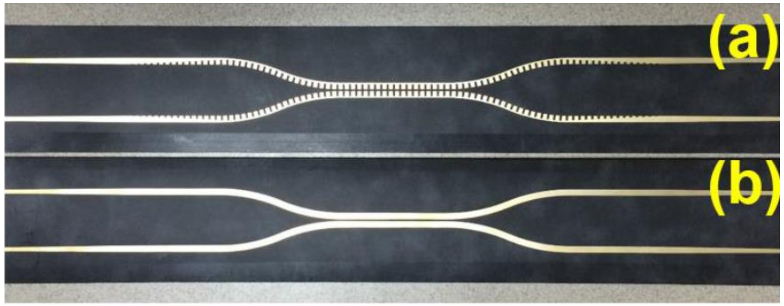
Laser Phot. Rev., 2015 (ESI Top 1%)



- **Realize the first microwave SPP amplifier and multiplier … More**

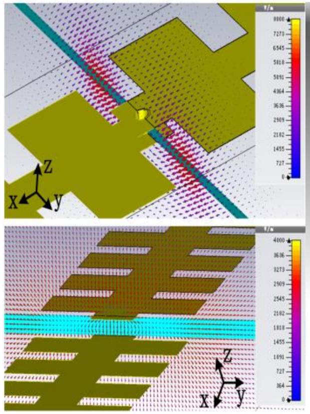
The 2nd Generation: Plasmonic Metamaterials

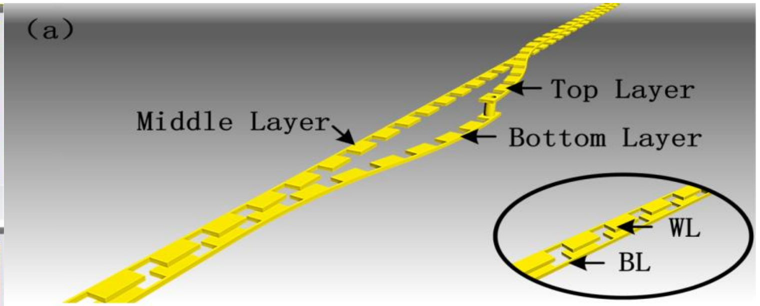




ACS Photonics, 2015.

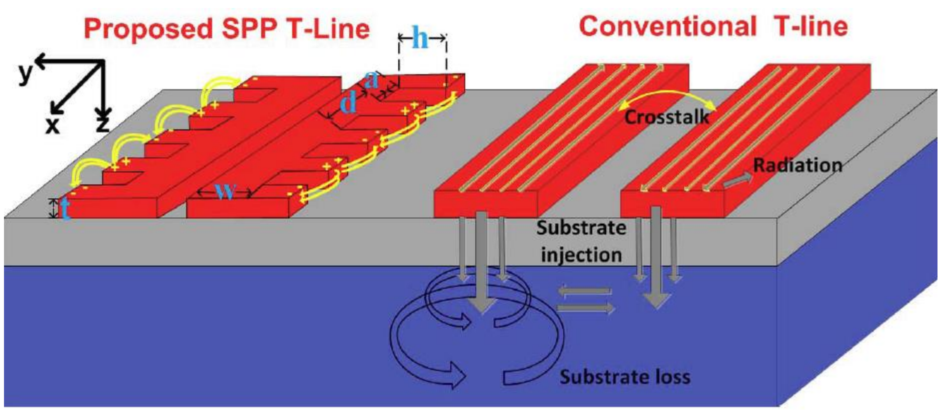
Mutual coupling reduction by SPP TLs: Solving the signal integrity problem from the physics level

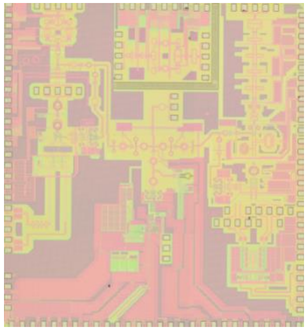




SPP TLs in Multi-Layers

Sci. Rep. + Adv. Mat. Tech, 2016





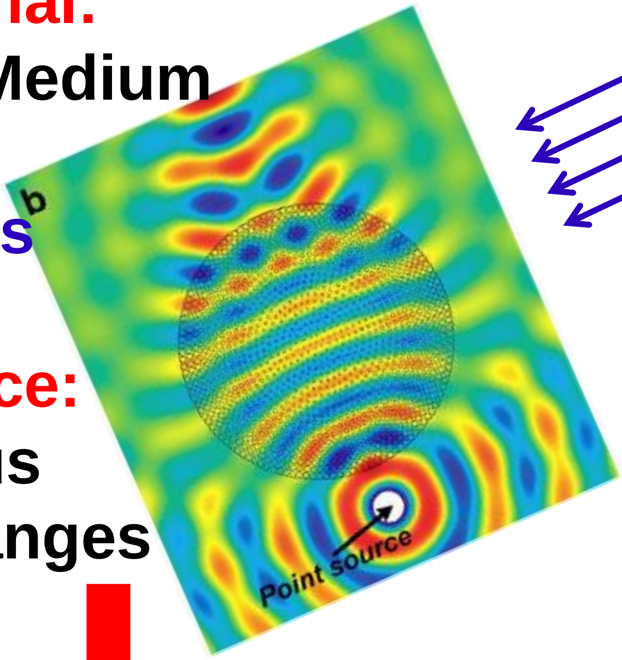
CMOS @ 220-325GHz
(SEU + NTU)
Sci. Rep., 2015.

Target: Systems and SPP ICs

Traditional Metamaterials

Metamaterial:
Effective Medium
Extreme Parameters

Metasurface:
Continuous Phase changes



Lights or EM Waves

Wave-Matter Interactions

Physical Principles

Problems & Challenges:
- ◆ Static; Fixed Features
- ◆ At most Tunable

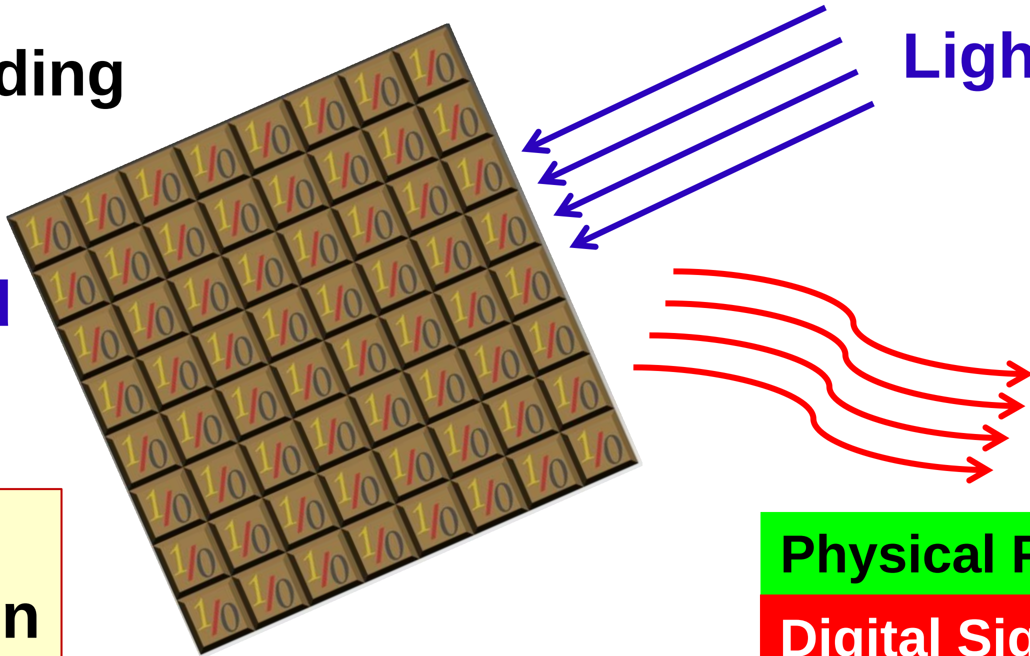
- ◆ New Physics (Exciting)
- ◆ New Devices
- ◆ New Applications

Information Metamaterials

Digital Coding

Digitally Controlled

Digital Information



Lights or EM Waves

Wave-Digital Interactions

Digital World on Physical World

Physical Principles

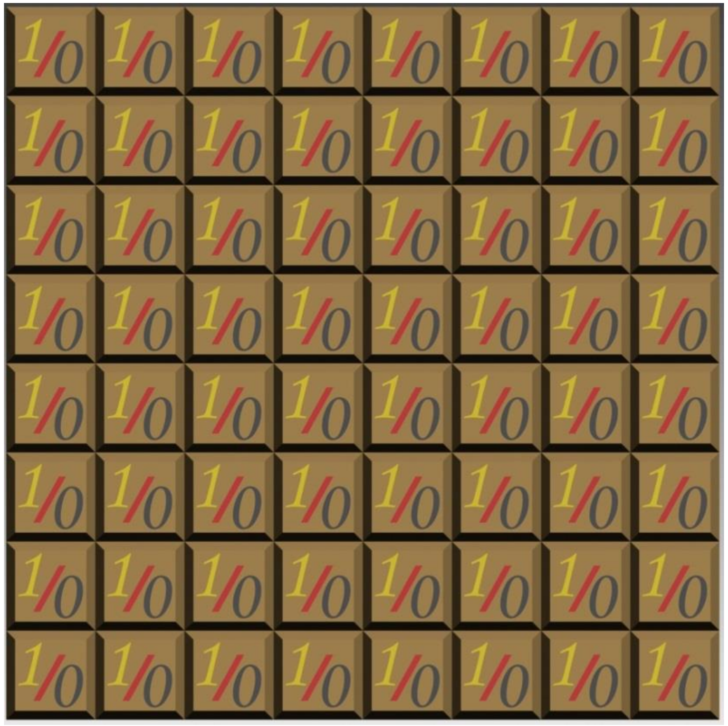
Digital Signal Processing
Information Theory

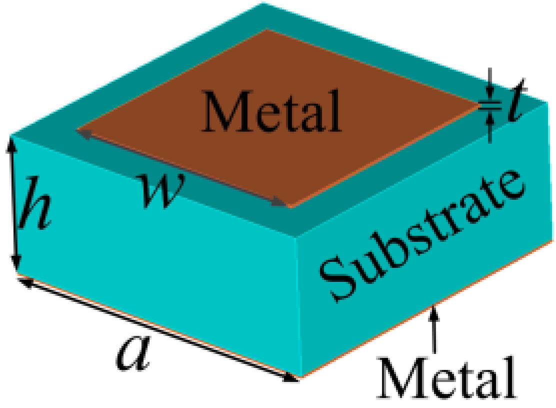
Metamaterial is not only a material, but a system and a real-time processor

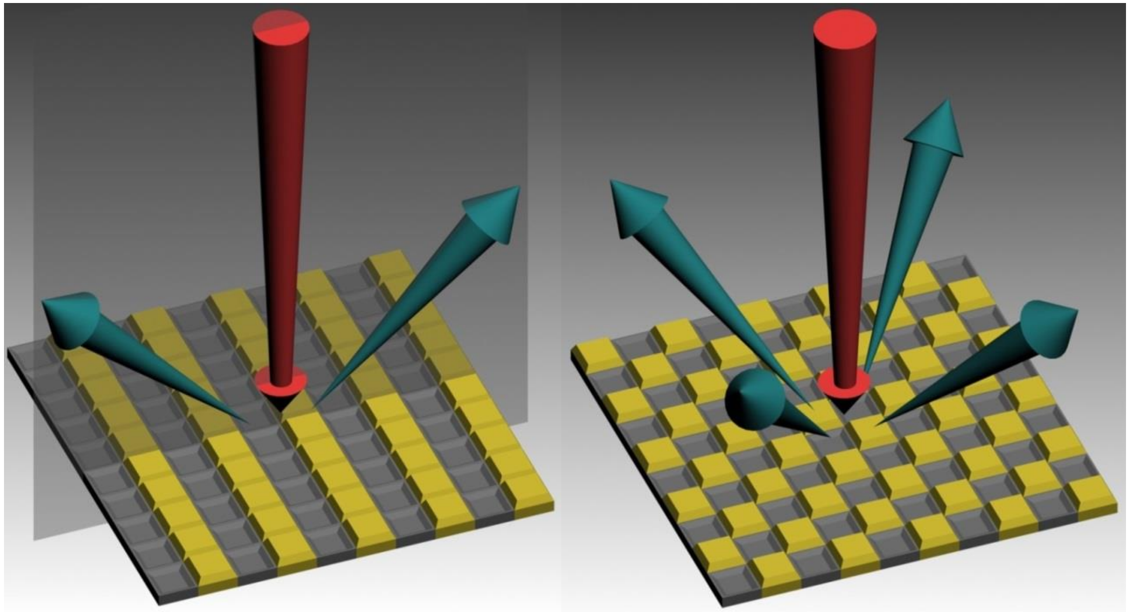
- New Physics
- New Devices
- New Applications
- New-Concept Systems

Coding Metamaterials

1-Bit Coding Metamaterial





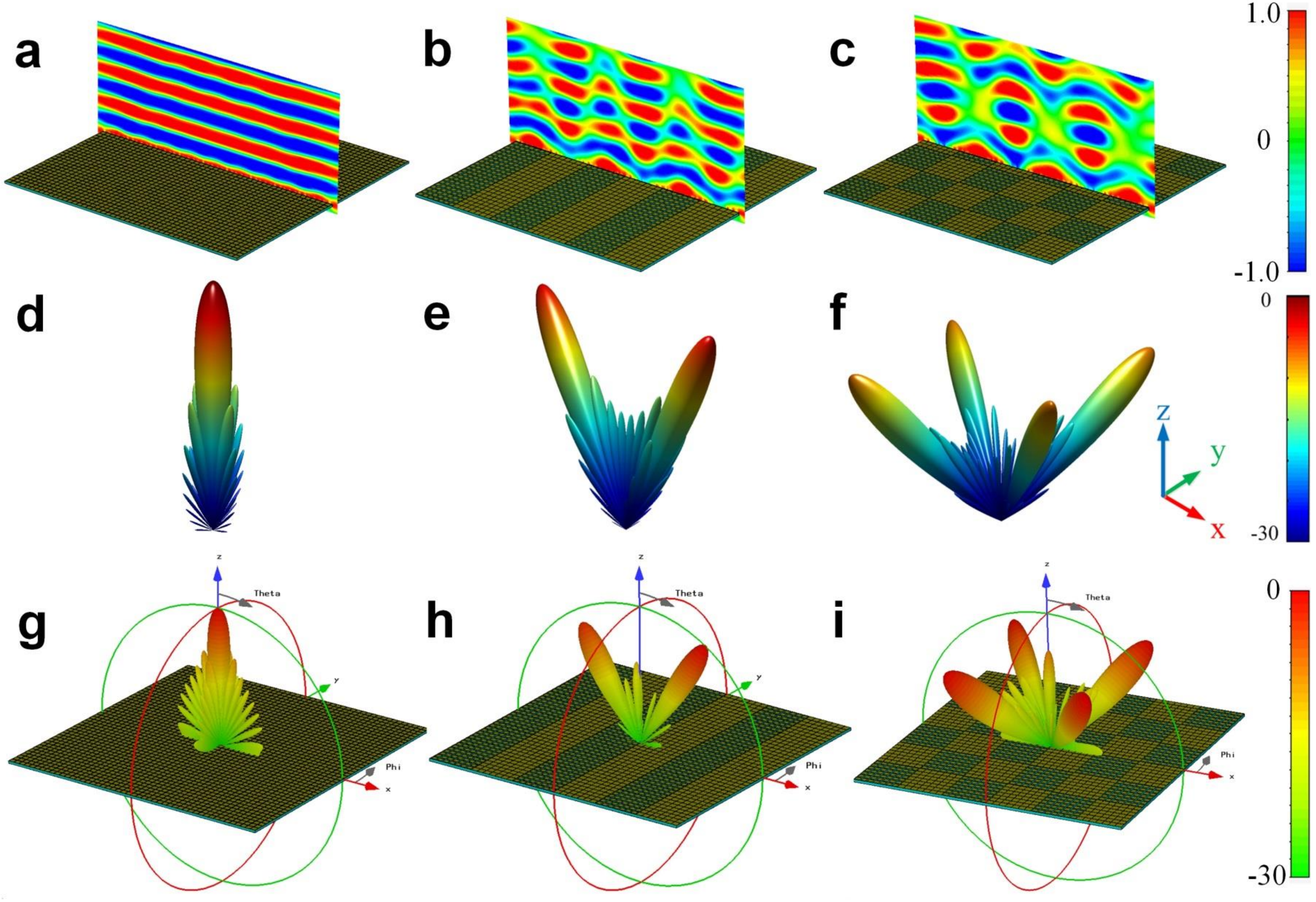


- ◆ **0 Unit: 0 Phase**
- ◆ **1 Unit: 180 Phase**

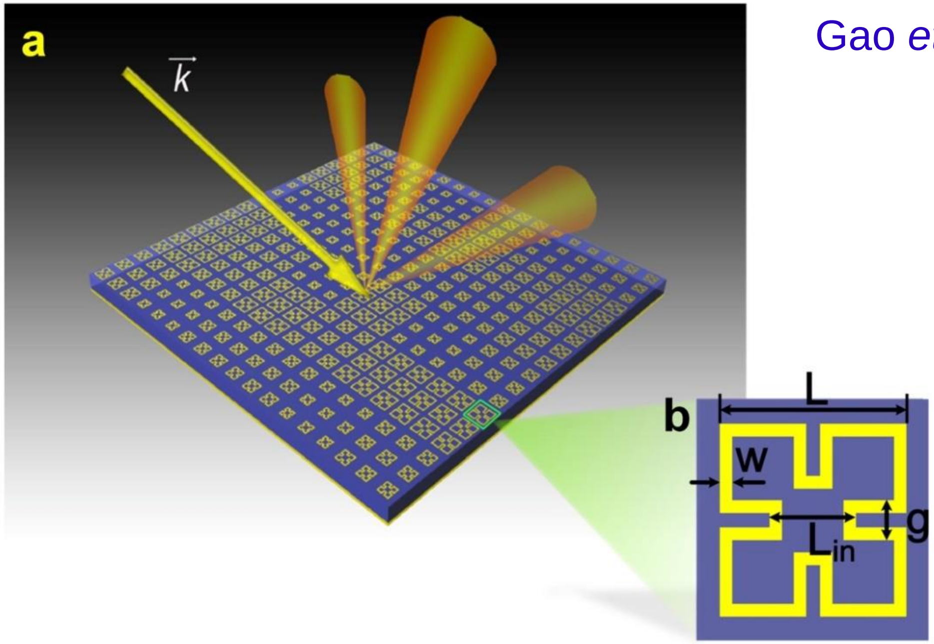
Cui et al., Light: Science & Applications 3, e218; 2014

Cited by 210 times; Light High Citation Award

Coding Metamaterials



Terahertz Coding Metasurface



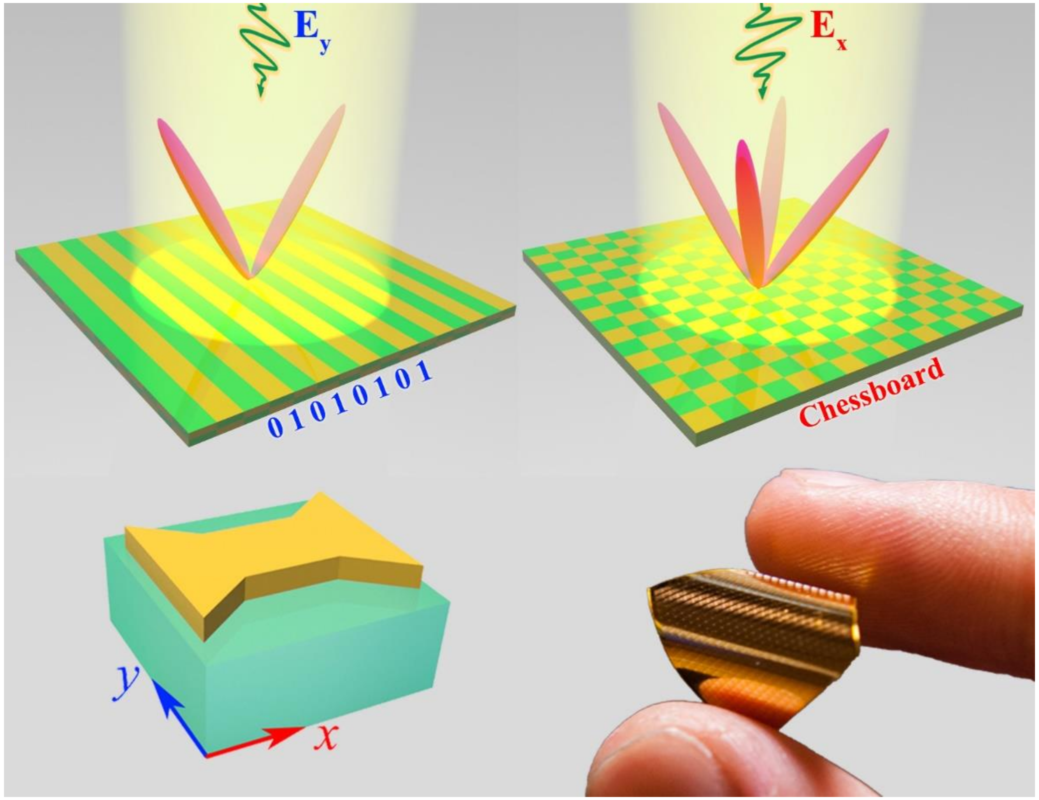
Gao *et* al., Light: Science & Applications 4, e324 (2015)

- **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**

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

Anisotropic Coding Metamaterial

y-pol *x*-pol



Anisotropic coding particle

Flexible and ultrathin sample

Features:

- **Anisotropic design**
- **Independent digital state**
- **Dual-functionality**

Best Paper Award of Chinese Optics in 2016

Manipulation of EM waves depends on the polarization

Liu et al., *Light Sci. Appl.* 5, e16076 (2016)

Digital Metamaterials

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

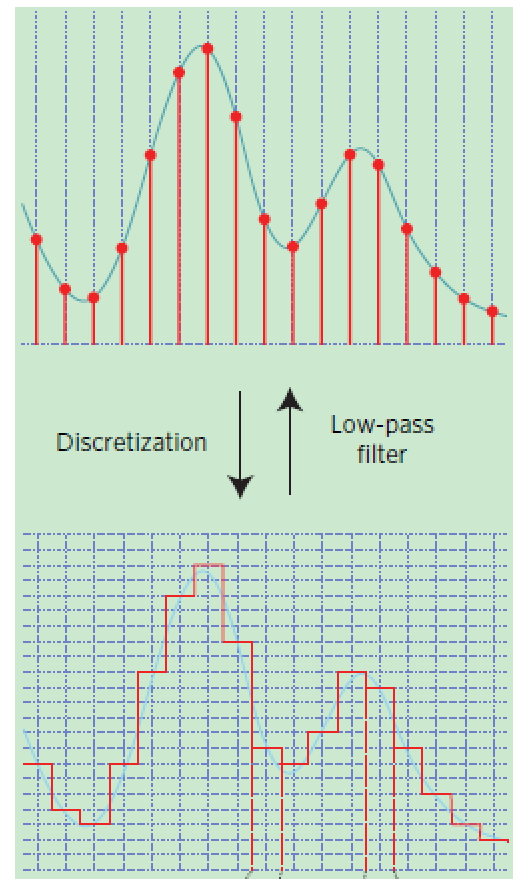

nature materials

ARTICLES

ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NMAT4082

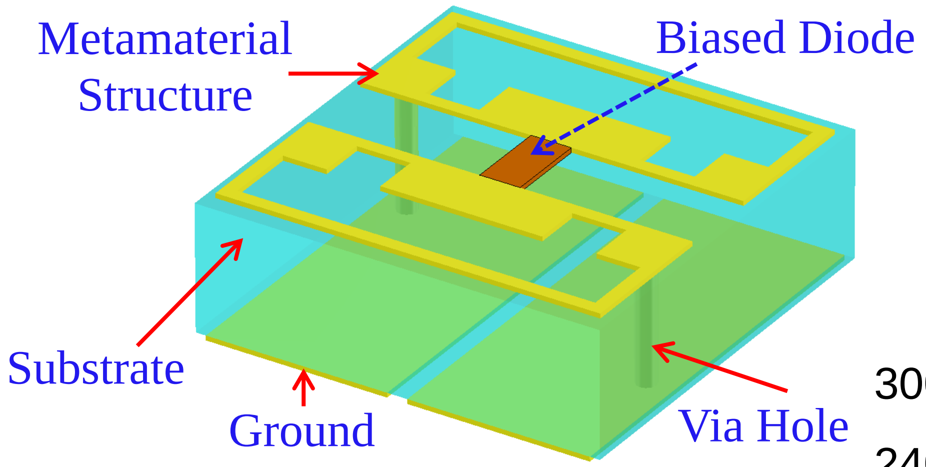
Digital metamaterials

Cristian Della Giovampaola and Nader Engheta*



- ◆ **The "digital" here in still in the scope of effective medium; Difficult for realization.**
- ◆ **Our concept is proposed independently, and has totally different meaning: digitally control**

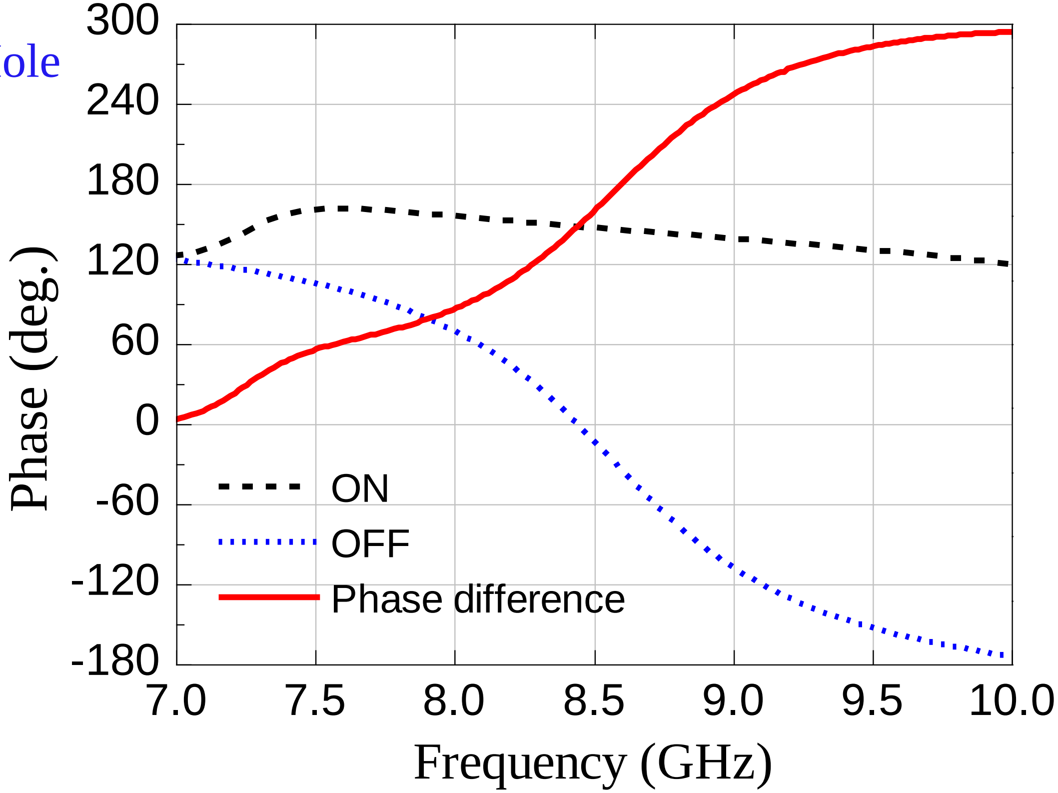
Digitally-Controlled Metamaterials



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

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

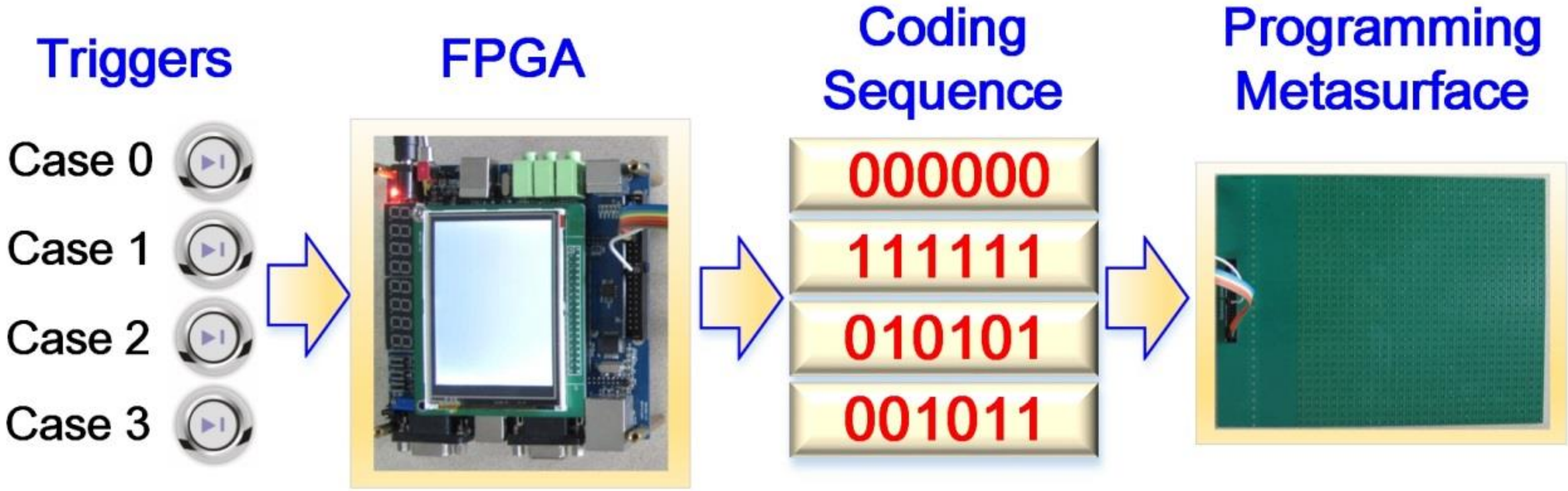
- **Importance:**
- **Make a bridge between the physical world and digital world**



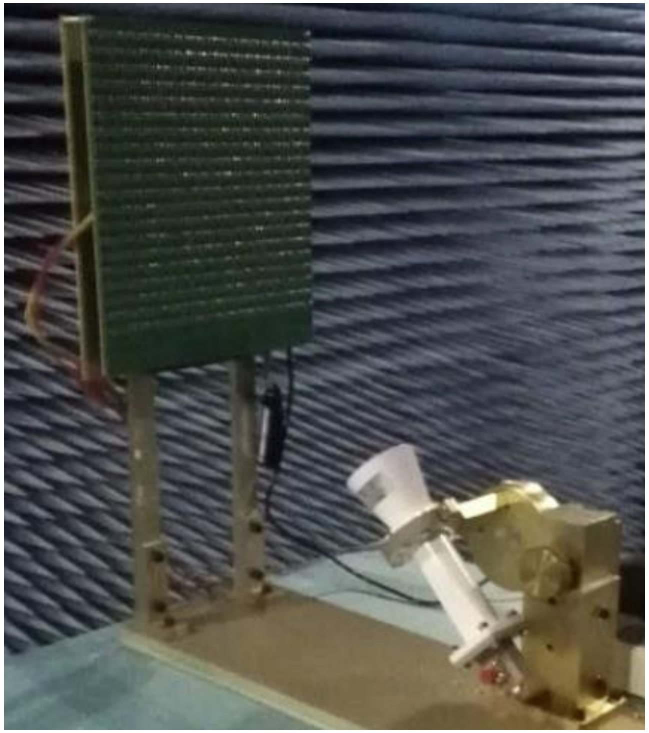
The Phase Responses

Programmable Metamaterials

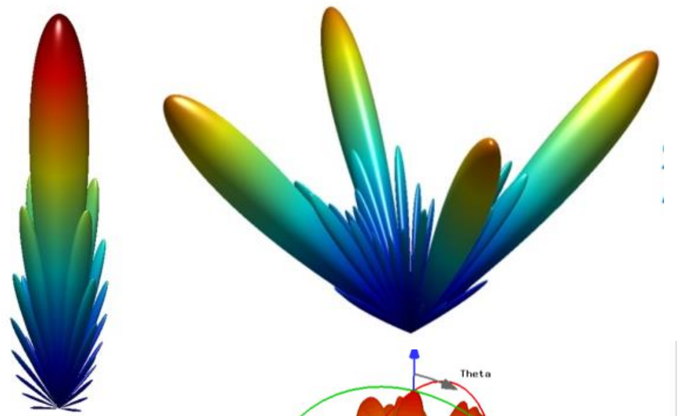
- **By using field-programmable gate array (FPGA) hardware, we realize digital control over the digital metamaterial.**
- **We can write a program consisting of many cases onto FPGA, which is used to control many functionalities in real-time: Programmable Metamaterial.**

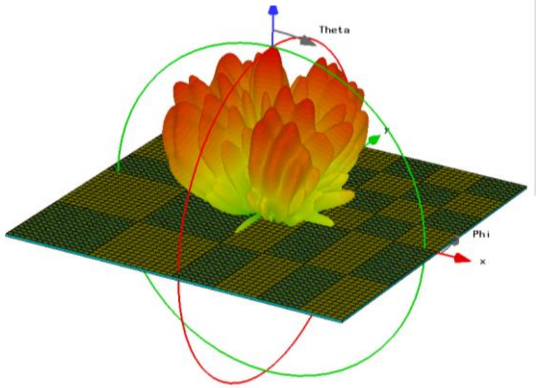


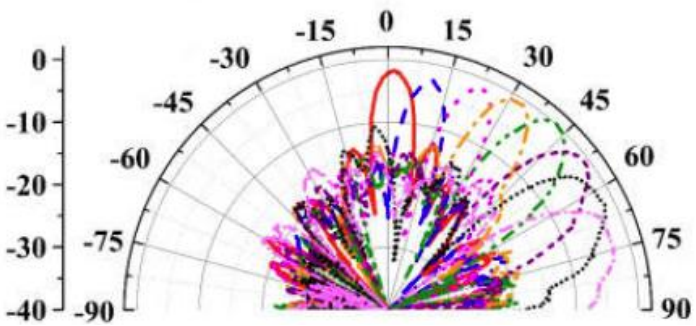
New-Concept Radar

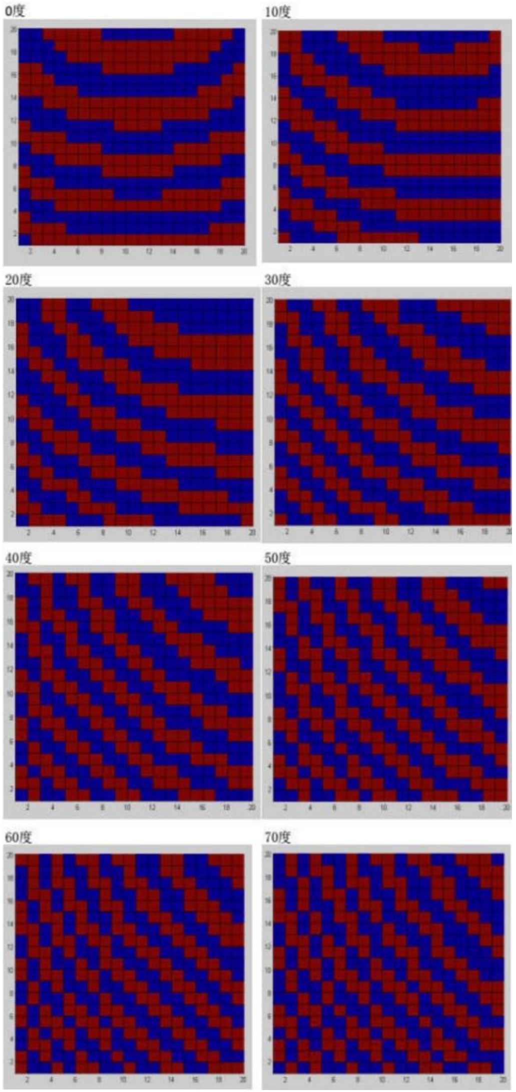


20X20 Programmable Information System





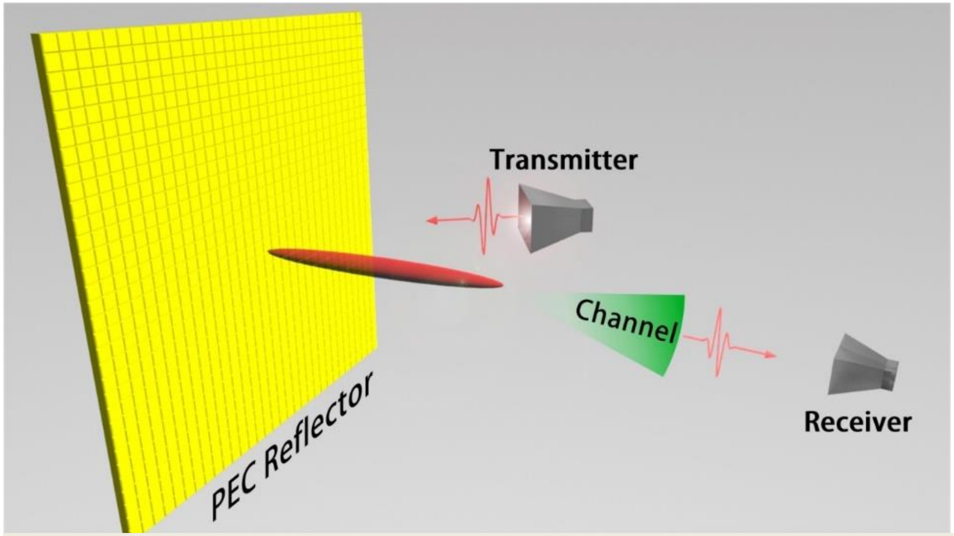


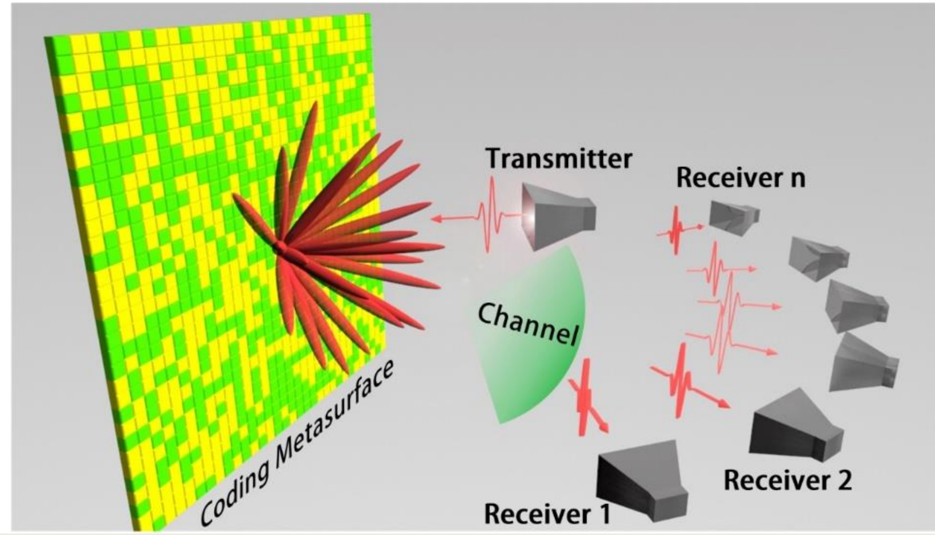


New-Concept Radar:

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

Basic-1: Information Entropy





The information contained in the metasurface is different

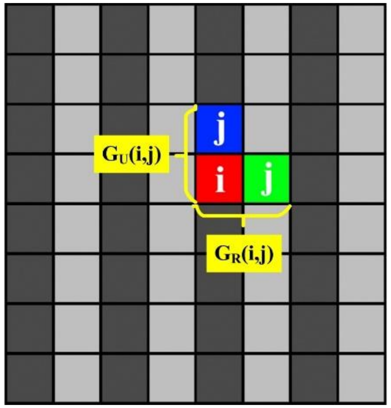
Using Shannon Entropy to Describe the Information

Shannon Entropy

$$H_1 = -\sum_{i=1}^{2} P(x_i)\log_2 P(x_i)$$

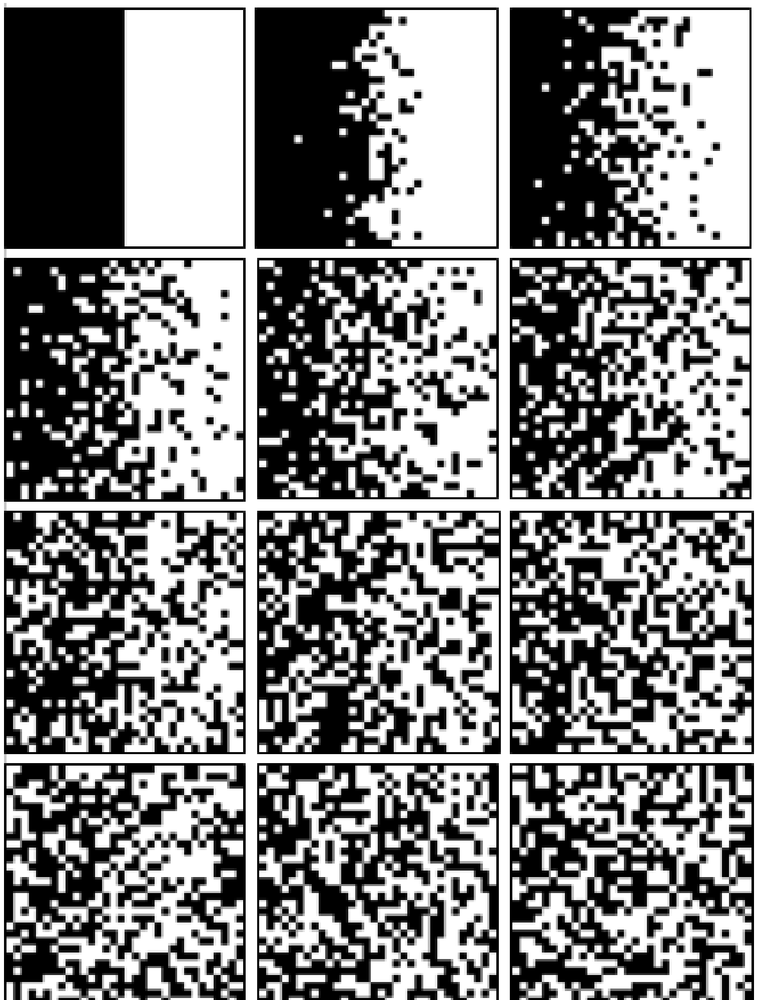
Modified Shannon Entropy

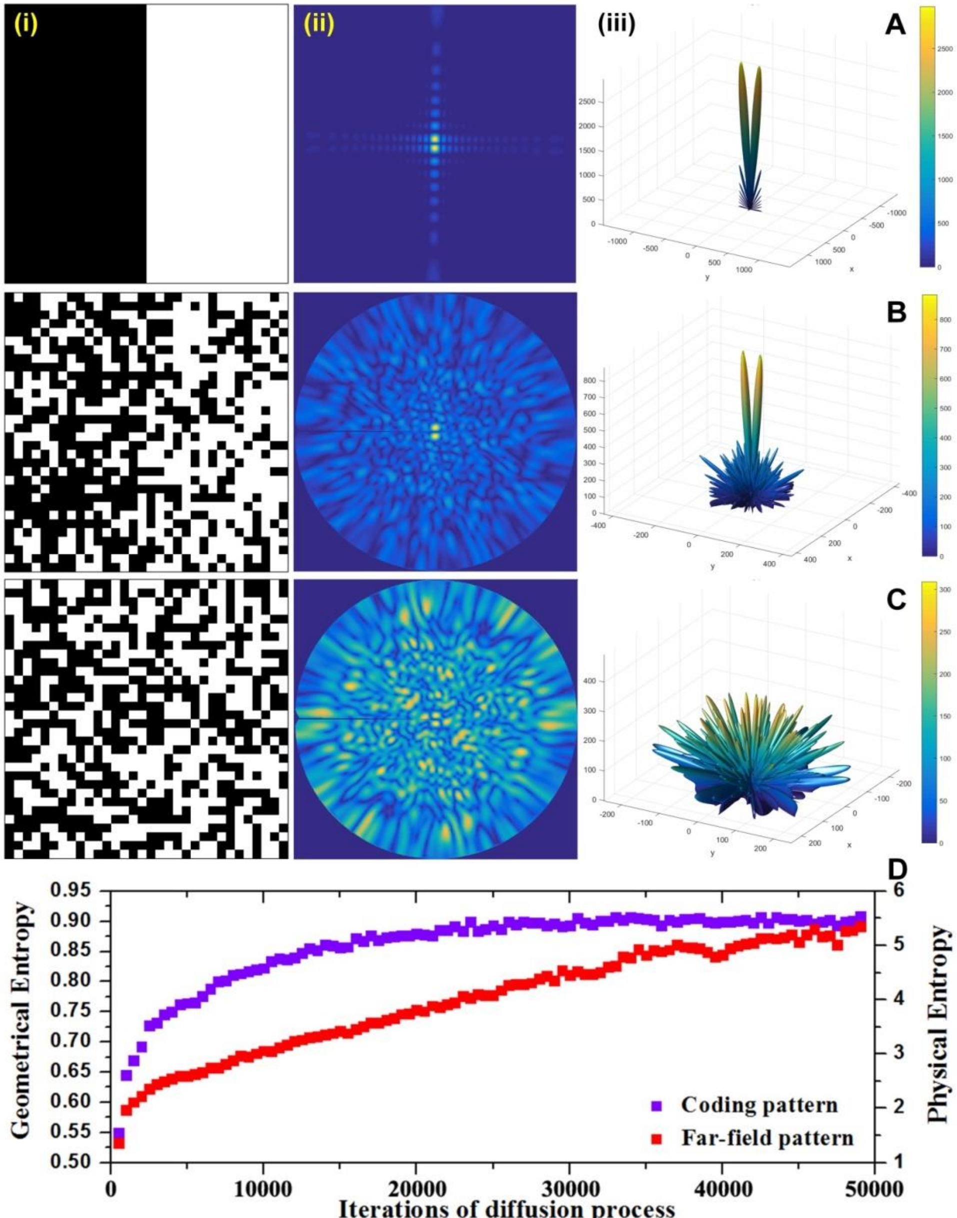
$$H_2 = -\frac{1}{2}\sum_{i=1}^{2}\sum_{j=1}^{2} P_{ij}\log_2 P_{ij}$$



Cui et al., Light: Science & Applications 5, e16172, 2016

Coding Metasurface and Entropy





The natural diffusion process leads to the increase of entropy

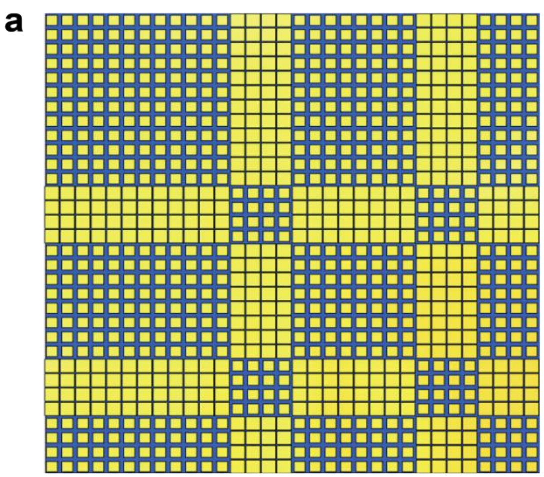
The Optimal RCS Reduction

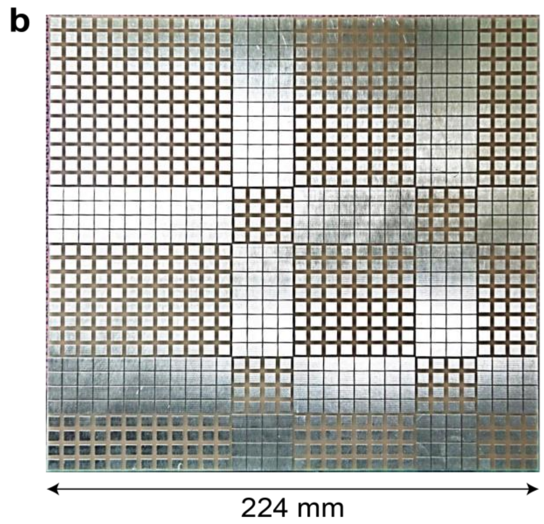
Vincenzo Galdi, University of Sannio, Italy

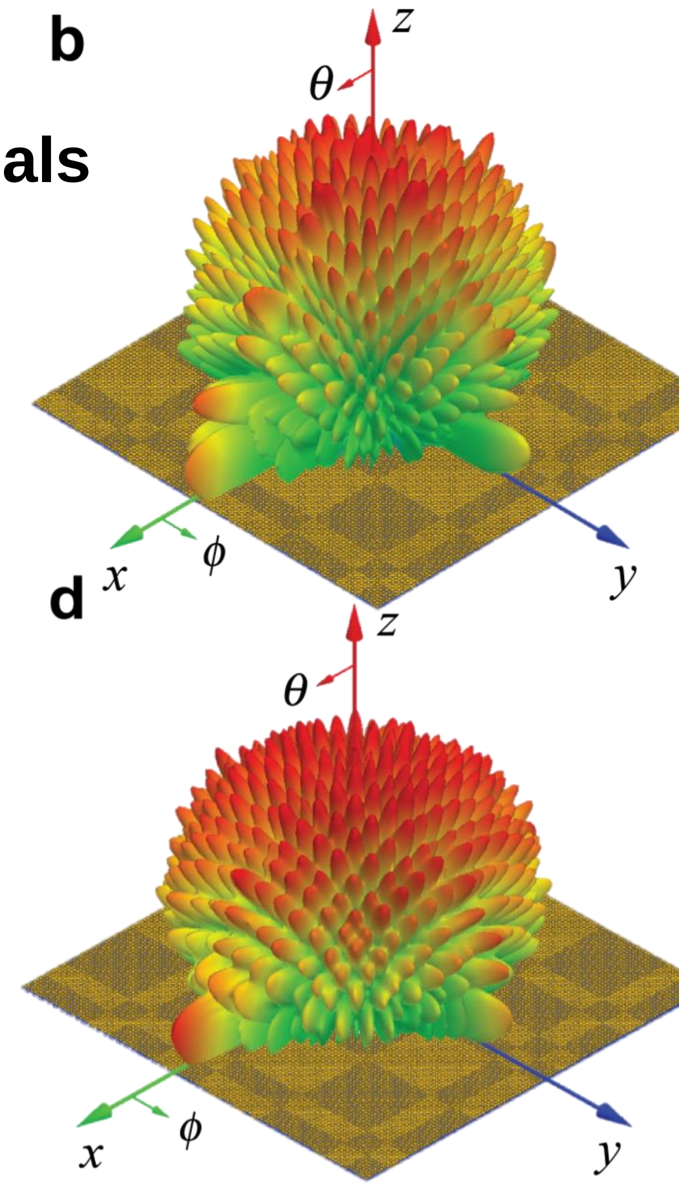
Golay-Rudin-Shapiro (GRS) Polynomials

$$P_{n+1}(x) = P_n(x) + x^{2^n} Q_n(x),$$

$$Q_{n+1}(x) = P_n(x) - x^{2^n} Q_n(x),$$





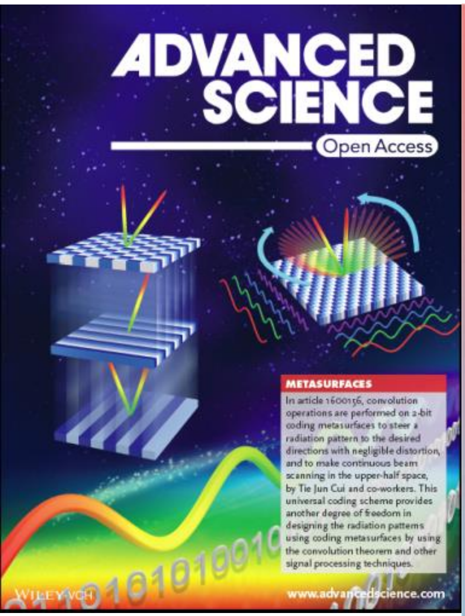


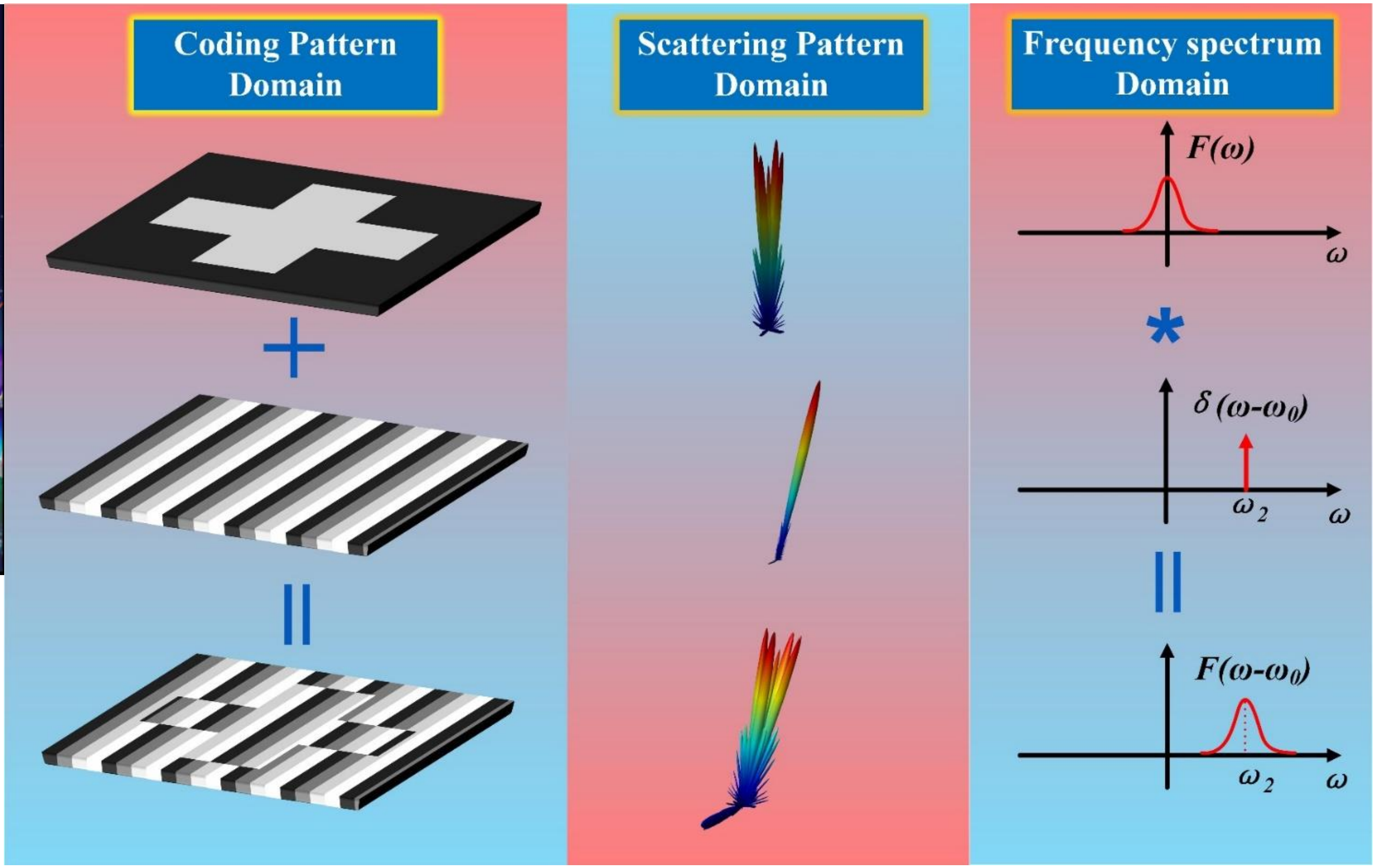
Advanced Optical Materials, 2017

Basic-2: Digital Convolutions

Digital coding representation makes it possible for digital signal processing

Perform Convolutions on Coding Metasurfaces



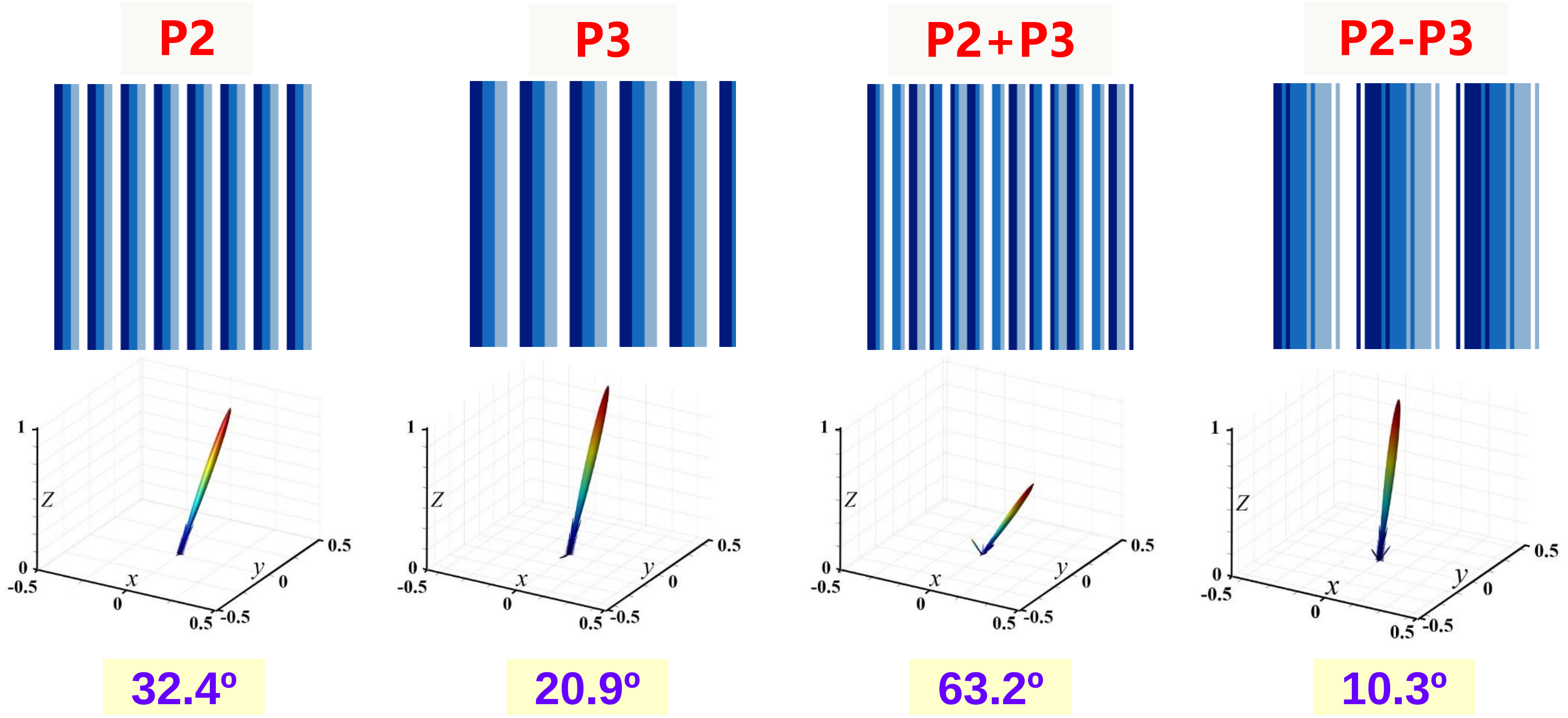


Liu et al., Adv. Sci. 2016, 1600156

Digital Convolutions

The convolution operation ensures 2-bit coding metasurfaces to reach the scattering beam to an arbitrary direction.

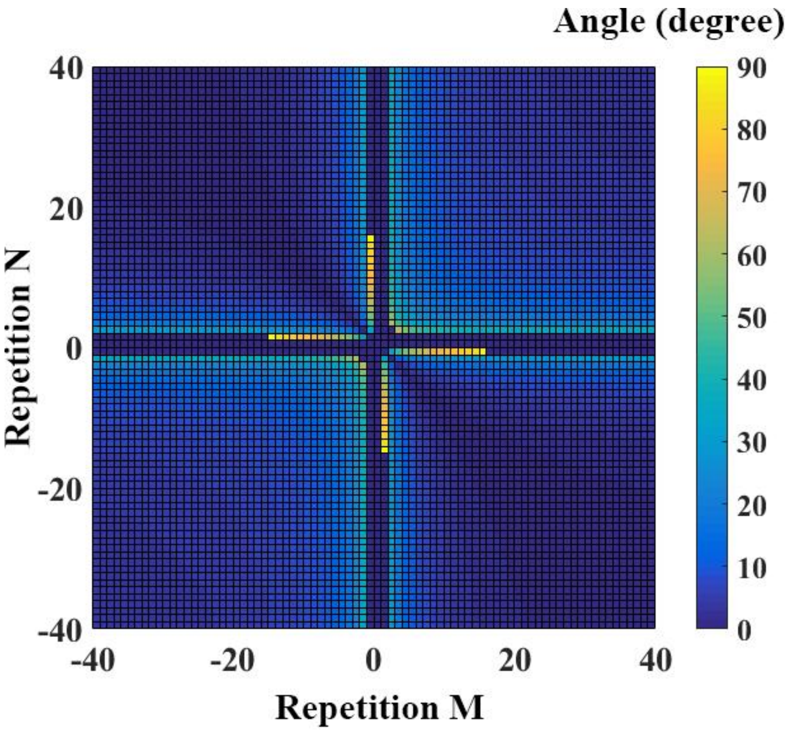
P2='00112233…' P3= '000111222333…'

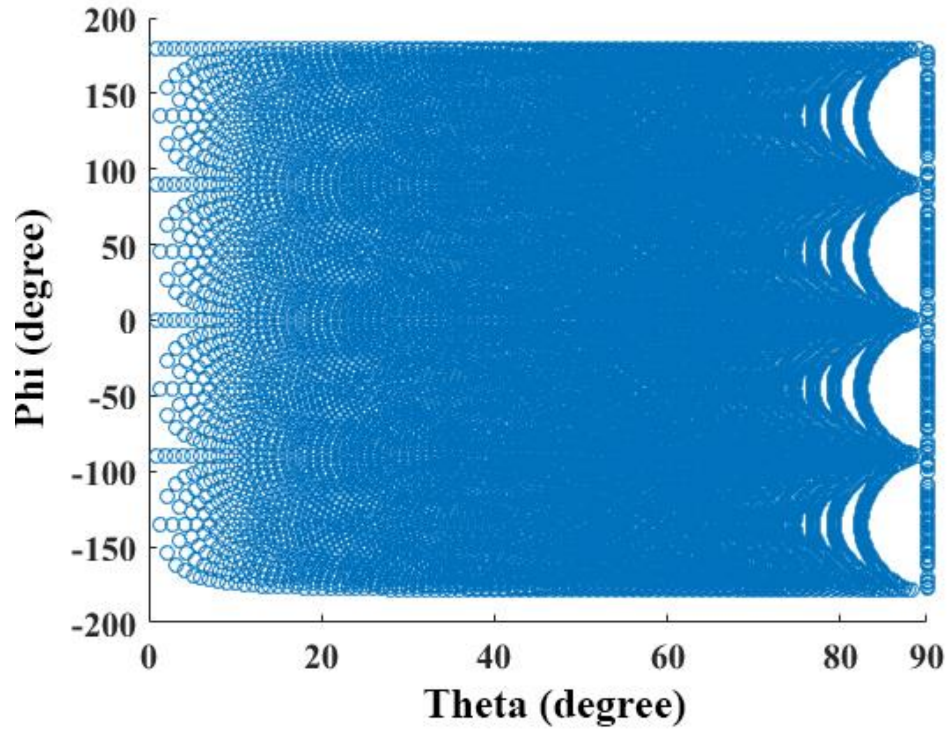


$$\theta = sin^{-1}(sin\,\theta_1 \pm sin\,\theta_2)$$

Liu et al., Adv. Sci. 2016, 1600156

Ability to Radiate at Arbitrary Angle





In-Plane Scanning

$$\theta = sin^{-1}(sin\,\theta_1 \pm sin\,\theta_2)$$

Full Upper-Space Scanning

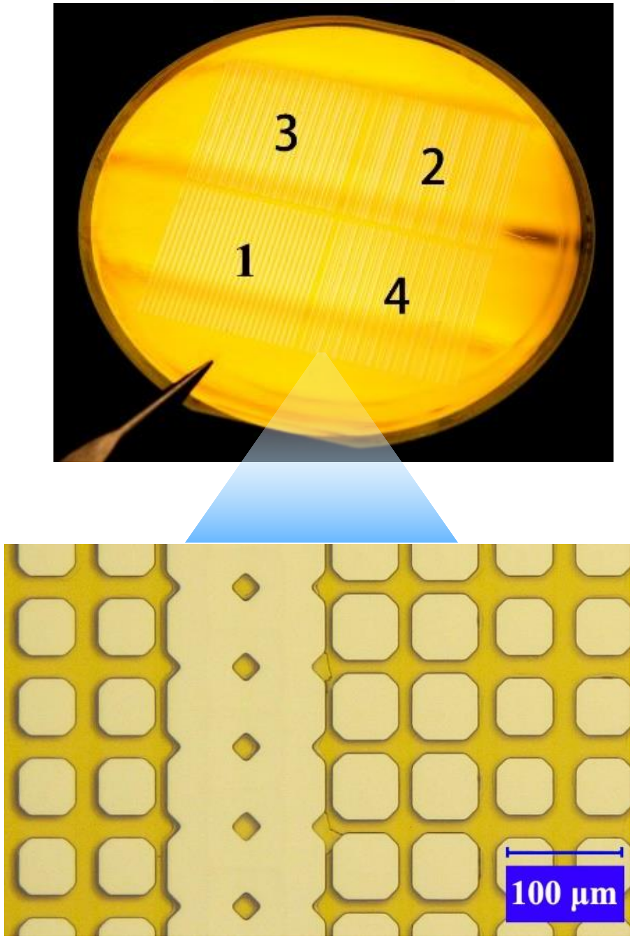
$$\begin{cases} \theta = sin^{-1}\left(\sqrt{sin^2\theta_1 \pm sin^2\theta_2}\right) \\ \varphi = tan^{-1}\left(\dfrac{sin\,\theta_2}{sin\,\theta_1}\right) \end{cases}$$

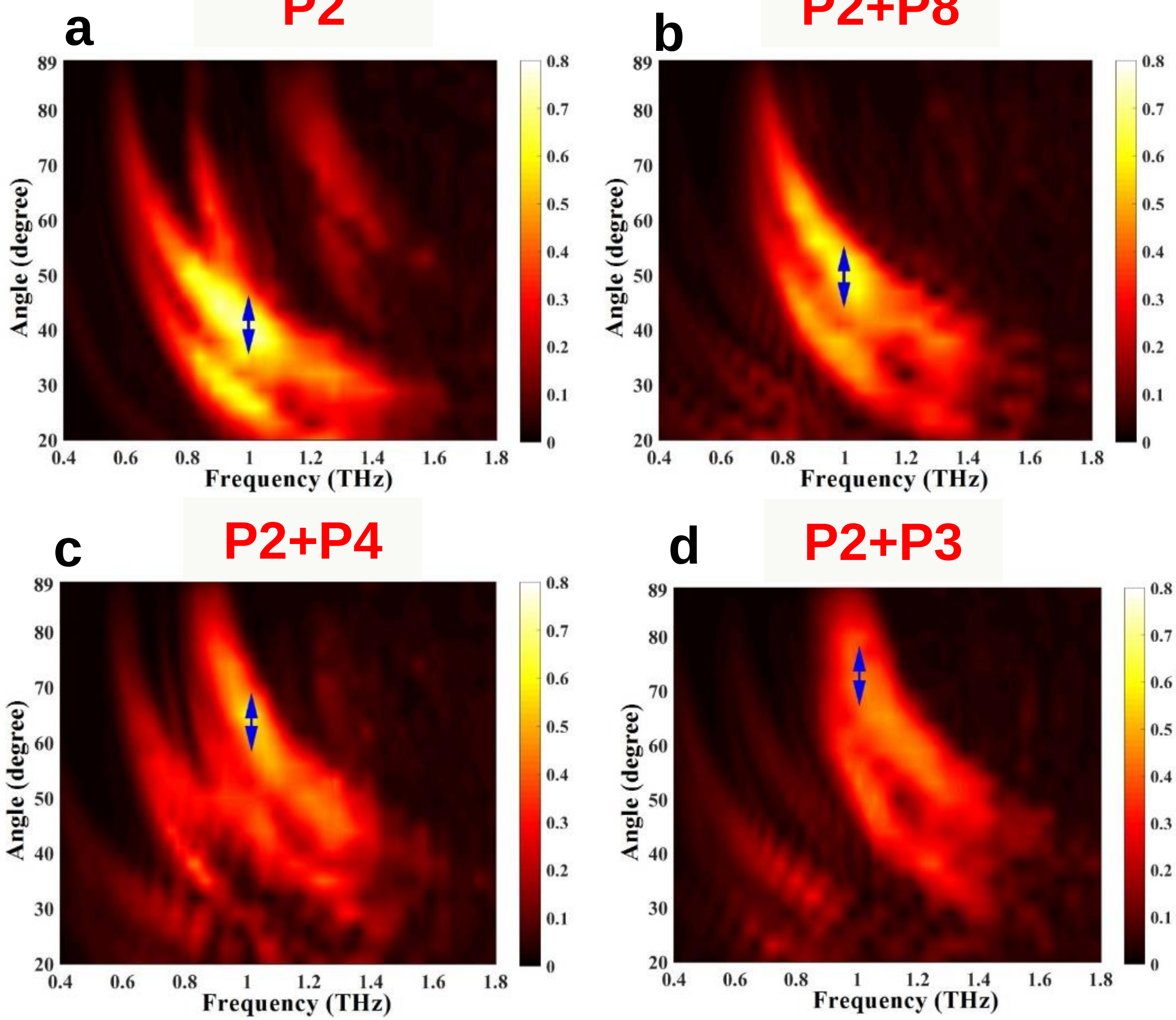
Liu et al., Adv. Sci. 2016, 1600156

Could generate single-beam radiation with arbitrary angle

Fabrication and Experiments

Sample



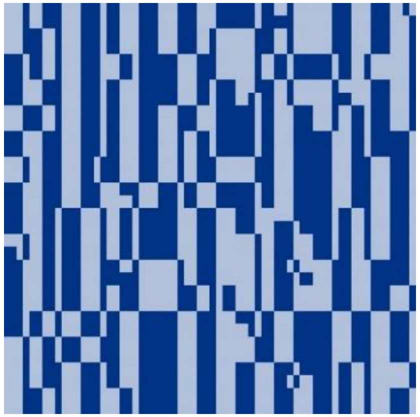
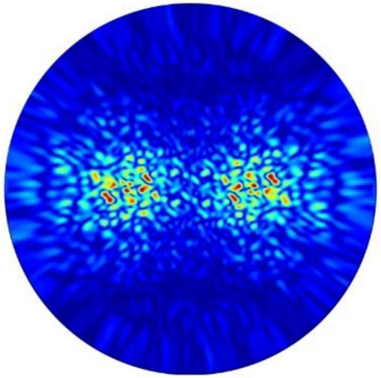


Excellent agreement between simulations and experiments

Multiple Scattering Clouds

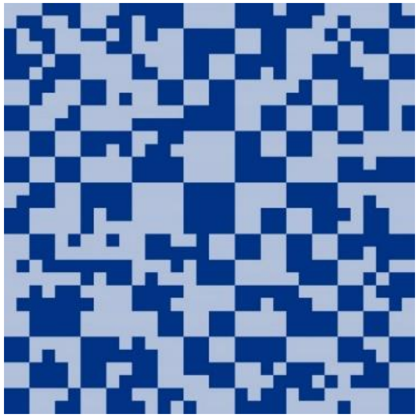
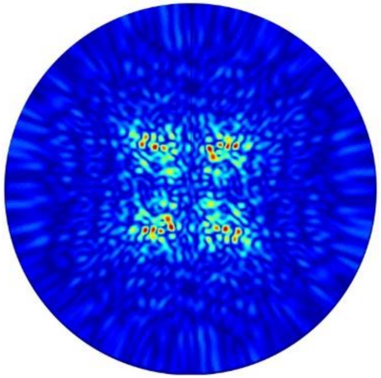
The addition of random coding pattern with periodic coding patterns

0101 + random

Two scattering clouds

Chessboard + random

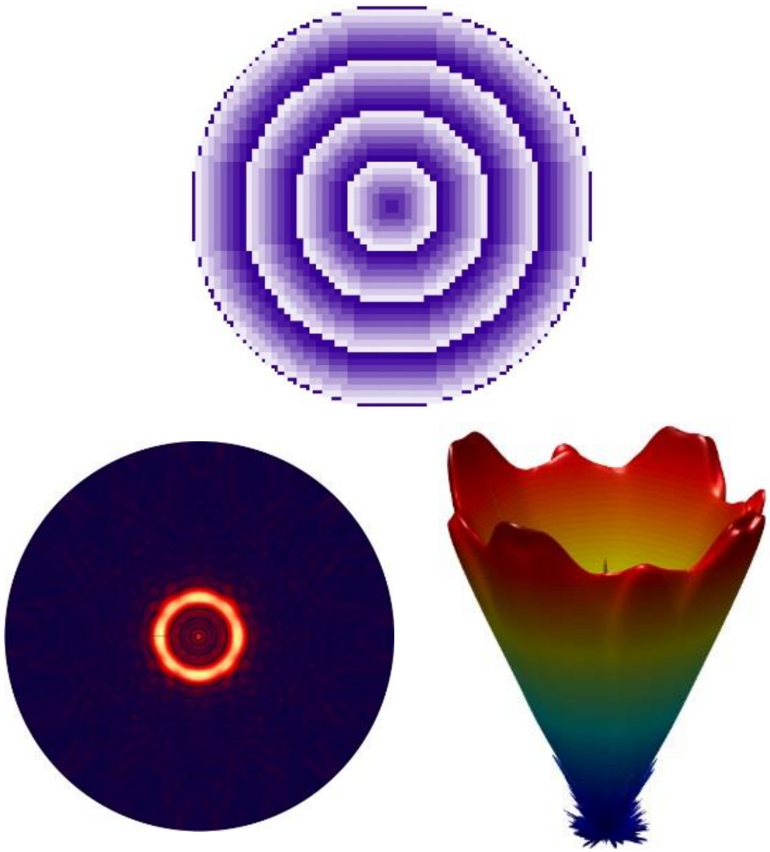



Four scattering clouds

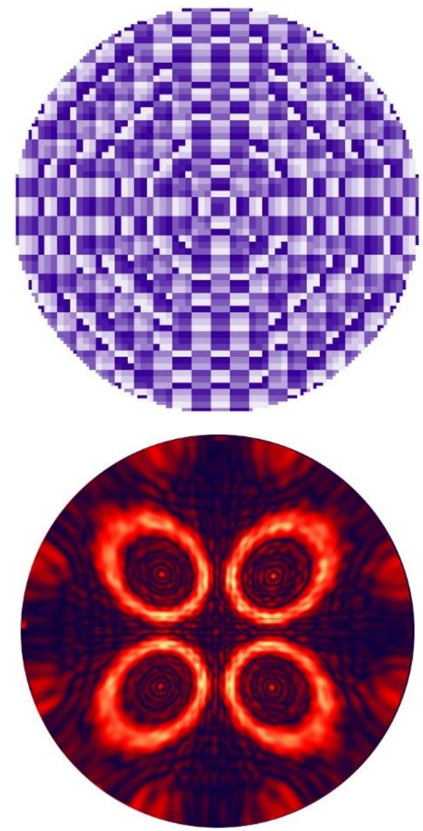
The number of scattering clouds can be arbitrarily designed

Cone-Shaped Scattering Pattern

0011223344556677



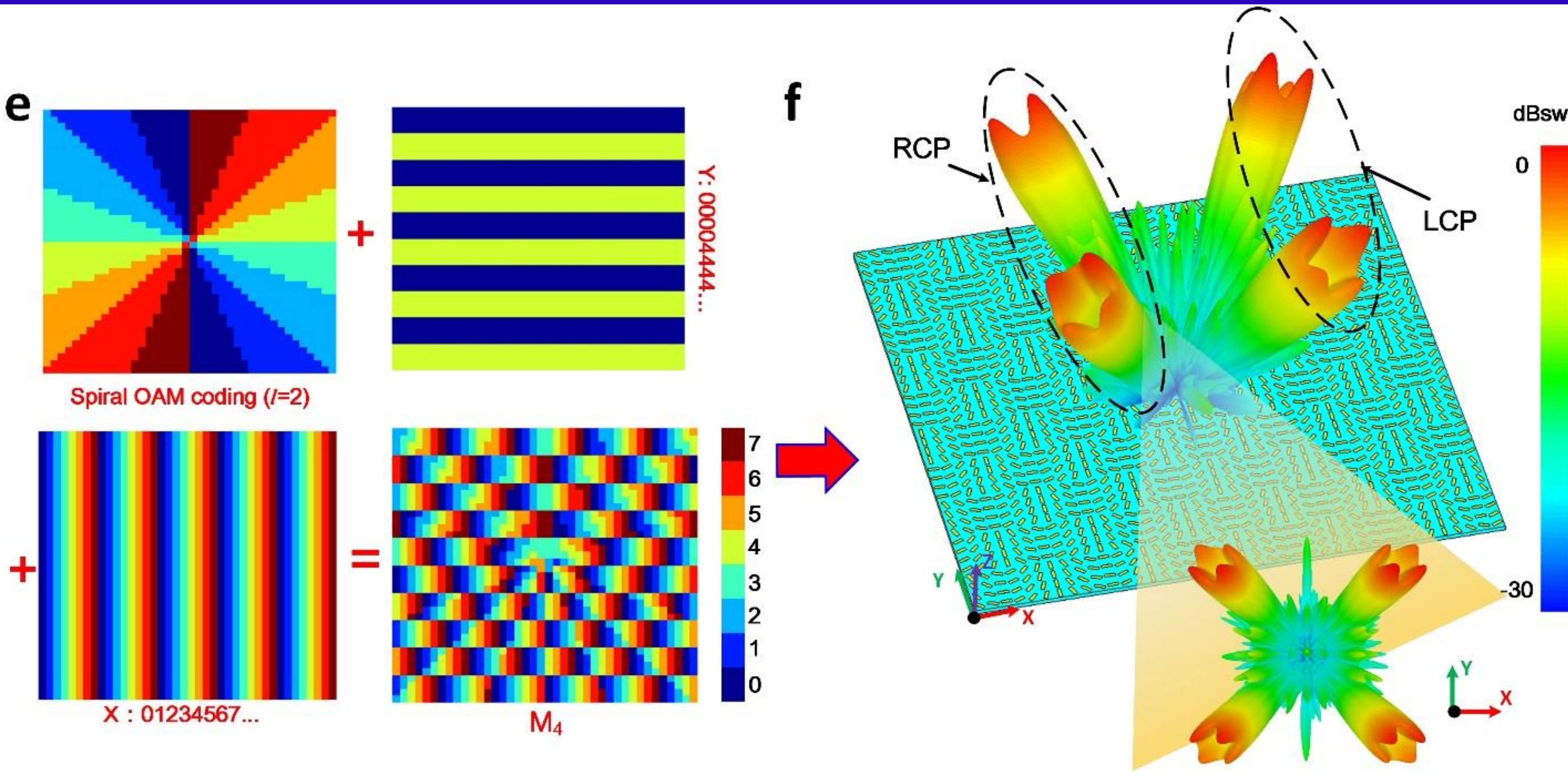
0011223344556677(radial) + Chessboard



◆ **The opening angle, number, and direction of the cone-shaped radiation pattern can be arbitrarily controlled**

Liu, et al. *Journal of Selected Topics in Quantum Electronics,* 23, 1, 2016.

Spin-Controlled Vortex Beams



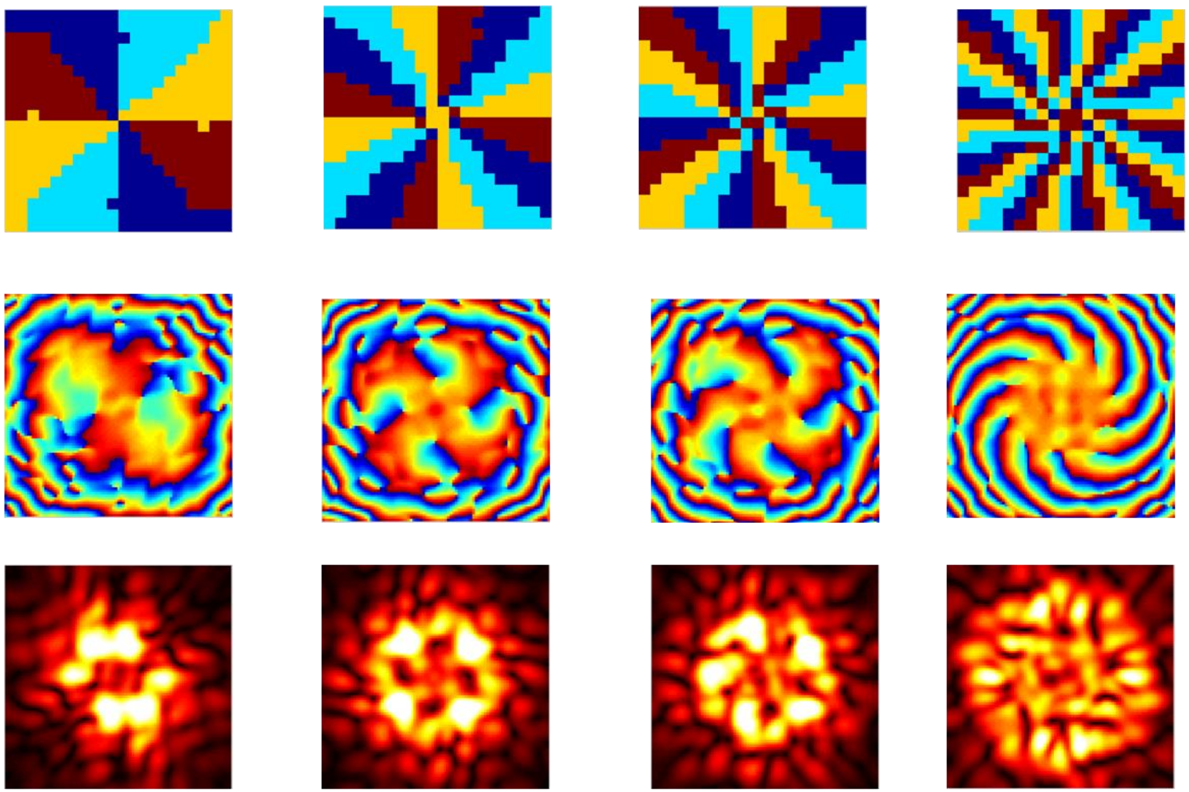
Zhang et al., ACS Applied Materials & Interfaces, 2017

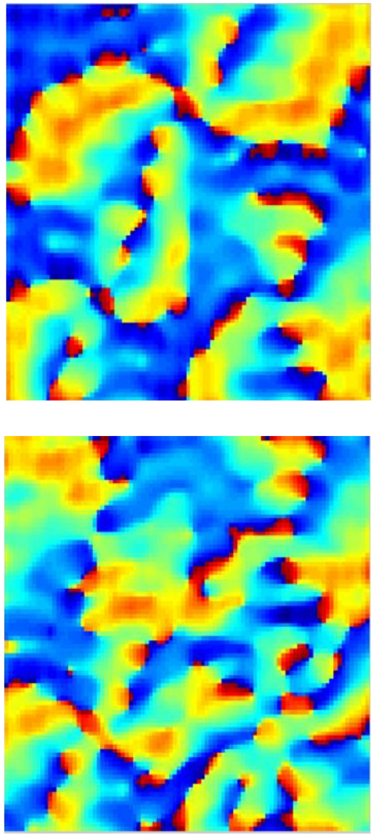
◆Mixing process of coding pattern for **four symmetrical vortex beams** (OAM mode n=2)

Programmable Vortex Generation

2-Bit Digital Coding Patterns

L. Li et al., unpublished, 2017





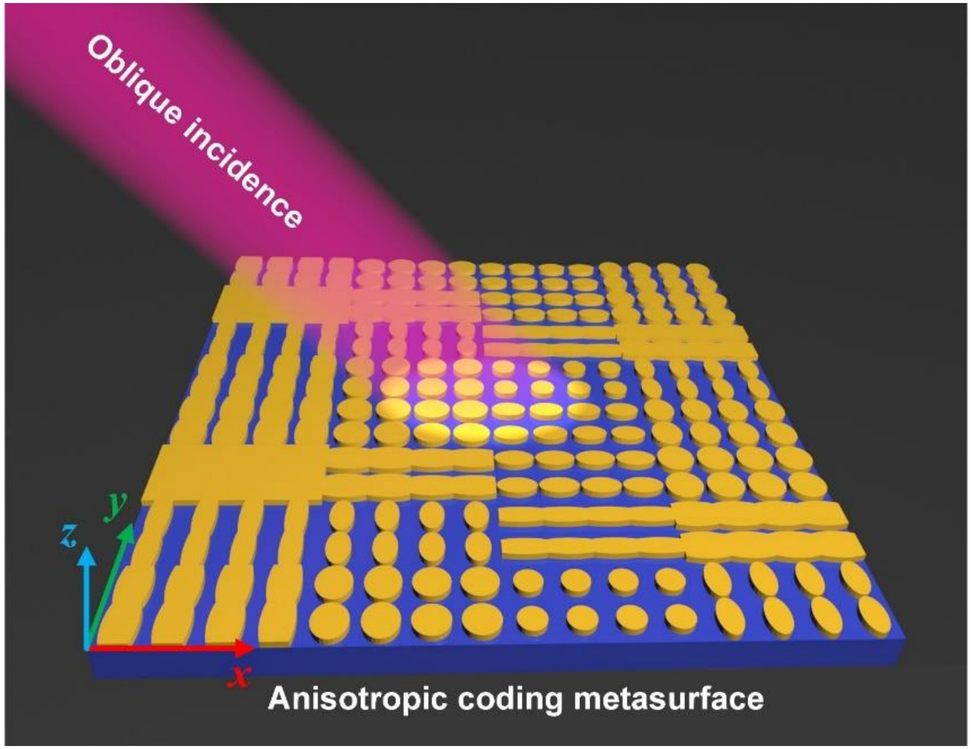
- **All Vortex Beams have been Generated by a Single Coding Metasurface in a Programmable Way**

Multi-Vortex Beams

Under Oblique Incidence

Liu et al., *Light Sci. Appl., accepted* (2018)

Oblique incidence can avoid blockage effect for the normal radiation



Basic Design

Normal Incidence Metasurface

+

Tilt Angle Compensation Coding Pattern

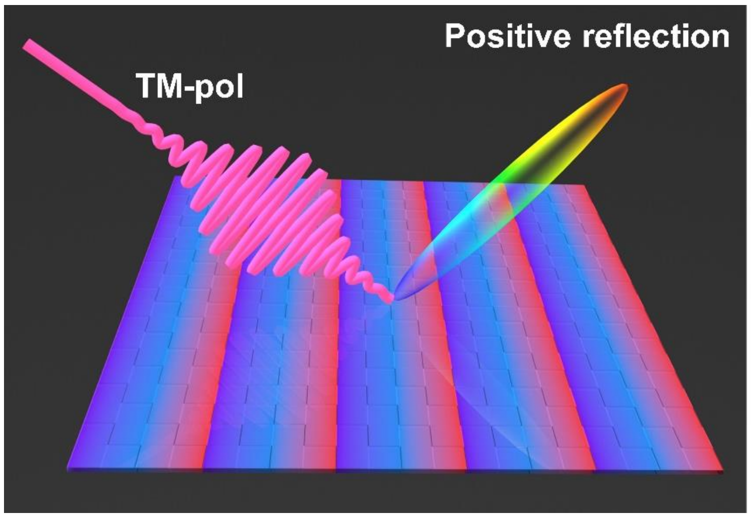
=

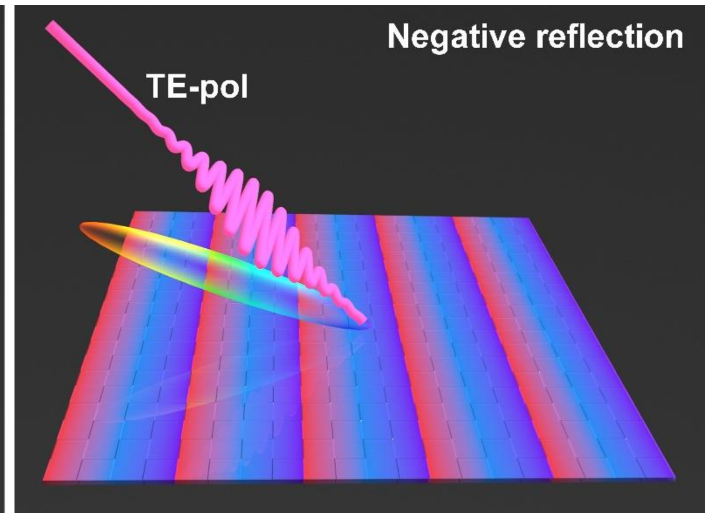
Oblique Incidence with Arbitrary Angle

Spatial-Wave Mode

Positive Reflection

Negative Reflection





The reflected wave should be in the opposite side of the incident wave for the conventional reflection

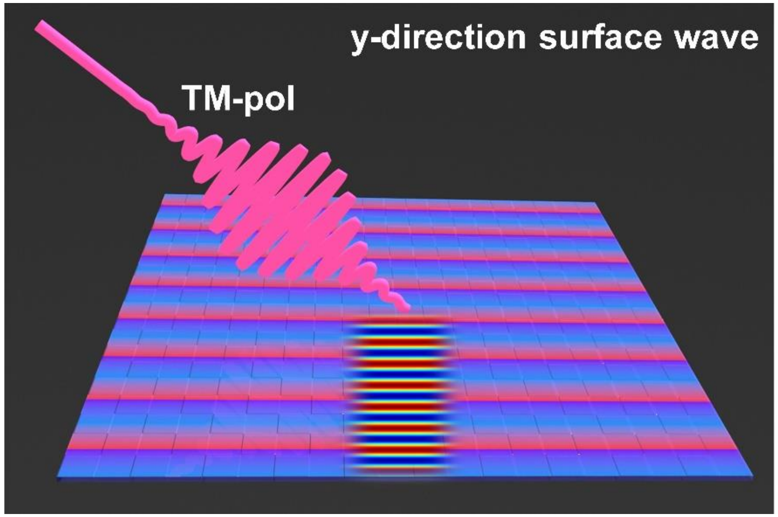
With proper gradient coding sequences, both reflected and incident beams can be on the same side

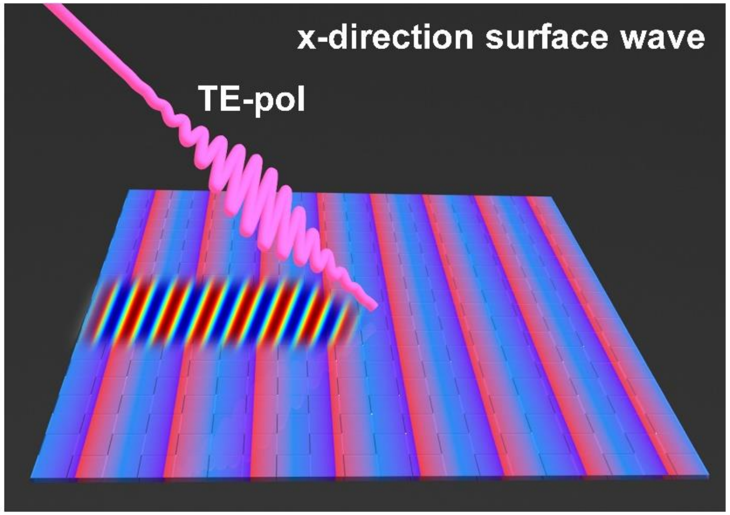
Liu et al., *Light Sci. Appl., accepted* (2018)

Surface-Wave Mode

90° turn, out-of-plane direction

180° turn, negative direction





Surface wave propagates in the orthogonal plane to the incident plane, which is enabled by the compensation technique

Negative surface wave, which is quite different to the conventional spatial-to-surface-wave conversions

Liu et al., *Light Sci. Appl., accepted* (2018)

Basic-3: Addition Theorem

Complex Digital Codes

Scalar Codes

The absolute phase ϕ for codes

The whole phase exp(jϕ) for codes

Complex Codes

φ	0	π/2	π	3π/2
Codes	00	01	10	11

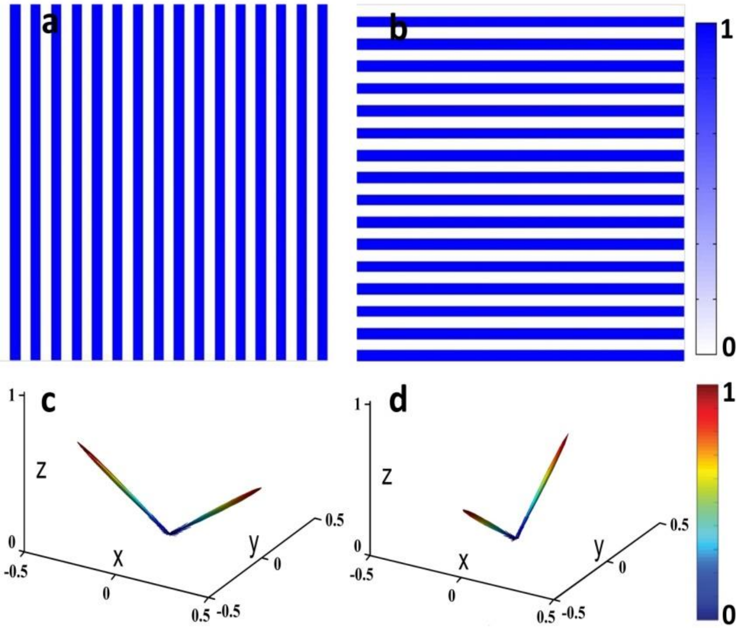
$$\dot{\vec{E}} = \overrightarrow{E_0} e^{-jkz + j\varphi}$$

2-bit Case

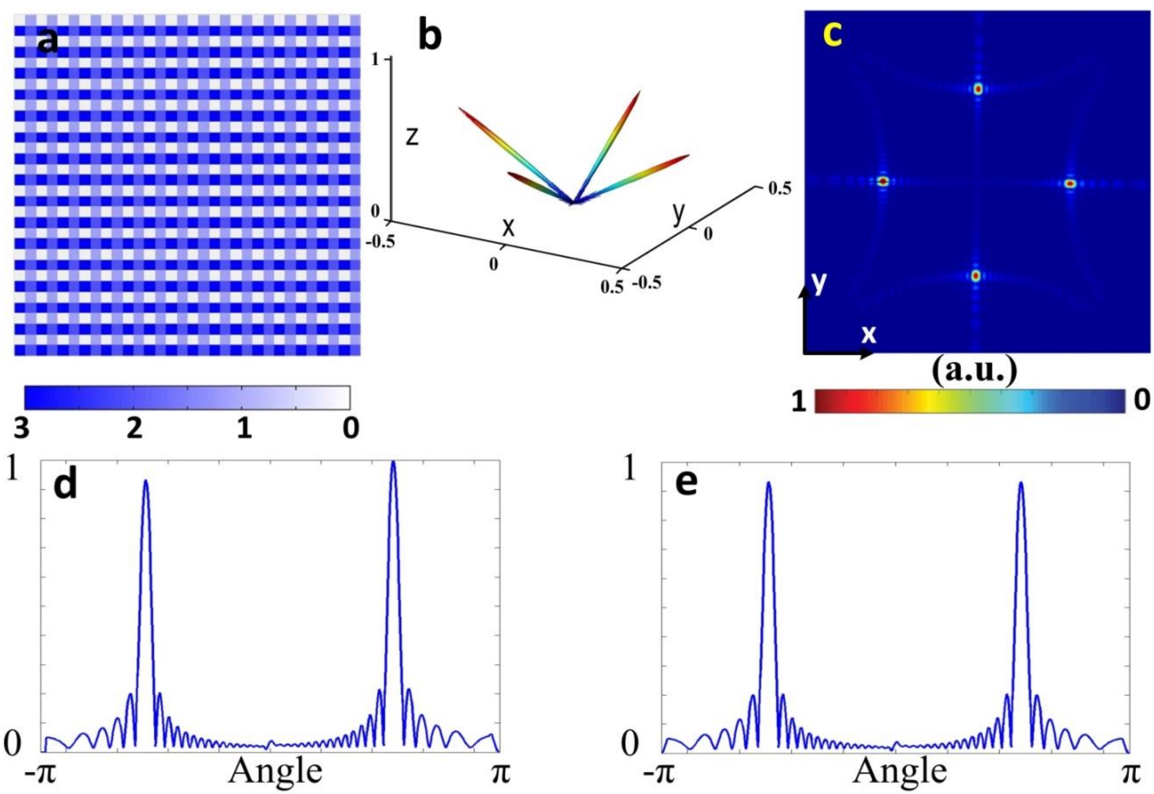
Exp(jφ)	Exp(j0)	Exp(jπ/2)	Exp(jπ)	Exp(j3π/2)
Codes	$\dot{0}0$	$\dot{0}1$	$\dot{1}0$	$\dot{1}1$

R. Y. Wu, et al. Adv. Opt. Mater., 1701236, 2018

Basic-3: Addition Theorem



- Complex coding #1 – Function #1
- Complex coding #2 – Function #2

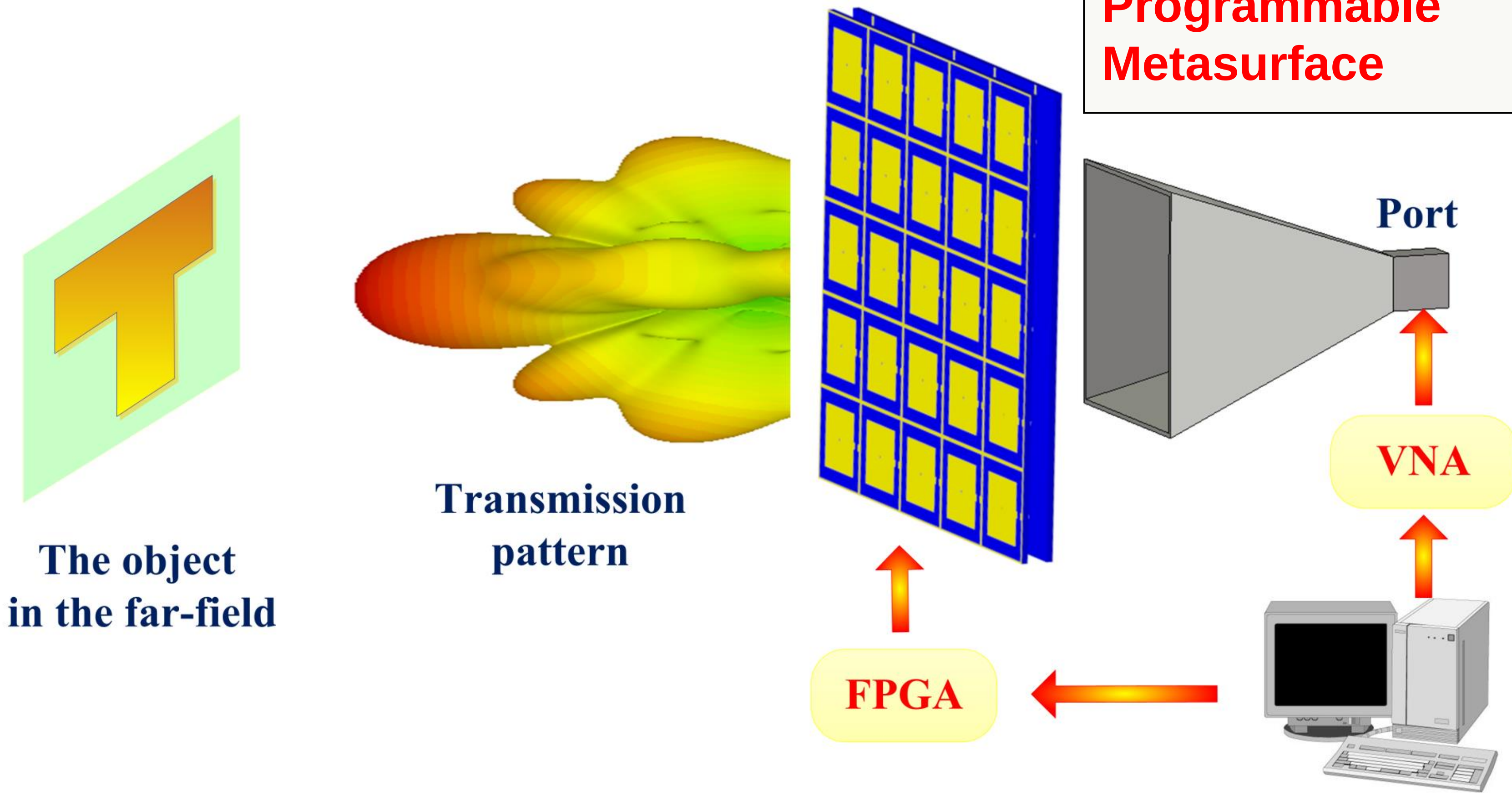


Complex digital codes

R. Y. Wu, et al. Adv. Opt. Mater., 1701236, 2018

New Imaging System

2-Bit Transmit-Type Programmable Metasurface



Single-Radar and Single-Frequency Imaging System

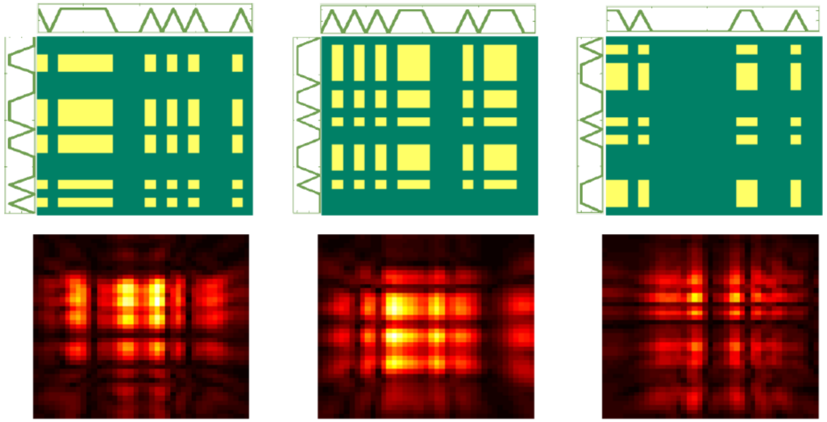
Y. B. Li et al., Sci. Rep. 6: 23731, 2016

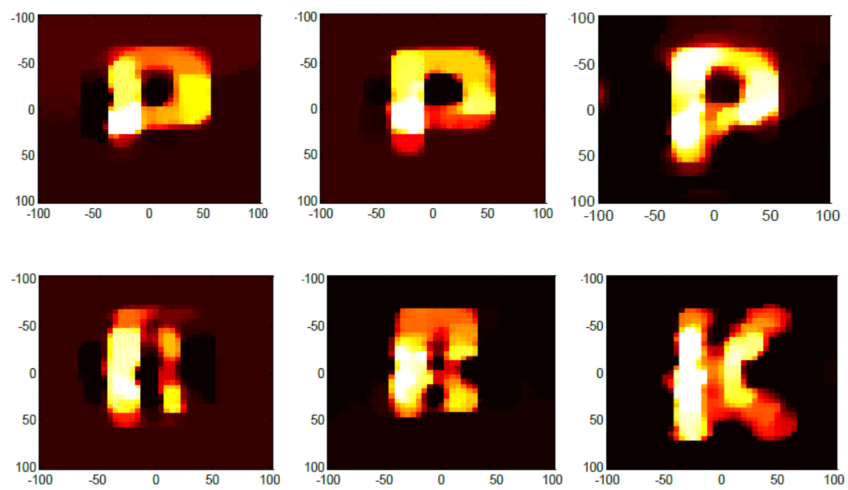
New Imaging System

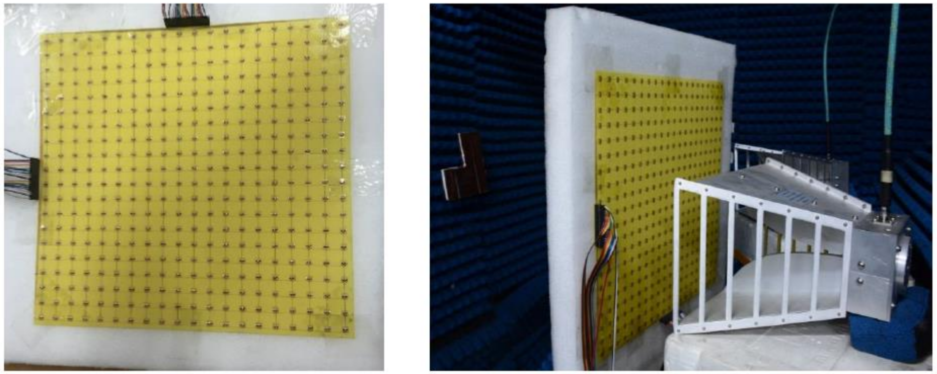
$$\min_{,\boldsymbol{O}}\left[\frac{1}{2}\sum_{m=1}^{M}\left(E^{(m)}-\langle\widetilde{\boldsymbol{A}}^{(m)},\widetilde{\boldsymbol{O}}\rangle\right)^{2}+\gamma||\boldsymbol{\Psi}(\widetilde{\boldsymbol{O}})||_{1}\right]$$

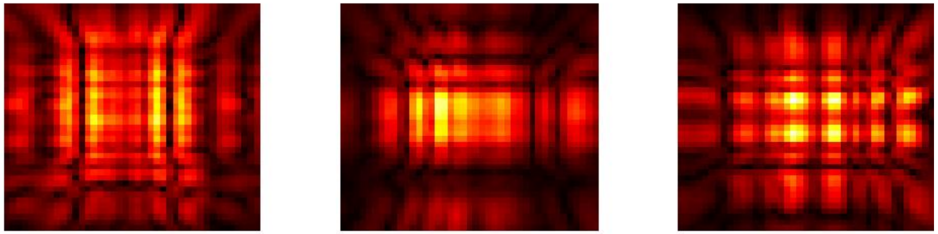
CS Algorithm: Sparsity-Regularized Optimization Problem

40x40 Pixels
Measurements:
200, 400, 600







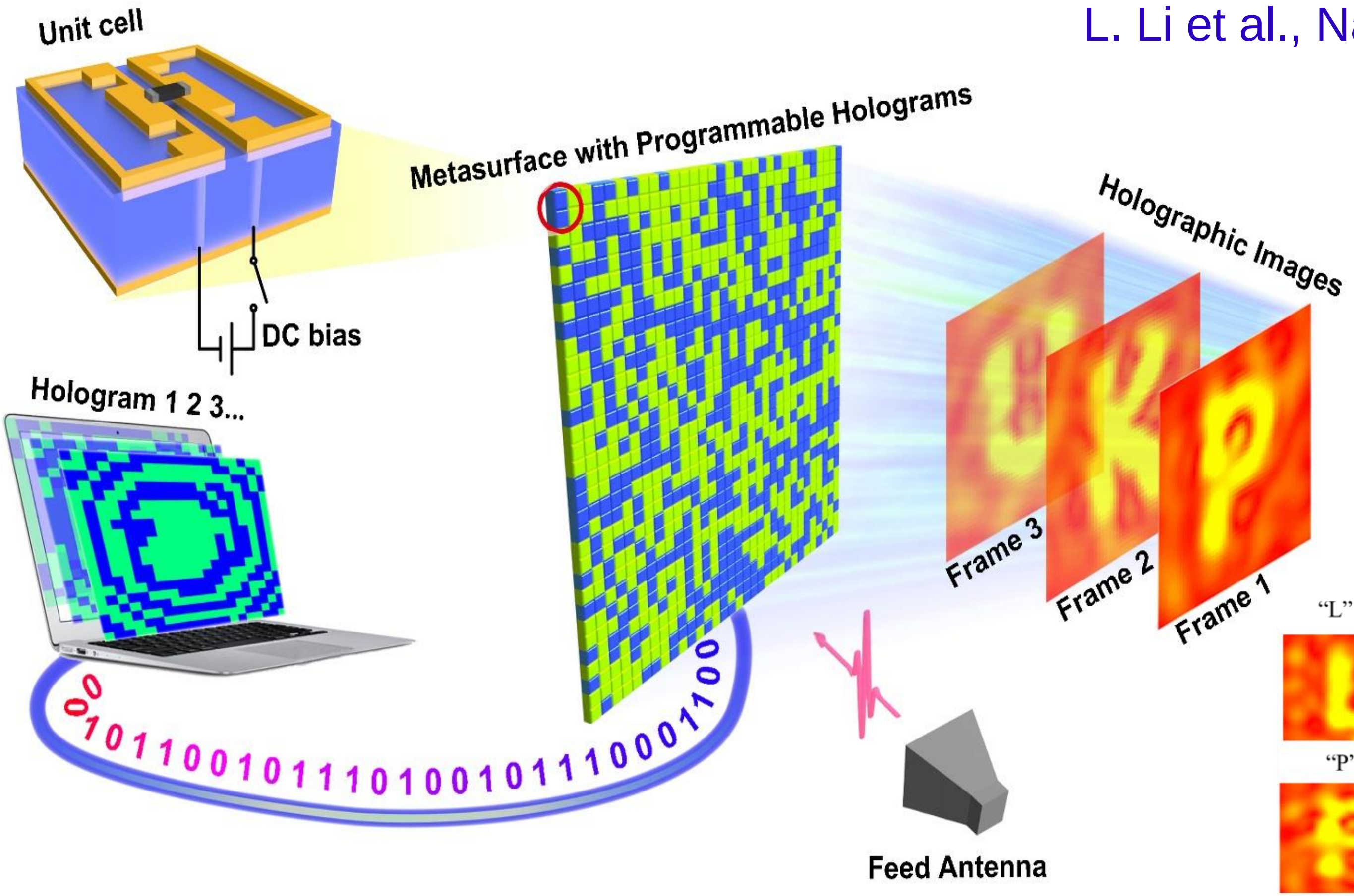


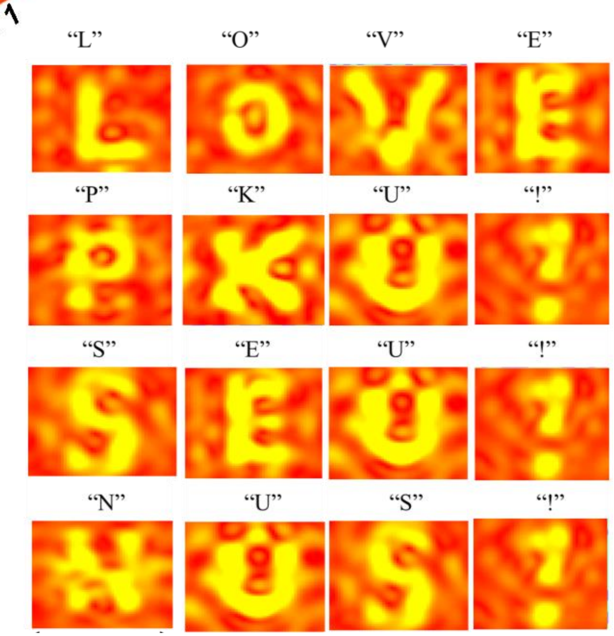
Simple, Beautiful & Powerful

L. L. Li et al., unpublished, 2018

Programmable Holographic Imaging

L. Li et al., Nature Communications, 8: 197, 2017

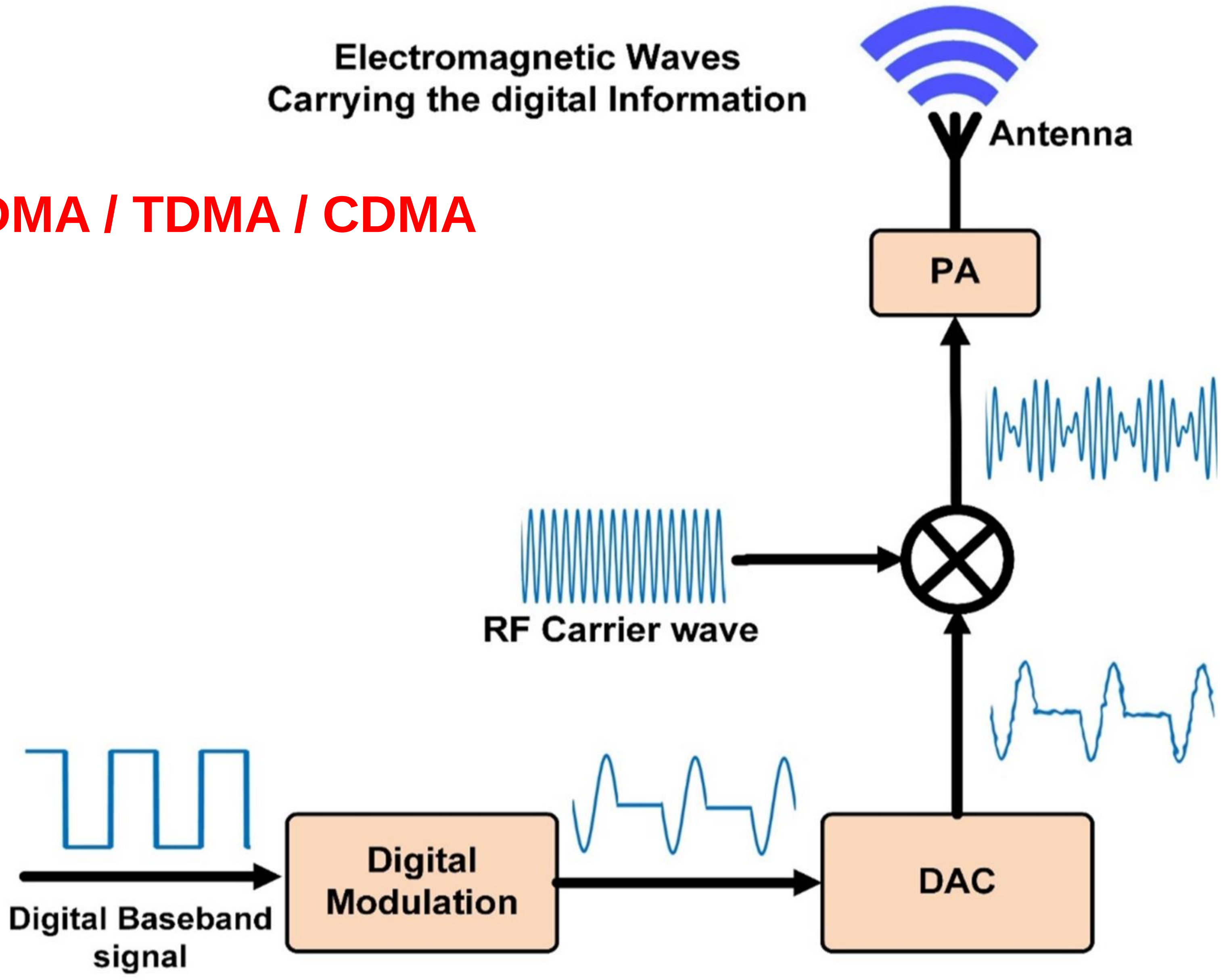




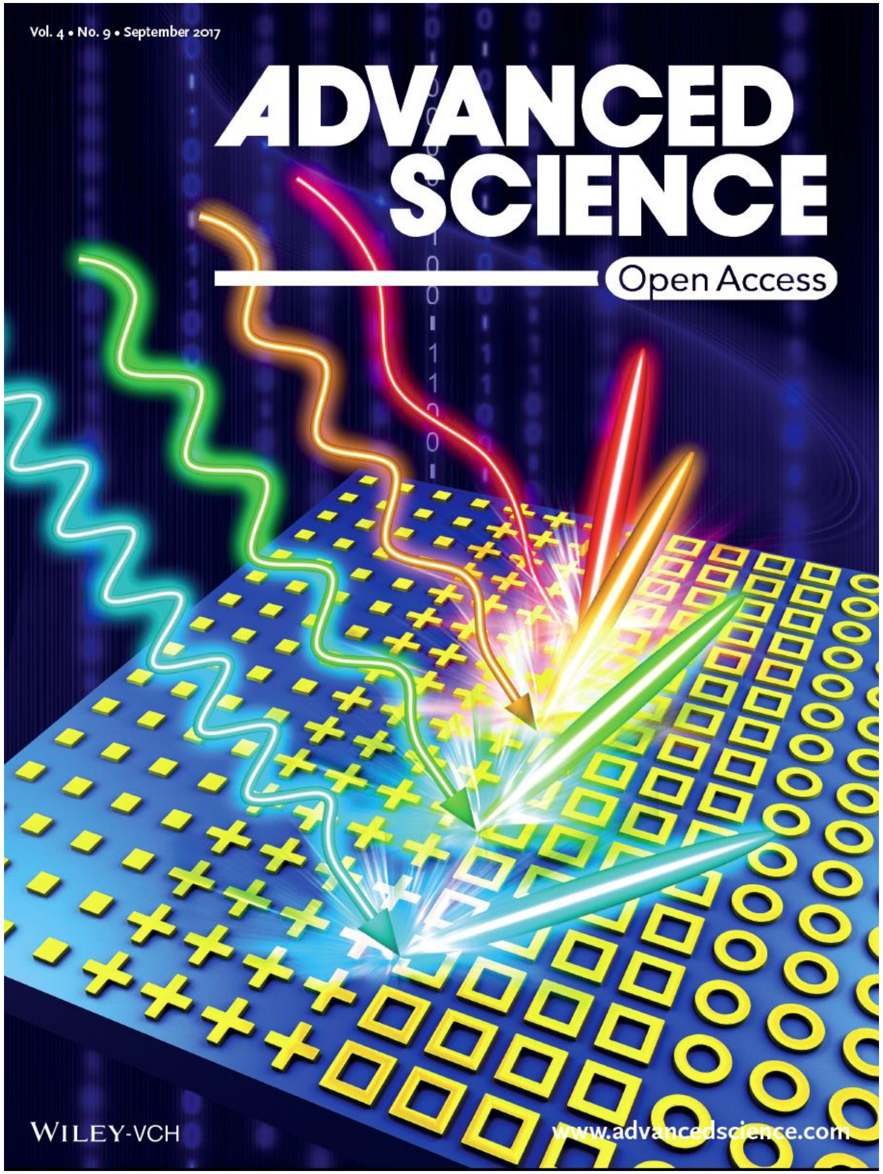
- ◆ **16 Holographic Images Controlled by FPGA**
- ◆ **Future Work: Holographic Movies**

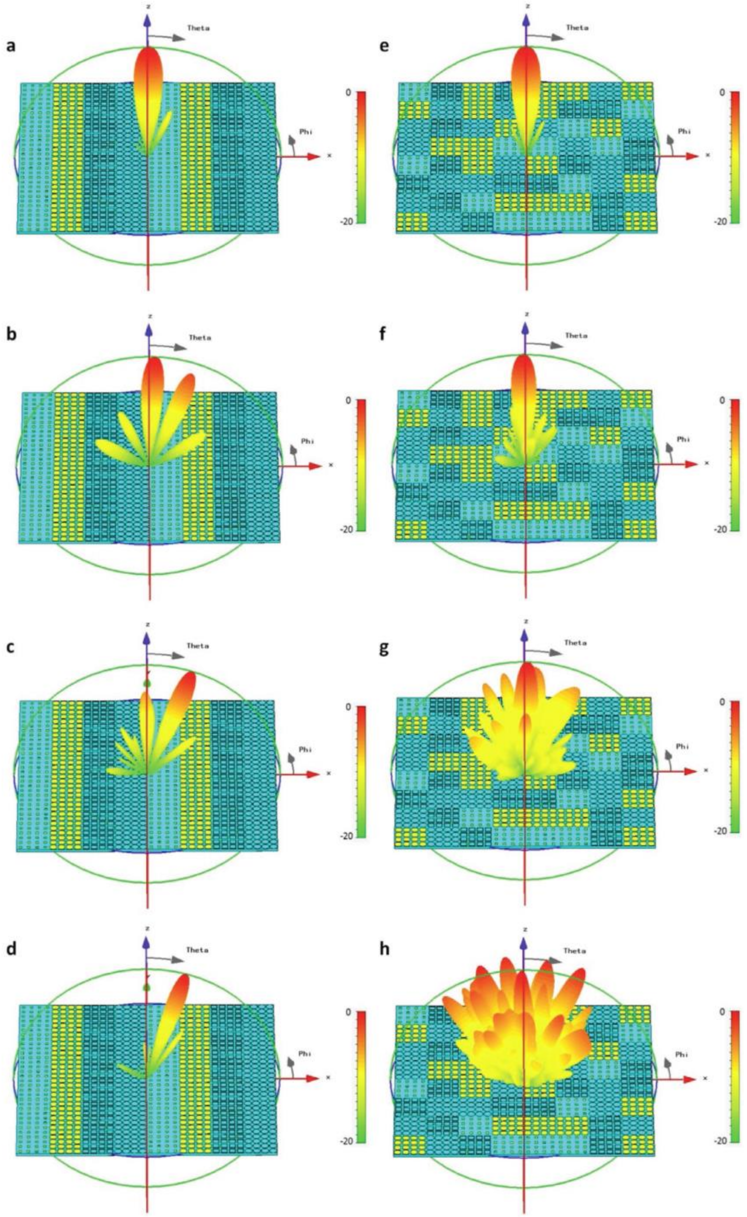
New Communication Systems

FDMA / TDMA / CDMA



Space-Frequency Coding





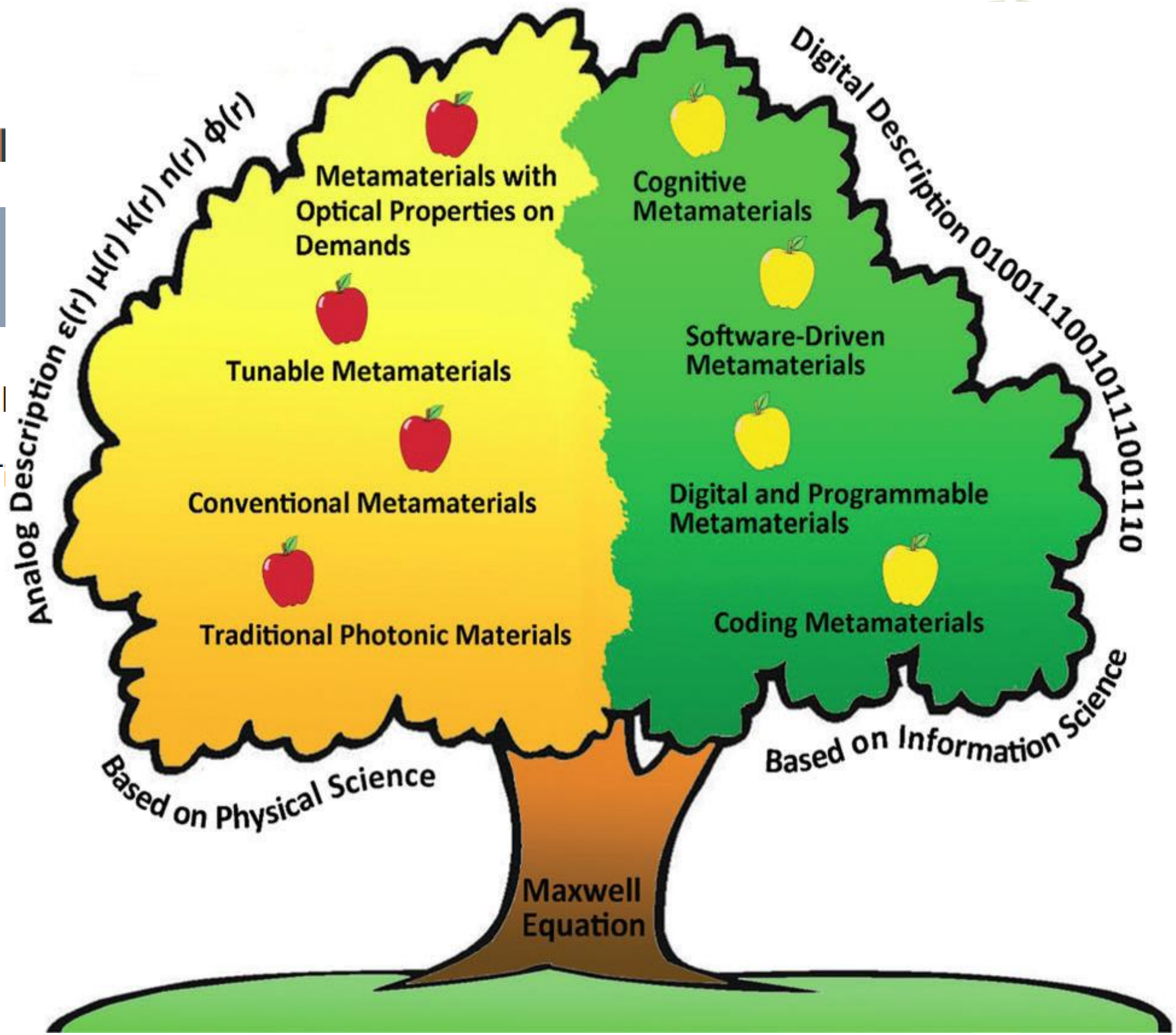
Information Metamaterials

Journal of
Materials Che

REVIEW

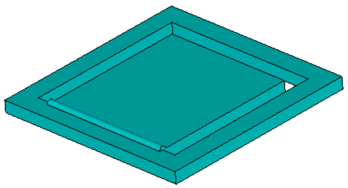
Check for updates

Cite this: DOI: 10.1039/c7tc00548b

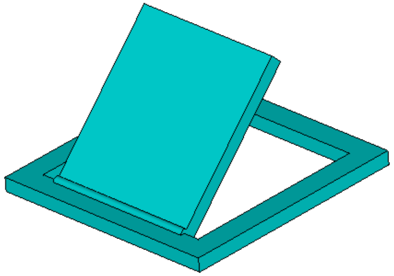


Digital Versions in Optics

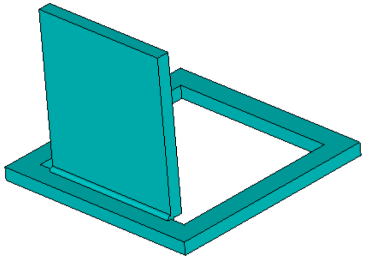
Terahertz and Optical Digital Metamaterials



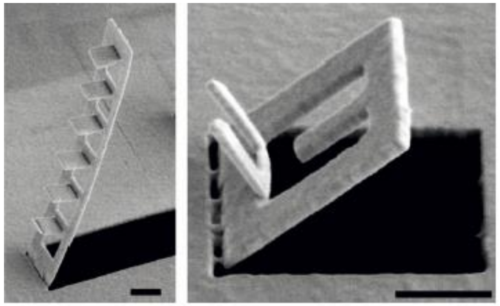
angle=0°



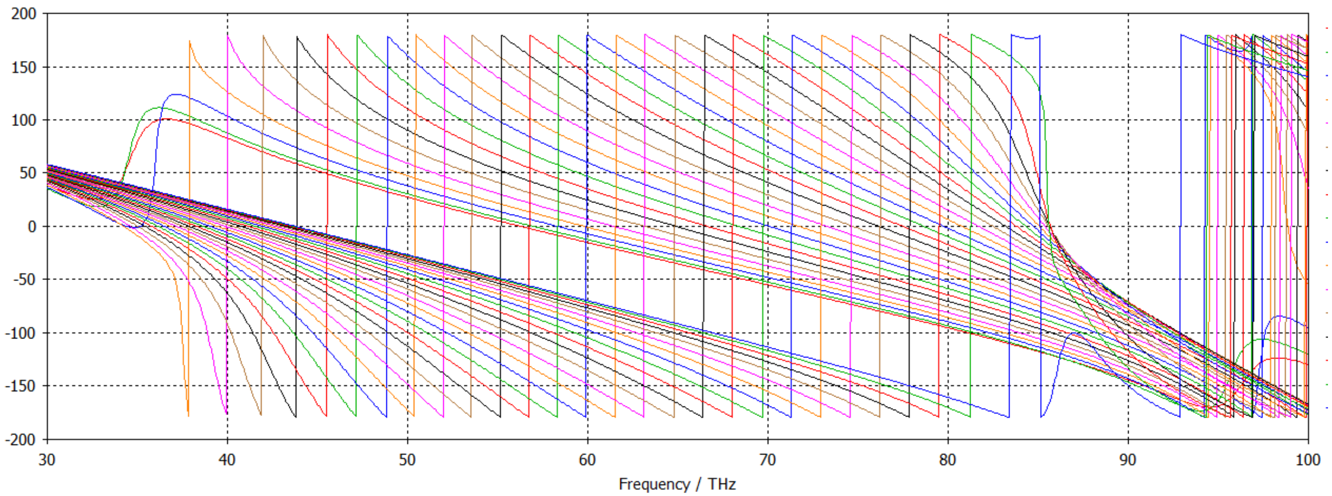
angle=45°



angle=90°

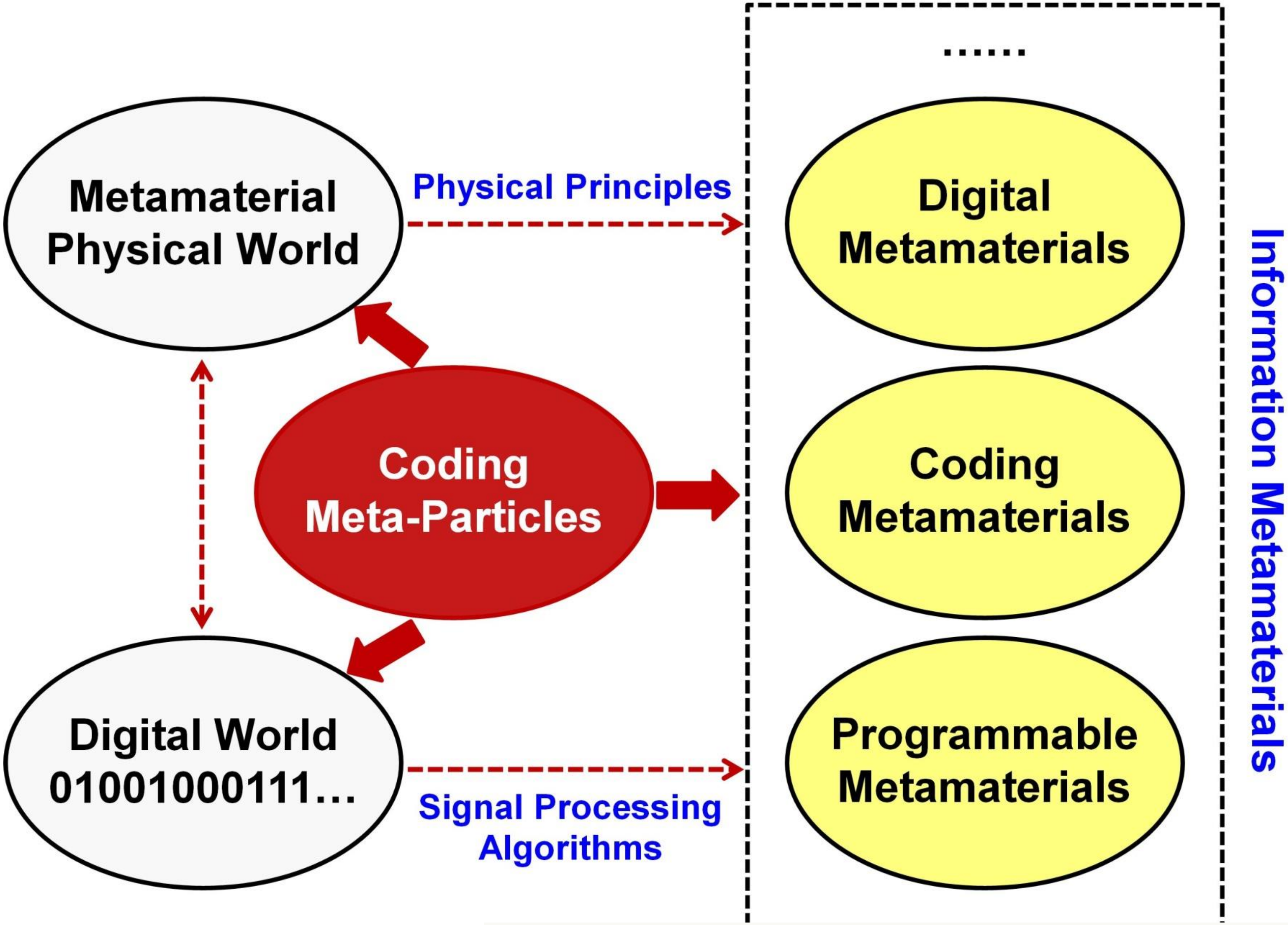


Reflection Phase Coverage is over 300 degrees



Collaborated with Prof. Jiafang Li @ Institute of Physics, CAS

Summary



Software Metamaterials, Cognitive Metamaterials