Engineered surfaces: from concept to applications

Shah Nawaz Burokur (Université Paris Nanterre)

Télécom Paris, Nov. 20 2024

Brief History of metamaterials / metasurfaces for wavefronts control

Left-handed medium
Negative refraction

Veselago

1964

Realized
$-\varepsilon$, $-\mu$

Pendry

1996 1999

Experimental verification
of negative refraction

Smith

2001

Transformation optics
Invisibility cloak

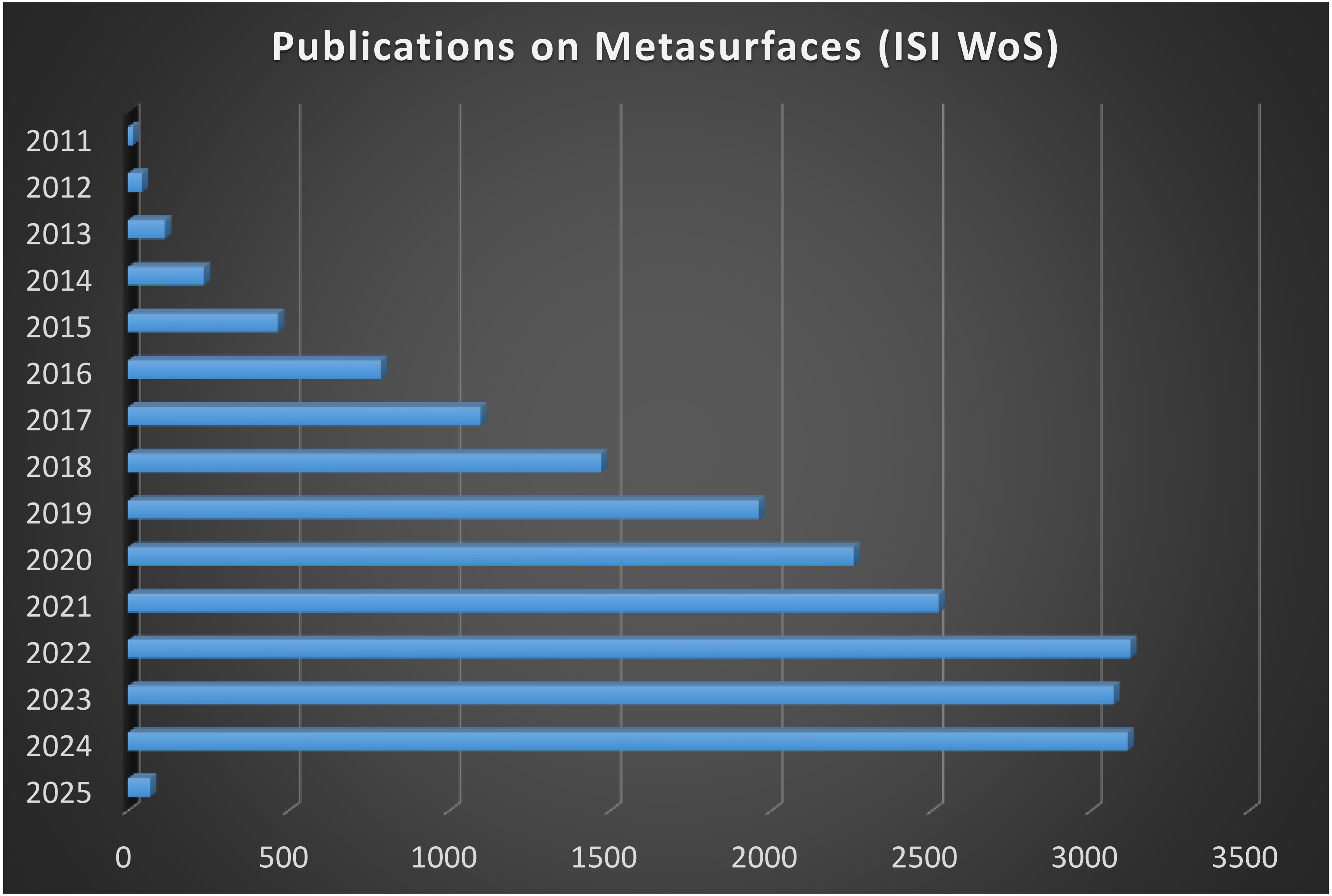
Pendry / Smith

2006

Metasurface
Generalized Snell's law

Capasso

2011


Publications on Metasurfaces (ISI WoS)
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
0
500
1000
1500
2000
2500
3000
3500


7,564
Optics
4,989
Materials Science Multidisciplinary
1,759
Physics Condensed Matter
931
Multidisciplinary Sciences
525
Computer Science Information Systems
7,126
Engineering Electrical Electronic
4,120
Telecommunications
1,224
Chemistry Multidisciplinary
430
Instruments Instrumentation
254
Chemistry Analytical
211
Compute Science Interdiscip Applications
1,108
Chemistry Physical
6,300
Physics Applied
2,876
Nanoscience Nanotechnology
191
Engineering Multidisciplinary
176
Engineering Mechanical
153
Acoustics
968
Physics Multidisciplinary
177
Mechanics
143

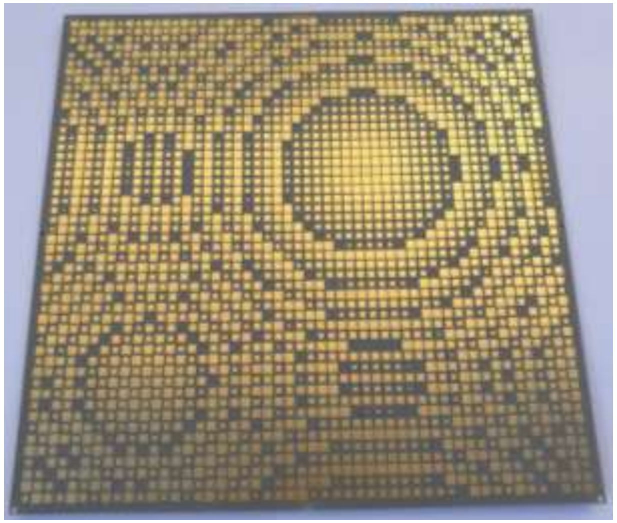
Outlines

1. Metasurface definition
2. Metasurface classification
3. Applications
4. Actual trends
5. Summary

1. Metasurface definition

- Two-dimensional arrays of subwavelength-scale artificial elements, arranged in a specific pattern to manipulate the propagation of light at subwavelength scales

- Geometry, size and arrangement of meta-atoms → Tailor EM response



- Planar structures that can be fabricated on flat substrates, making them compatible with existing fabrication techniques

- Metasurfaces can control the phase, amplitude, and polarization of incident light across a planar surface, enabling unprecedented control over the wavefront of light

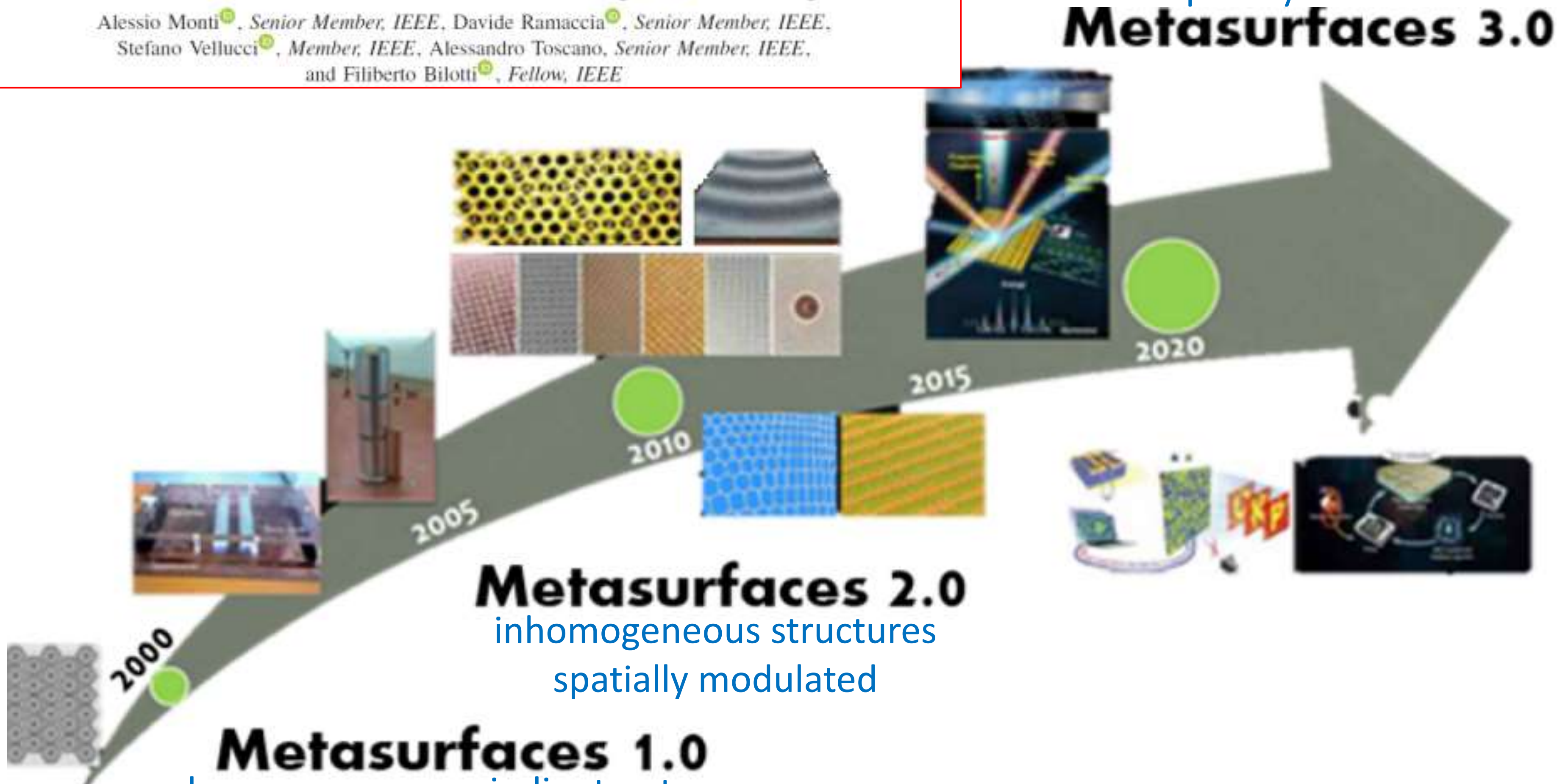
1. Metasurface definition: Design evolution

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 70, NO. 10, OCTOBER 2022 8883

Metasurfaces 3.0: A New Paradigm for Enabling Smart Electromagnetic Environments

Mirko Barbuto, *Senior Member, IEEE*, Zahra Hamzavi-Zarghani, Michela Longhi, Alessio Monti, *Senior Member, IEEE*, Davide Ramaccia, *Senior Member, IEEE*, Stefano Vellucci, *Member, IEEE*, Alessandro Toscano, *Senior Member, IEEE*, and Filiberto Bilotti, *Fellow, IEEE*

(in)homogeneous structures
temporally modulated



inhomogeneous structures
spatially modulated

homogeneous periodic structures

1. Metasurface definition: Design evolution

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Metasurfaces 3.0: A New Paradigm for Enabling Smart Electromagnetic Environments

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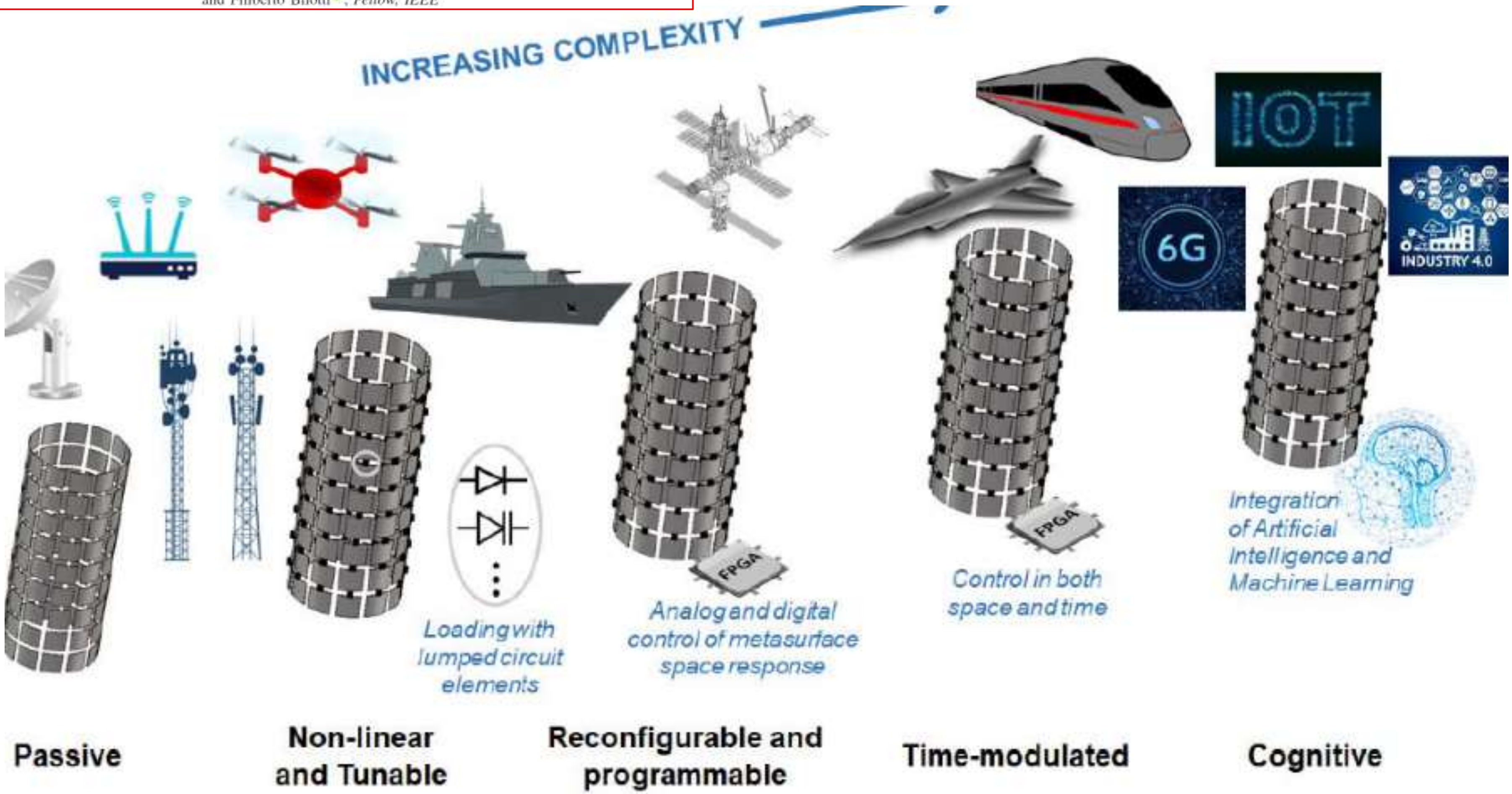

Université Paris Nanterre

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2. Metasurface classification

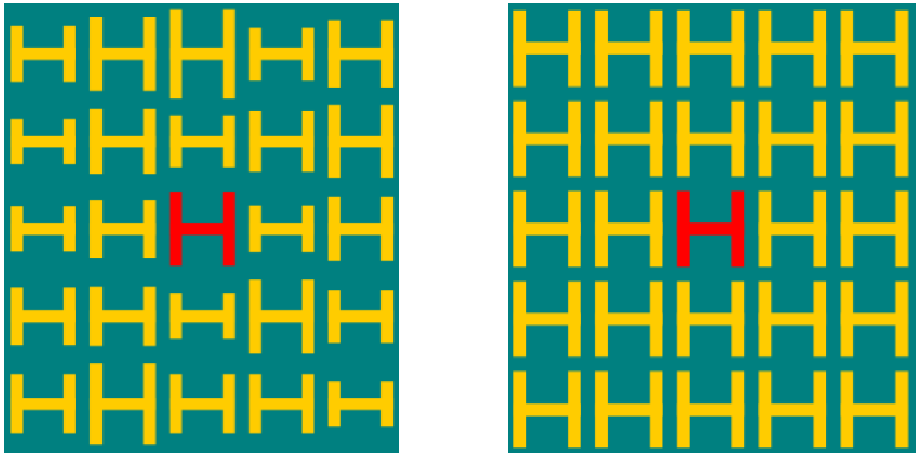
3 main categories

- Dense metasurfaces
- Metagratings
- Sparse metasurfaces

Dense Metasurfaces

- Continuous impedance sheets, i.e., they require dense distribution of unit cells
- Designed by means of local periodic approximation (LPA)
- So far, metasurfaces present narrow-band performances

Non-uniform array Uniform array



characteristic of the whole array:

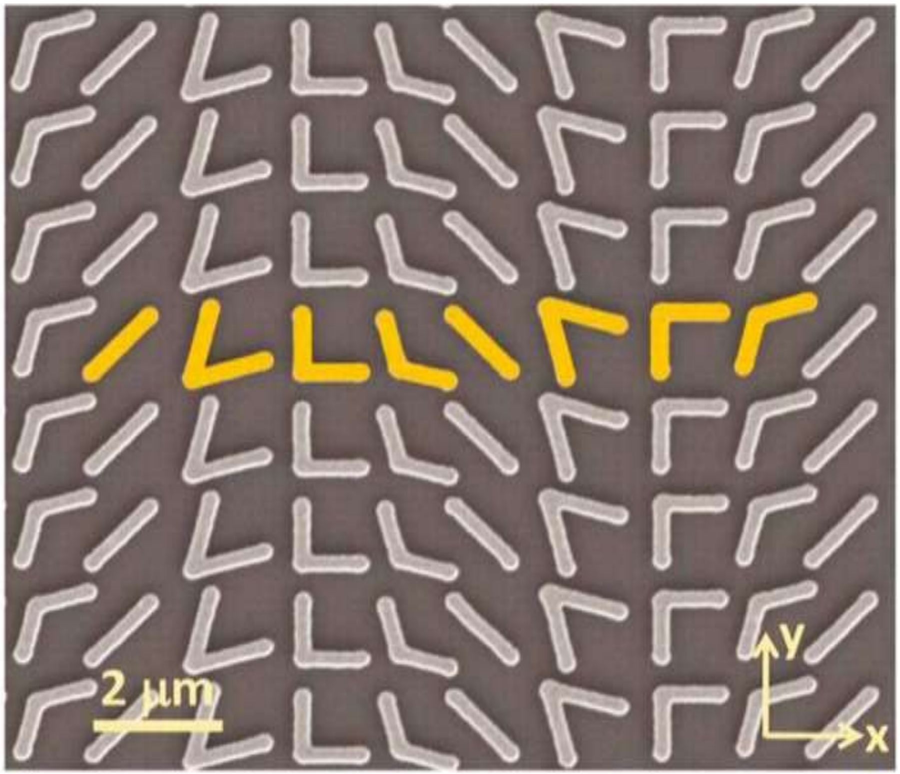
$$Z_{in} = Z_0 \frac{1+S_{11}}{1-S_{11}}$$

Dense Metasurfaces

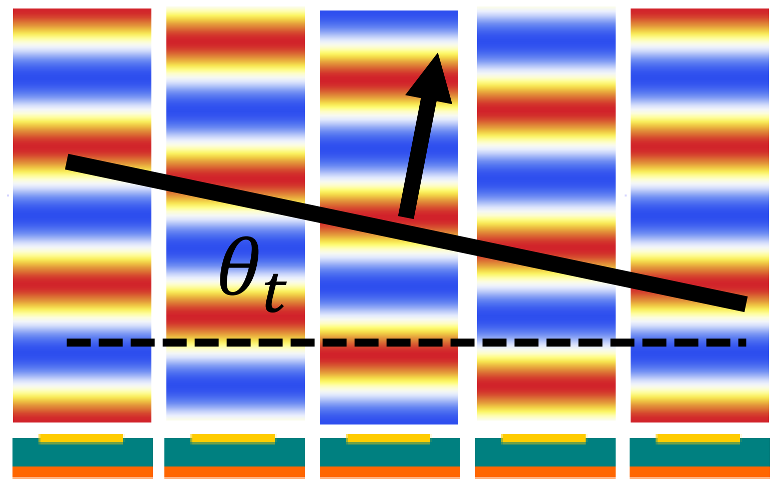
Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

NANFANG YU, PATRICE GENEVET, MIKHAIL A. KATS, FRANCESCO AIETA, JEAN-PHILIPPE TETIENNE, FEDERICO CAPASSO, AND ZENO GABURRO

SCIENCE • 1 Sep 2011 • Vol 334, Issue 6054 • pp. 333-337 • DOI: 10.1126/science.1210713

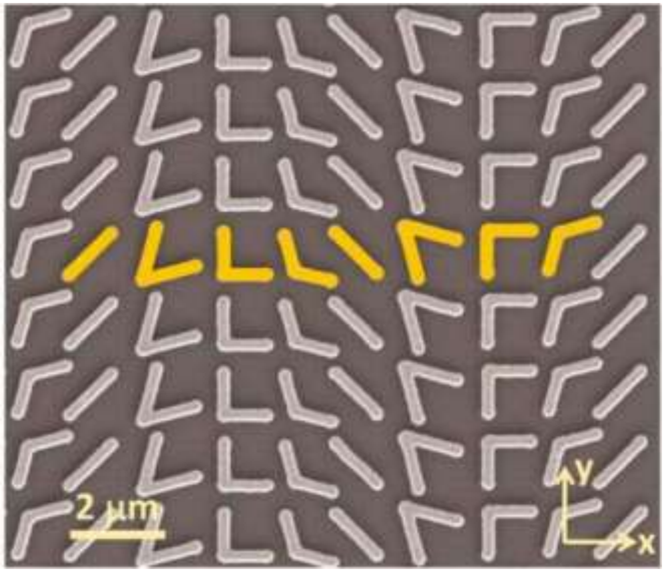


$$\sin[\theta_t]n_t - \sin[\theta_i]\,n_i = \frac{\lambda_0}{2\pi}\frac{\mathrm{d}\Phi(x)}{\mathrm{d}x}$$



Dense Metasurfaces

Phase-gradient metasurfaces



Performance is fundamentally limited: increased side-lobes level

Many elements: high absorption because of many tunable elements

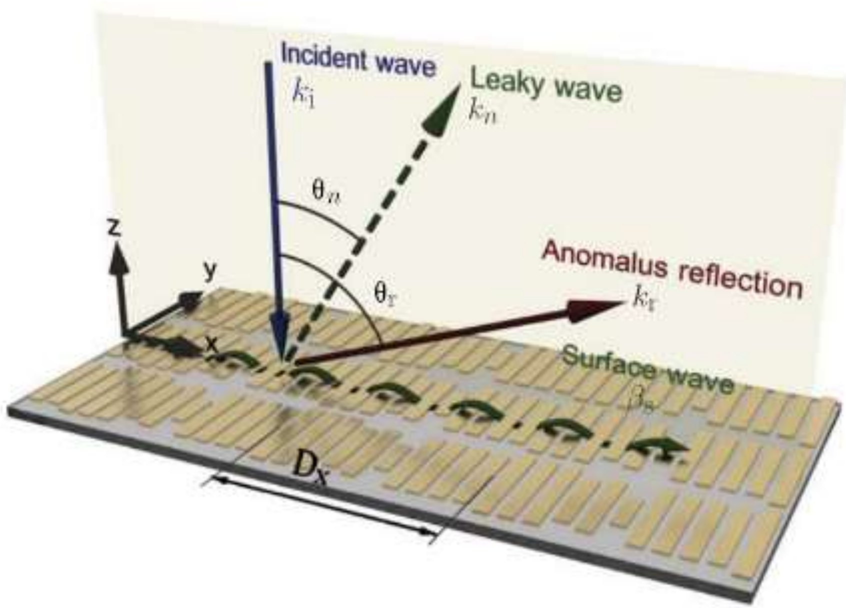
Dense Metasurfaces

From the generalized reflection law to the realization of perfect anomalous reflectors

ANA DÍAZ-RUBIO , VIKTAR S. ASADCHY, AMR ELSAKKA, AND SERGEI A. TRETYAKOV Authors Info & Affiliations

SCIENCE ADVANCES • 11 Aug 2017 • Vol 3, Issue 8 • DOI: 10.1126/sciadv.1602714

- Concept: strong non-locality



engineering the interaction between distant parts by SW

- Drawbacks

Complicated design procedure strongly relying on 3D full-wave optimization

Dense arrangement of elements

Dense Metasurfaces: Huygens' metasurfaces

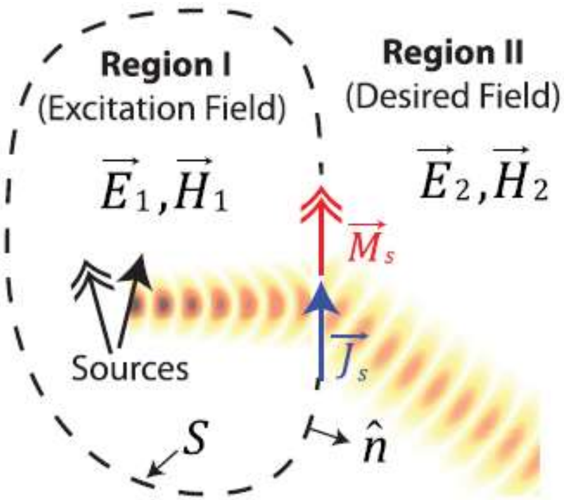
Selected for a Viewpoint in *Physics*
PRL **110,** 197401 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

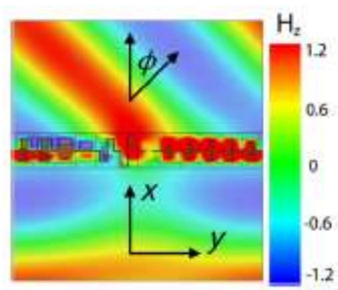
Metamaterial Huygens' Surfaces: Tailoring Wave Fronts with Reflectionless Sheets

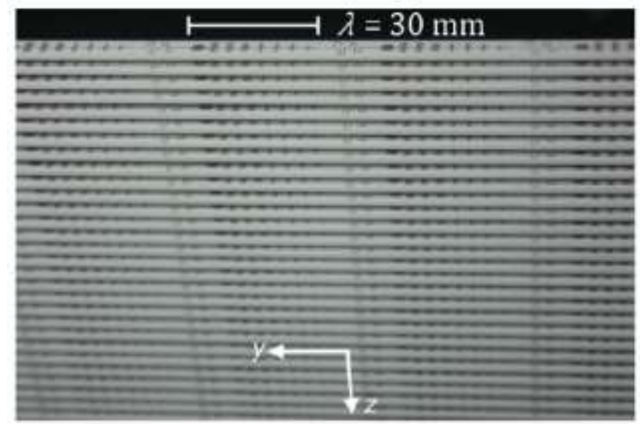
Carl Pfeiffer and Anthony Grbic*

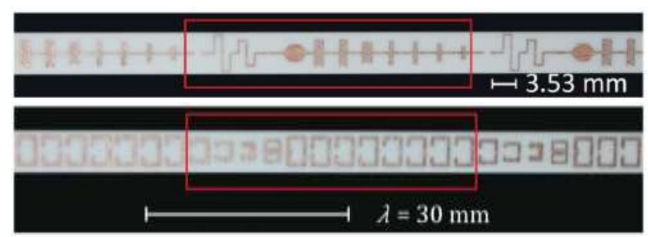
- Huygens' principle:

each point on a wavefront acts as a secondary source of outgoing waves









$$\vec{J}_s = \hat{n} \times (\vec{H}_2 - \vec{H}_1), \qquad \vec{M}_s = -\hat{n} \times (\vec{E}_2 - \vec{E}_1)$$

$$Y_{es} = \frac{2(1 - T - R)}{\eta(1 + T + R)}, \qquad Z_{ms} = \frac{2\eta(1 - T + R)}{(1 + T - R)}$$

Dense Metasurfaces: PB phase metasurfaces

July 1, 2002 / Vol. 27, No. 13 / OPTICS LETTERS 1141

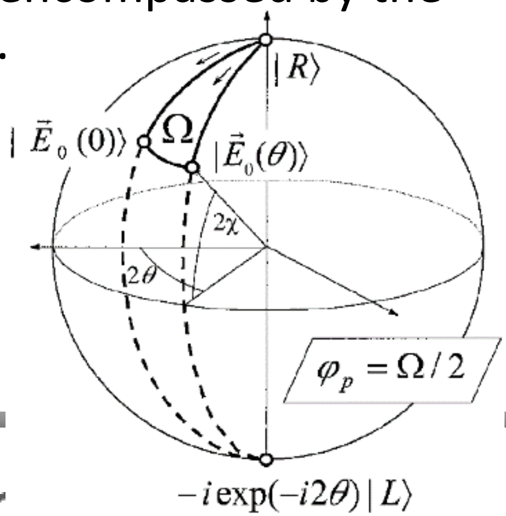
Space-variant Pancharatnam–Berry phase optical elements with computer-generated subwavelength gratings

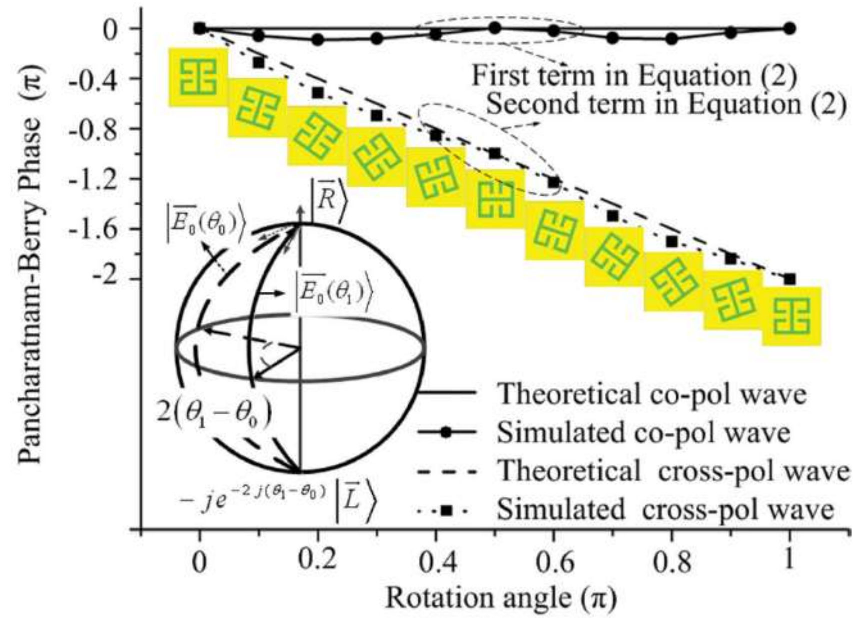
Ze'ev Bomzon, Gabriel Biener, Vladimir Kleiner, and Erez Hasman

- Pancharatnam-Berry phase:

geometric phase associated with the polarization of light. When the polarization of a beam traverses a closed loop on the Poincaré sphere, the final state differs from the initial one by a phase factor equal to half of the Ω area, encompassed by the loop on the sphere.

A rotation of θ will introduce a phase shift of 2θ





Dense Metasurfaces: Coding metasurfaces

OPEN

Light: Science & Applications (2014) 3, e218; doi:10.1038/lsa.2014.99

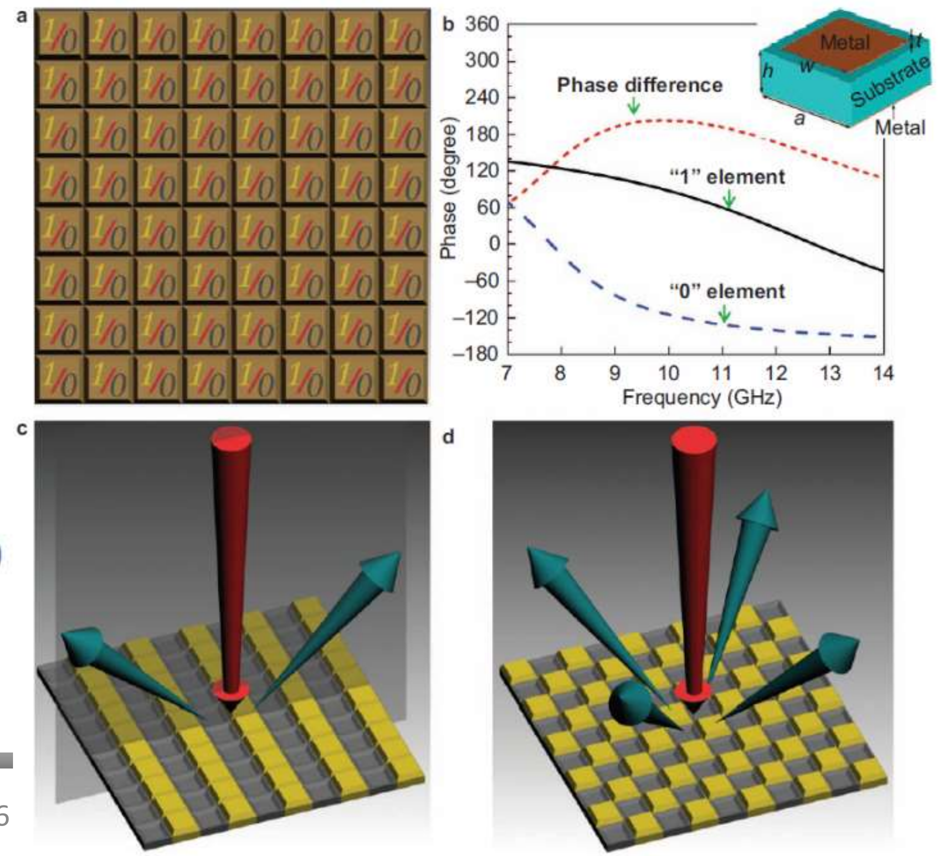
www.nature.com/lsa

Coding metamaterials, digital metamaterials and programmable metamaterials

Tie Jun Cui[1,2,*], Mei Qing Qi[1,*], Xiang Wan[1,*], Jie Zhao[1] and Qiang Cheng[1,2]

By coding ‘0’ and ‘1’ elements with controlled sequences (i.e., 1-bit coding), EM waves can be manipulated to realize different functionalities

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



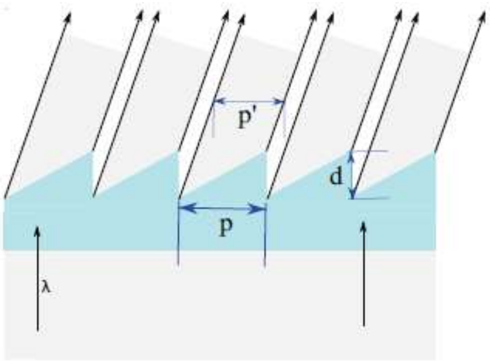
Metagratings

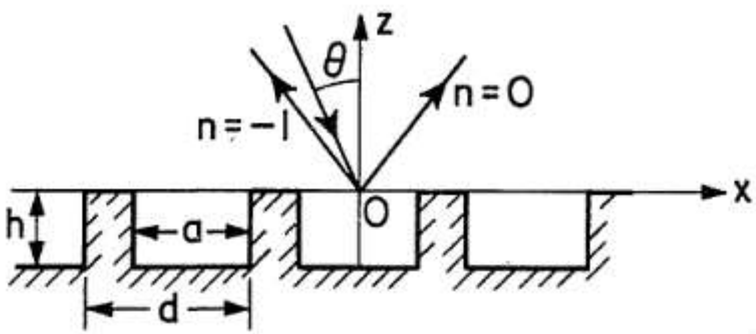
Diffraction grating:

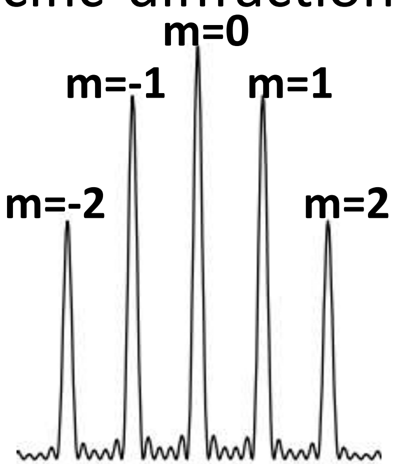
- periodic optical structure with infinite extent in one direction, which is able to diffract light incident on its surface[1]

Blazed (echelette) grating:

- capable of scattering an incident wave into a specific diffraction order[2]







[1]M. Born, E. Wolf, “Principles of Optics,” chap. Element of the theory of diffraction, pp. 412–516.
[2]E. V. Jull et al., “Gratings that diffract all incident energy,” J. Opt. Soc. Am. **67**(4), 557 (1977).

Metagratings

PRL **119,** 067404 (2017) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2017

Metagratings: Beyond the Limits of Graded Metasurfaces for Wave Front Control

Younes Ra'di, Dimitrios L. Sounas, and Andrea Alù*

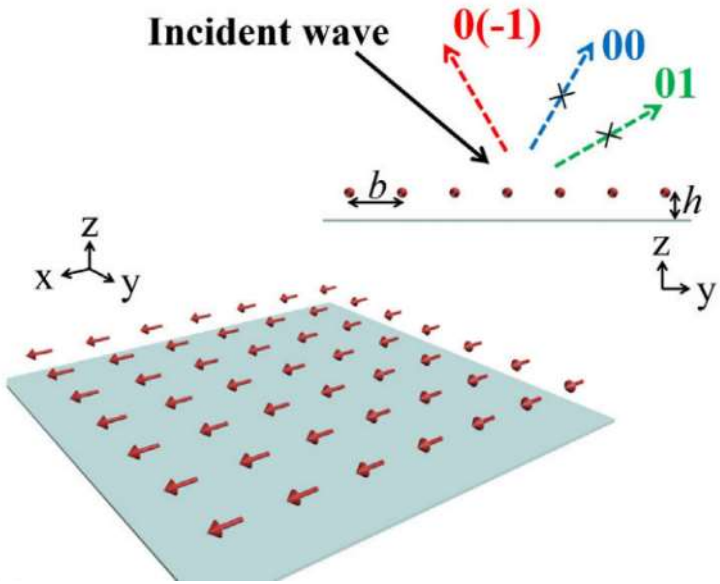
Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712, USA

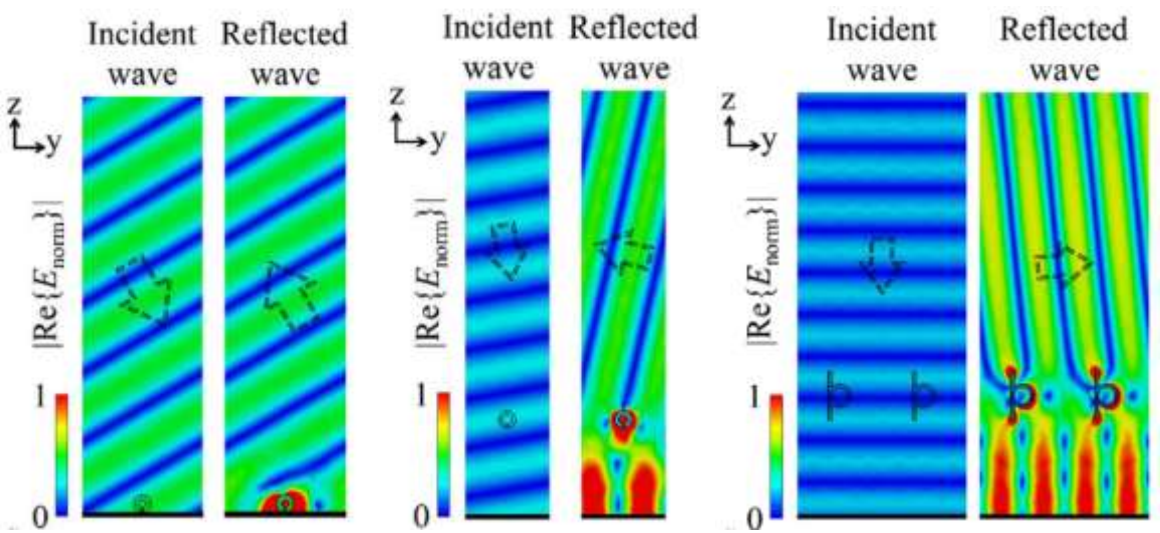
- Metasurfaces: limitations in terms of efficiency and fabrication, in particular for extreme manipulation

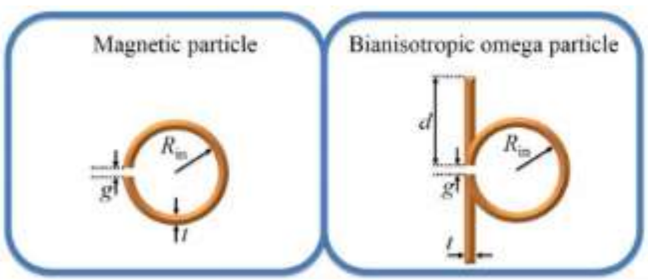
- 1D gratings: profile modulation in one direction, a translational symmetry in the other and no control of energy in the orders

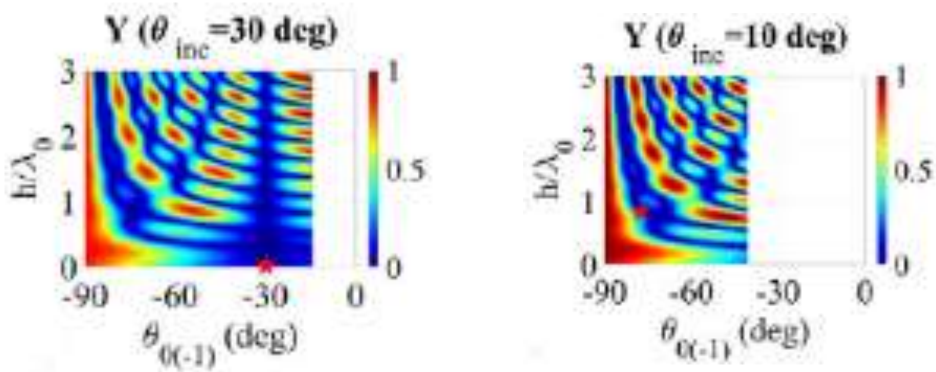
- Metagratings:
  - evolution of 1D diffraction gratings (construction from meta-atoms whose scattering properties can be judiciously engineered)
  - translation-invariant direction is engineered at a scale < λ
  - definition of an averaged macroscopic quantity (impedance density)

Metagratings









Metagratings

PHYSICAL REVIEW APPLIED 11, 024074 (2019)

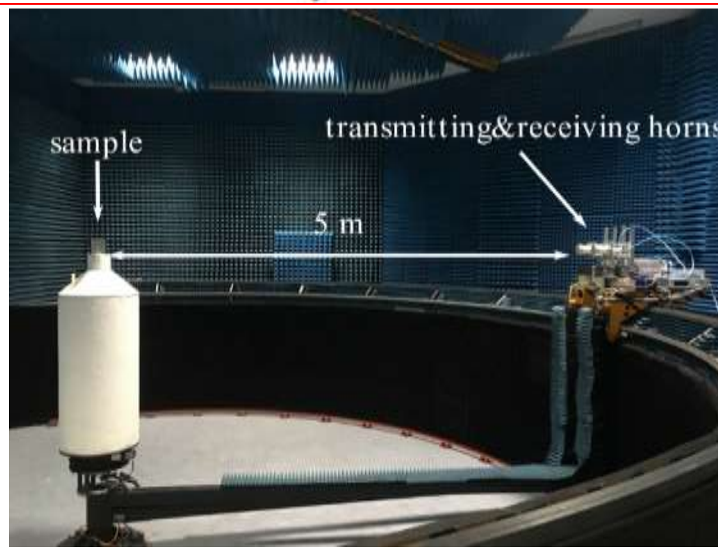
Constructing the Near field and Far field with Reactive Metagratings: Study on the Degrees of Freedom

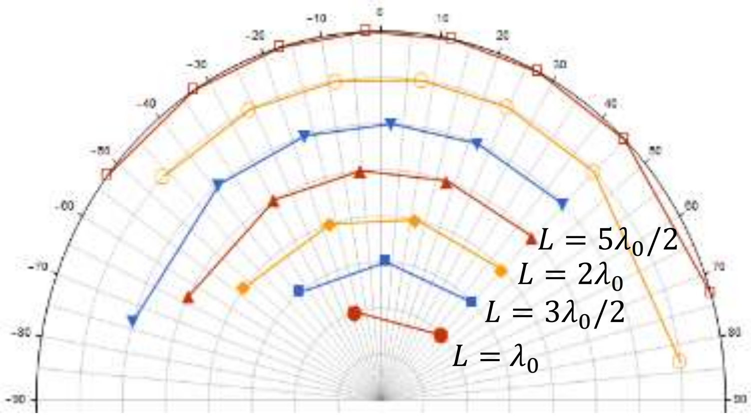
Vladislav Popov,[1,*] Fabrice Boust,[1,2] and Shah Nawaz Burokur[3]

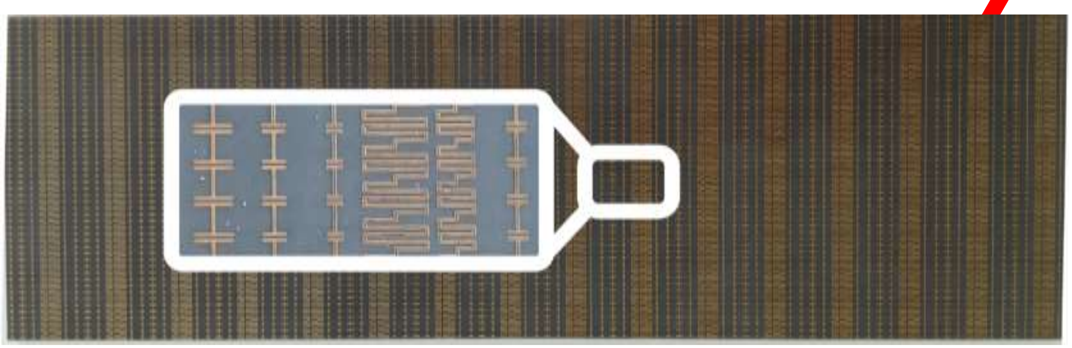
Periodic structures

Plane-wave illumination

Only discrete angles are accessible







Metagratings

The diffraction problem can be solved exactly:

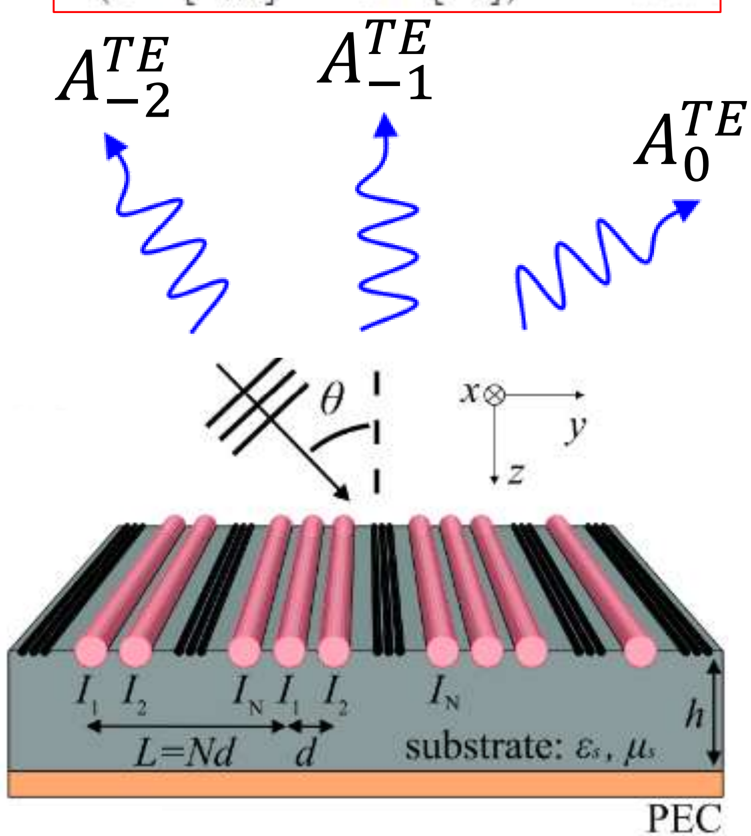
$$E_x^{ref}(y, z < -h) = \sum_{m=-\infty}^{+\infty} A_m^{TE} e^{-j\xi_m y + j\beta_m z}$$

$$A_m^{TE} = -\frac{k\eta}{2L}\frac{\rho_m^{(I)}(1+R_m^{TE})e^{j\beta_m h}}{\beta_m} + \delta_{m0} R_0^{TE} e^{2j\beta_0 h}$$

$$I_q = \frac{1}{N}\sum_{m=-l}^{r} \rho_m^{(I)} \exp[-j\xi_m (q-1)d]$$

diffraction angles :

$$L(\sin[\theta_m] - \sin[\theta_i]) = m\lambda$$



Load impedance densities Z_q of the line currents I_q are found from:

$$Z_q I_q = E_x^{(exc)}(y_{0q}, -h) - Z_{in} I_q - \sum_{p=1}^{N} Z_{qp}^{(m)} I_p$$

Excitation field

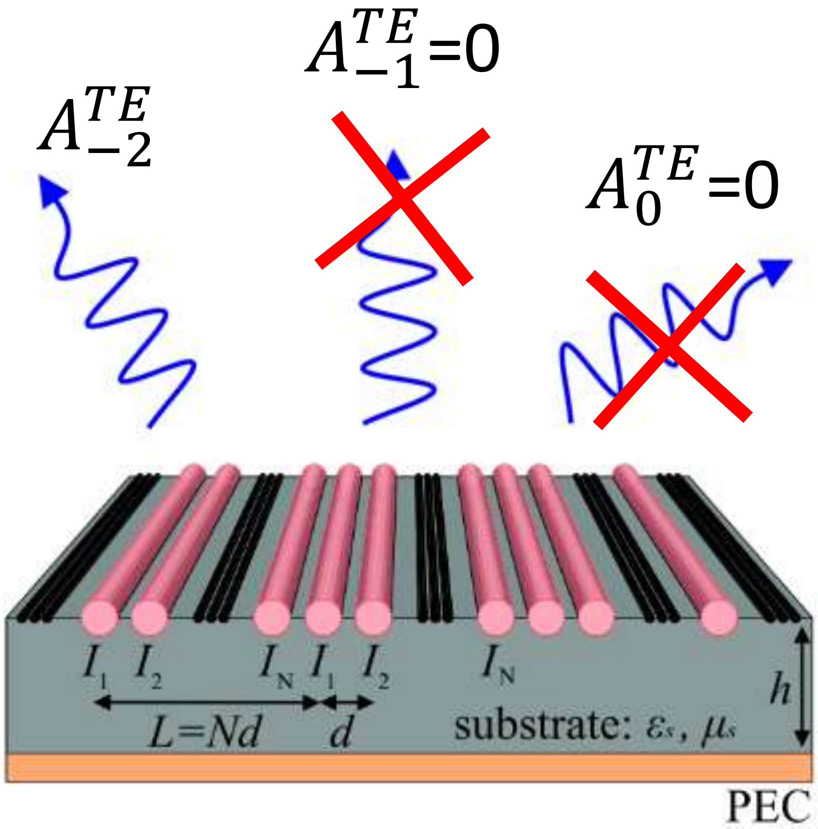
Input impedance

Mutual impedance

Metagratings

In order to deal only with loads $\Re[Z_q] = 0$ the following equation has to be satisfied:

$$\Re\left[E_x^{(exc)}(y_{0q}, -h)I_q^* - \sum_{p=1}^{N} Z_{qp}^{(m)} I_p I_q^*\right] = \Re[Z_{in}]|I_q|^2$$



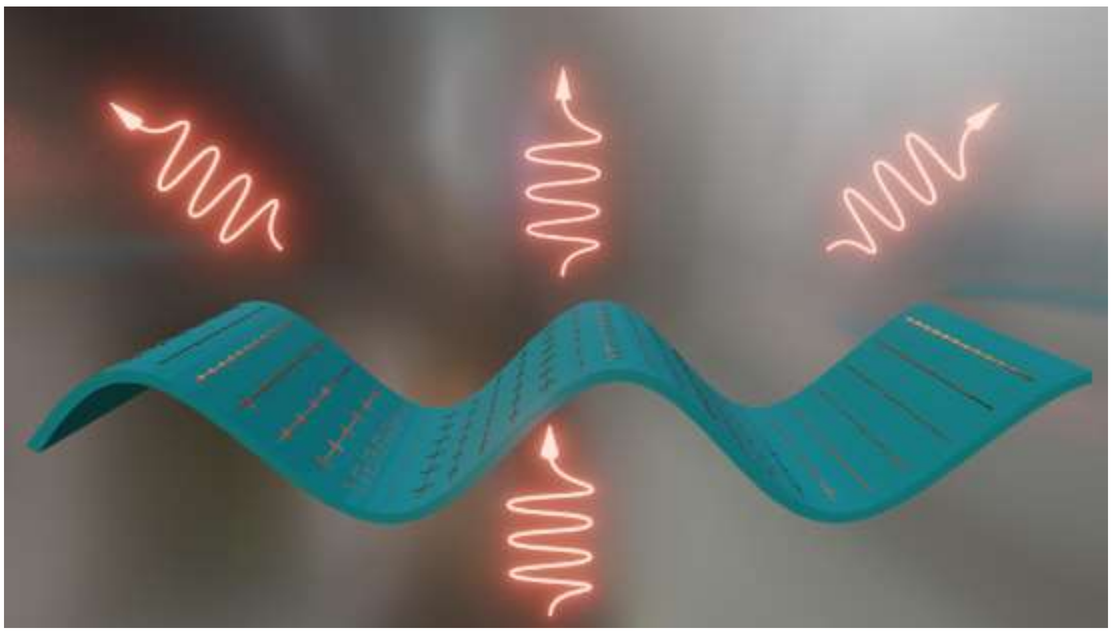
- It is a set of N second order algebraic equations
- When $N = M$, it is impossible to satisfy both equations in general
- Scattering losses appear

Sparse Metasurfaces

PHYSICAL REVIEW APPLIED 14, 044007 (2020)

Conformal Sparse Metasurfaces for Wavefront Manipulation

Vladislav Popov,[1,*] Shah Nawaz Burokur,[2,†] and Fabrice Boust[1,3]



- ❑ N loaded wires are distributed along the surface of an arbitrarily-shaped substrate
- ❑ The structure is illuminated by an arbitrary wave

Scattering problem

The total field can be written as follows:

$$E_x(\boldsymbol{r}) = E_x^{(exc)}(\boldsymbol{r}) + E_x^{(sct)}(\boldsymbol{r})$$

$$E_x^{(sct)}(\boldsymbol{r}) = \int G_{xx}(\boldsymbol{r},\boldsymbol{r}')J_x(\boldsymbol{r}')d\boldsymbol{r}'$$

Model of infinitely thin wires:

$$J_x(\boldsymbol{r}) = \sum_{q=1}^{N} I_q \delta(\boldsymbol{r} - \boldsymbol{r}_q)$$

$$E_x(\boldsymbol{r}) = E_x^{(exc)}(\boldsymbol{r}) + \sum_{q=1}^{N} G_{xx}(\boldsymbol{r},\boldsymbol{r}_q)I_q$$

Ohm's law:

$$Z_q I_q = E_x^{(ext)}(\boldsymbol{r}_q) - \sum_{p=1}^{N} Z_{qp}^{(m)} I_p$$

Mutual-impedance densities

Sparse Metasurfaces

Green's function

A Green's function is defined as:

$$\left(\frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_r(\boldsymbol{r})k_0^2\right) G_{xx}(\boldsymbol{r}, \boldsymbol{r}') = j\omega\mu_0\delta(\boldsymbol{r} - \boldsymbol{r}')$$

Mutual-impedance densities are calculated as:

$$Z_{qp}^{(m)} = -G_{xx}(\boldsymbol{r}_q, \boldsymbol{r}_p), q \neq p,$$

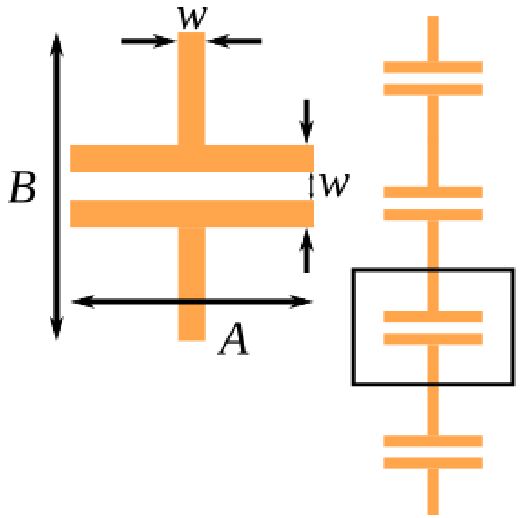
$$Z_{qq}^{(m)} = -\frac{1}{2\pi r_{eff}} \oint G_{xx}(\boldsymbol{r}, \boldsymbol{r}_q) \mathrm{d}\boldsymbol{r}.$$

A Green's function can be calculated numerically by means of full-wave simulations

Implementation of loaded wires

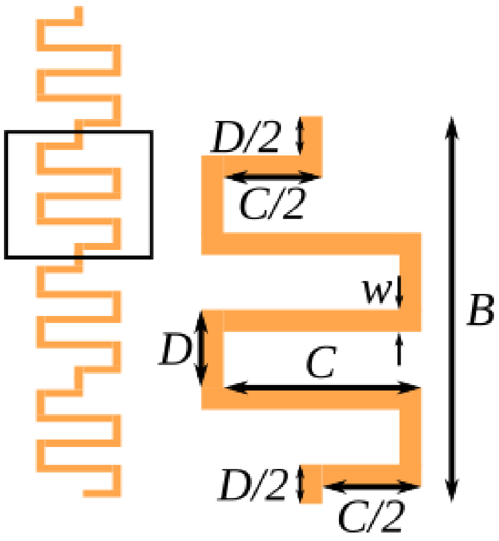
$\mathrm{Im}[Z_L]<0$

Printed capacitor



$\mathrm{Im}[Z_L]>0$

Printed inductor



Change the **gap** to engineer the capacitive response

Change the effective **length** to engineer the inductive response

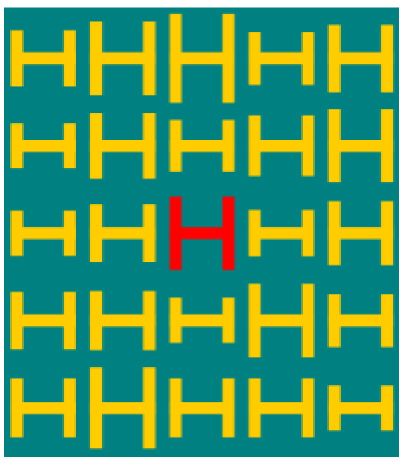
Sparse Metasurfaces

Designing sparse Metasurfaces

LPA of dense metasurfaces cannot be used for sparse ones

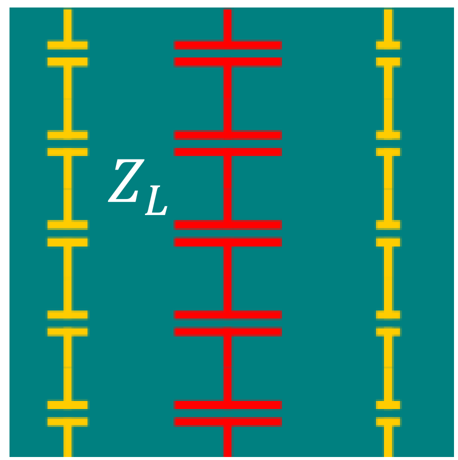
Dense Metasurface

Non-uniform array

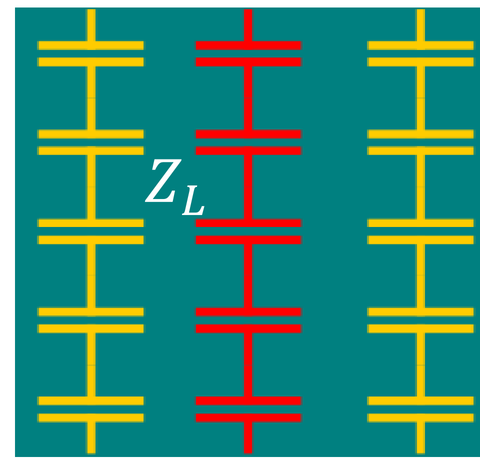


Sparse Metasurface

Non-uniform array



Uniform array



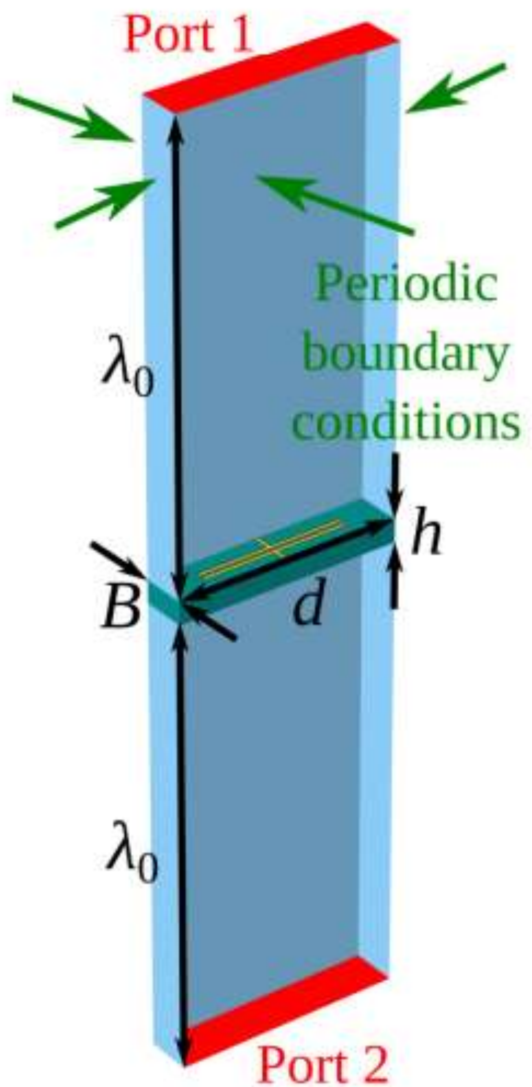
Sparse Metasurfaces

Load-impedance density engineering

- 3D full-wave simulations are used to calculate A_0^{TE} (S_{11} scattering parameter) for a uniform array of loaded wires

- After that, analytical formulas are used to retrieve load-impedance density

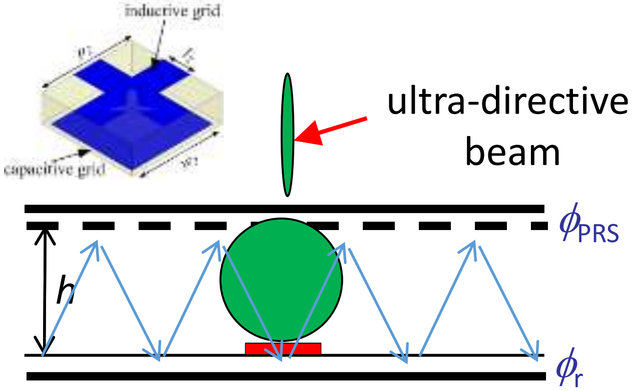
  - $I = -\frac{2d\beta_0}{k\eta}\frac{A_0^{TE} - R_0^{TE} e^{2j\beta_0 h}}{(1+R_0^{TE})e^{j\beta_0 h}}$
  - $Z_q I = E_0 - \frac{k\eta}{4} I H_0^{(2)}(k_0 r_{eff}) - Z_m I$
  - $E_0 = (1 + R_0^{TE})e^{j\beta_0 h}$



3. Metasurface applications

- Antennas
- Lenses
- Absorbers
- Polarization converters
- Wavefront engineering

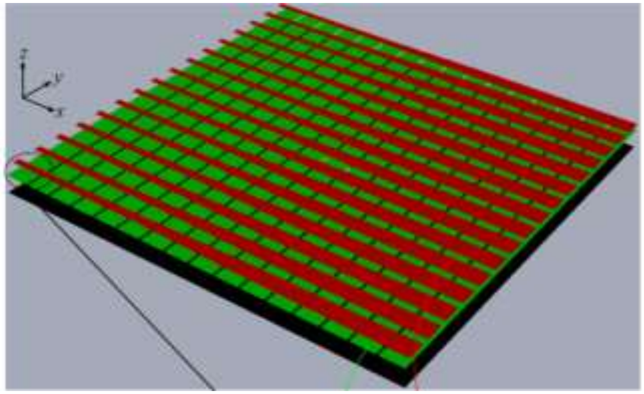
3. Metasurface applications: antennas

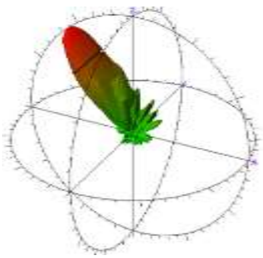


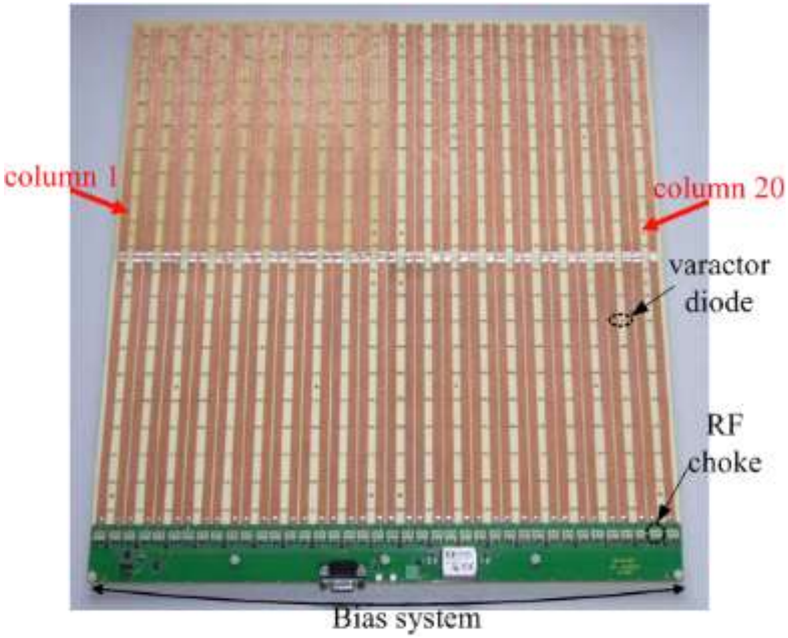
Thickness *h* of the cavity at resonance:

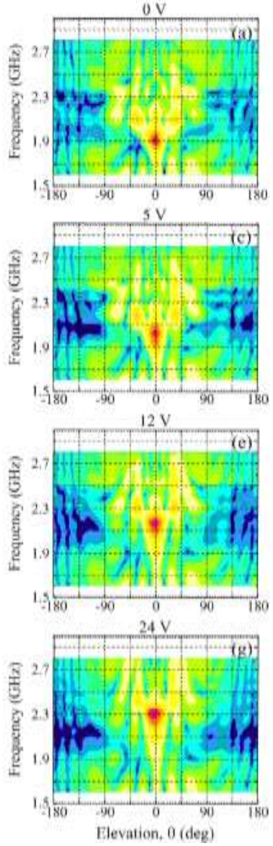
$$h = \frac{\lambda}{4\pi}(\phi_{\mathrm{PRS}} + \phi_{\mathrm{r}}) \pm N\frac{\lambda}{2}$$

We minimize ($\phi_{PRS}+\phi_r$) to reduce h → Metasurface[1]







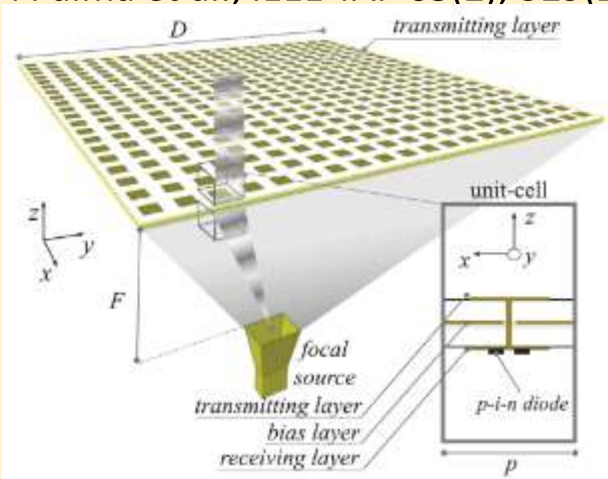


[1]S. N. Burokur et al., Metasurfaces for high directivity antenna applications in book Metamaterial, ISBN 978-953-51-0591-6, InTech.

3. Metasurface applications: antennas

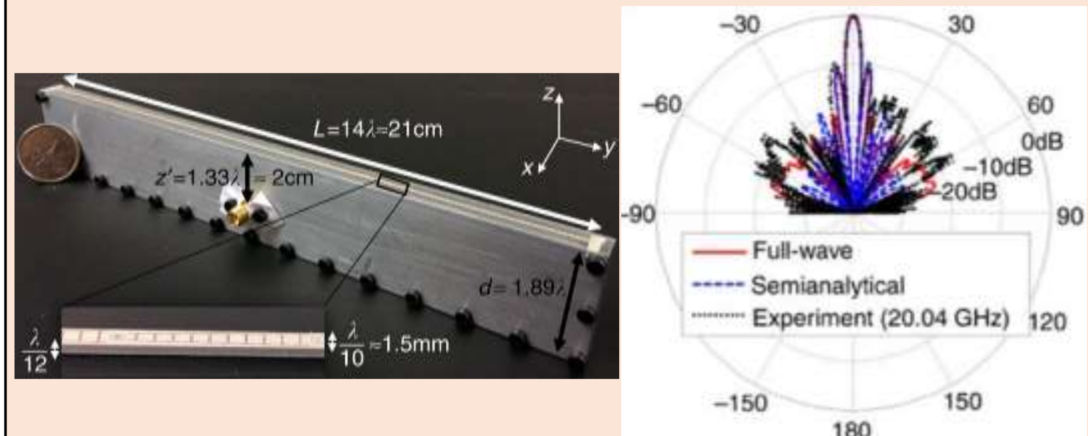
Transmit-array antenna

L. Di Palma et al., IEEE TAP **65**(2), 529(2017)



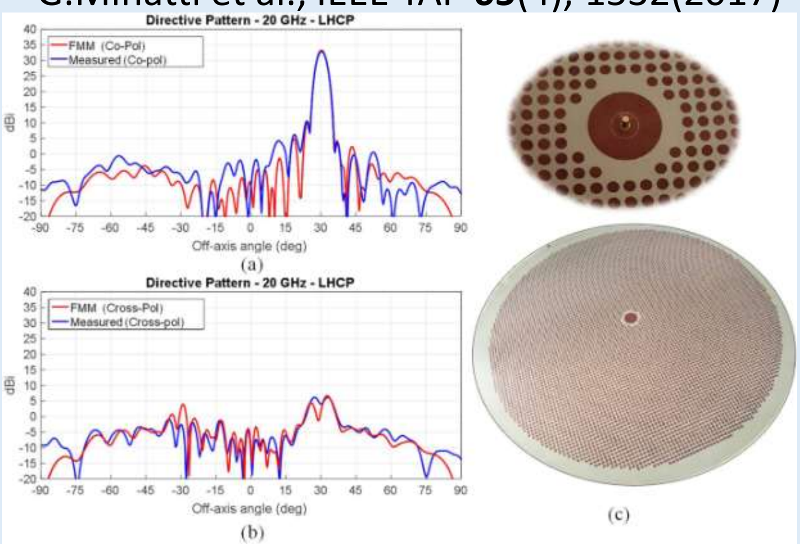
Cavity-excited Huygens' metasurface antenna

A. Epstein et al., Nat. Commun. **7**, 10360(2016)



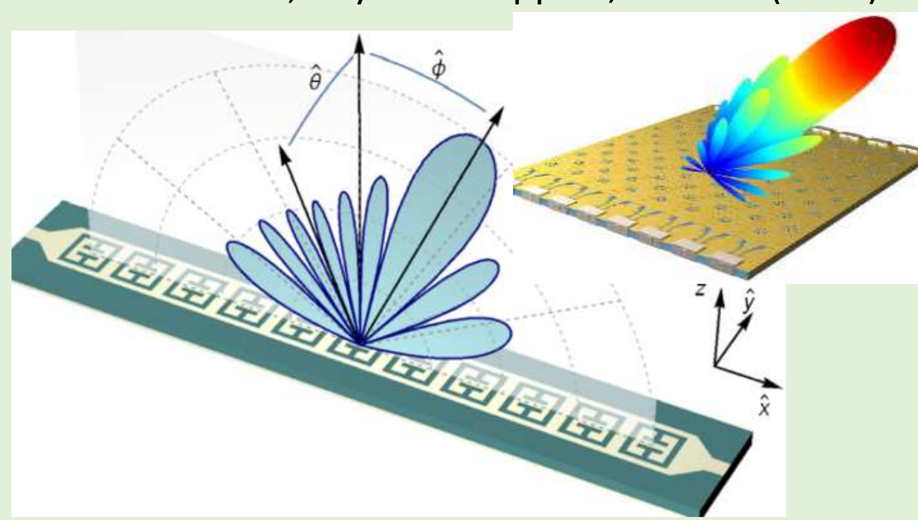
Modulated metasurface antenna

G.Minatti et al., IEEE TAP **65**(4), 1532(2017)



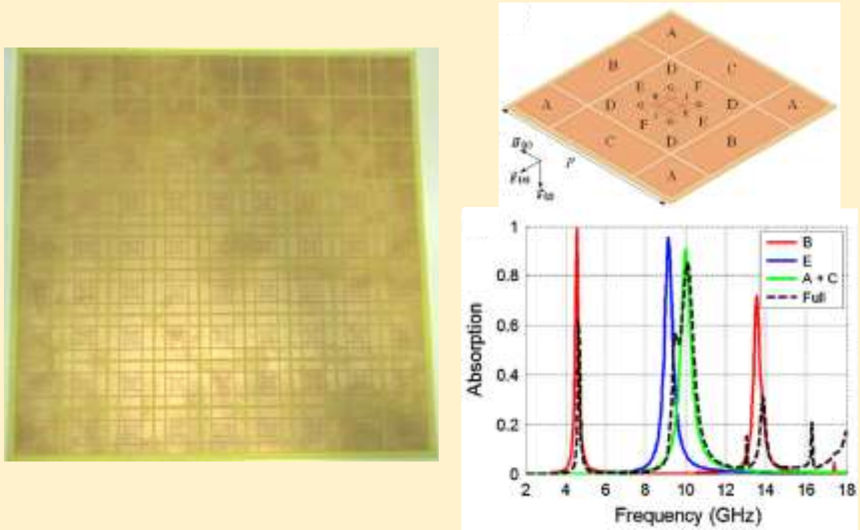
Waveguide-fed metasurface antenna

D. R. Smith et al., Phys. Rev. Appl. **8**, 054048 (2017)

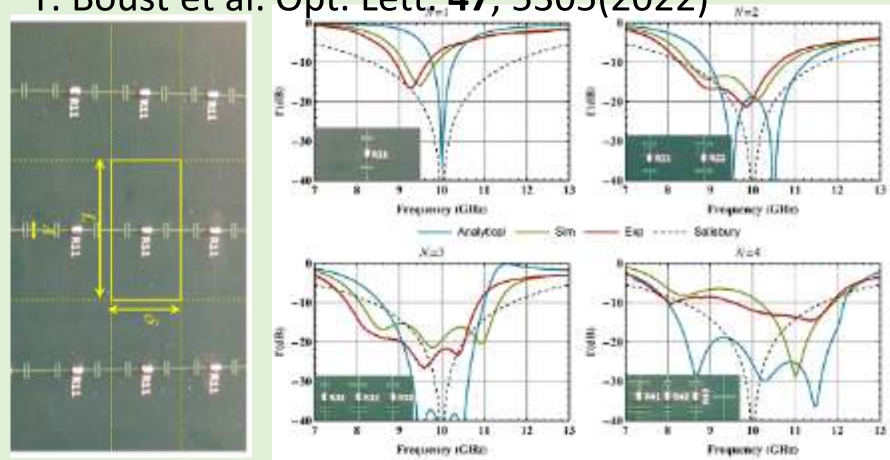


3. Metasurface applications: absorbers

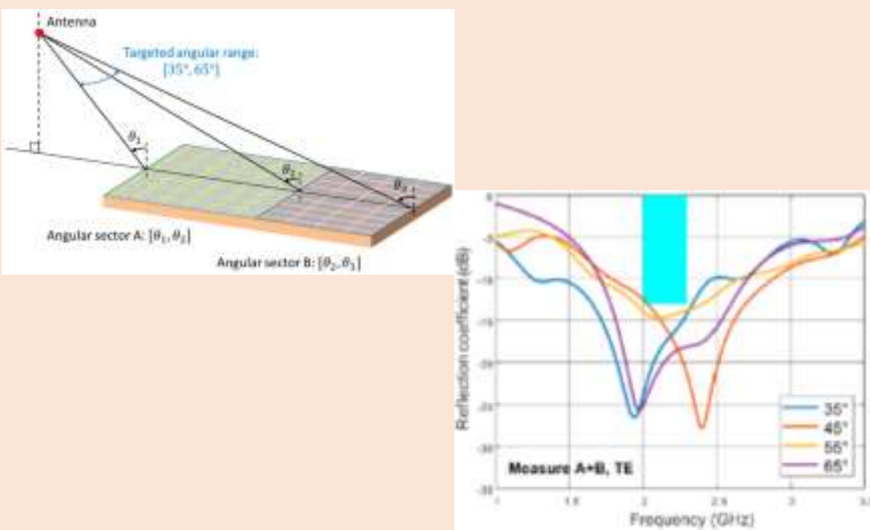
A. Sellier et al., Appl. Phys. A **117**, 739(2014)



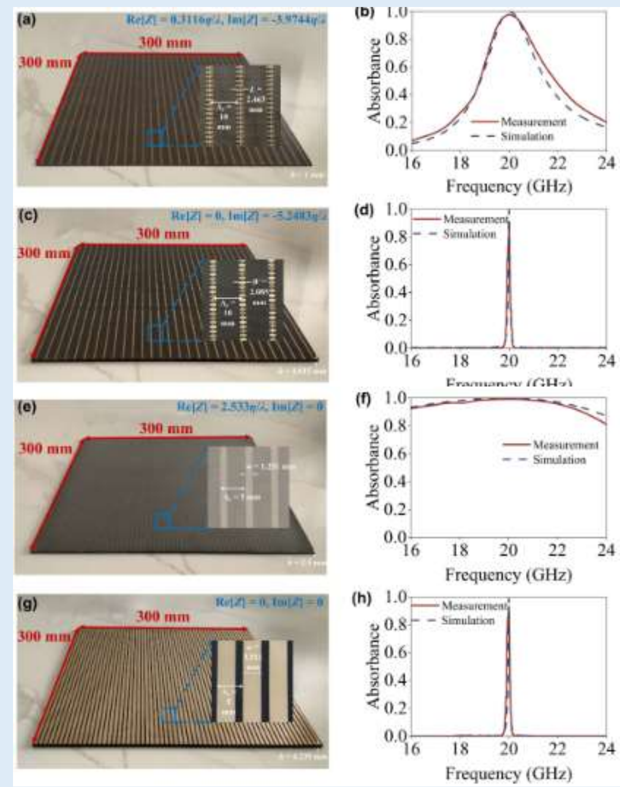
F. Boust et al. Opt. Lett. **47**, 5305(2022)



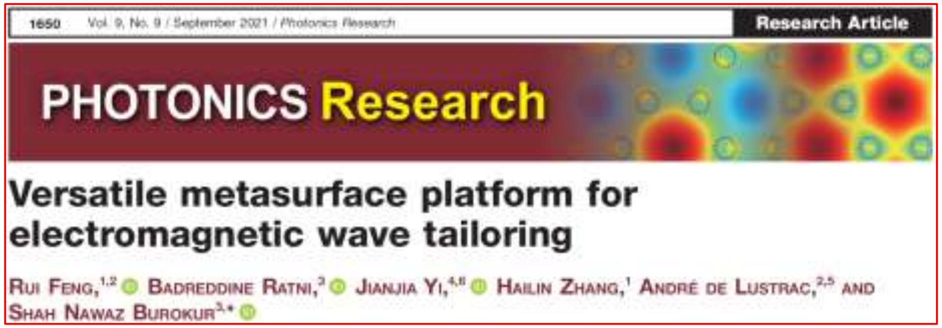
O. Rance et al., Appl. Sci. **9**(16), 3425(2019)



Z. Tan et al., IEEE TAP **71**, 1832(2023)



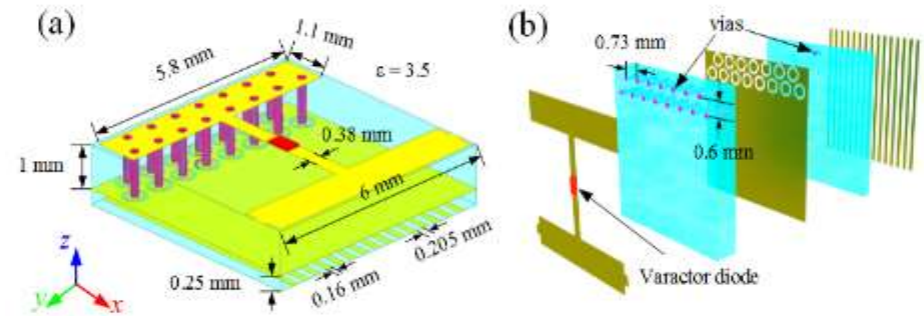
3. Metasurface applications: complex waves

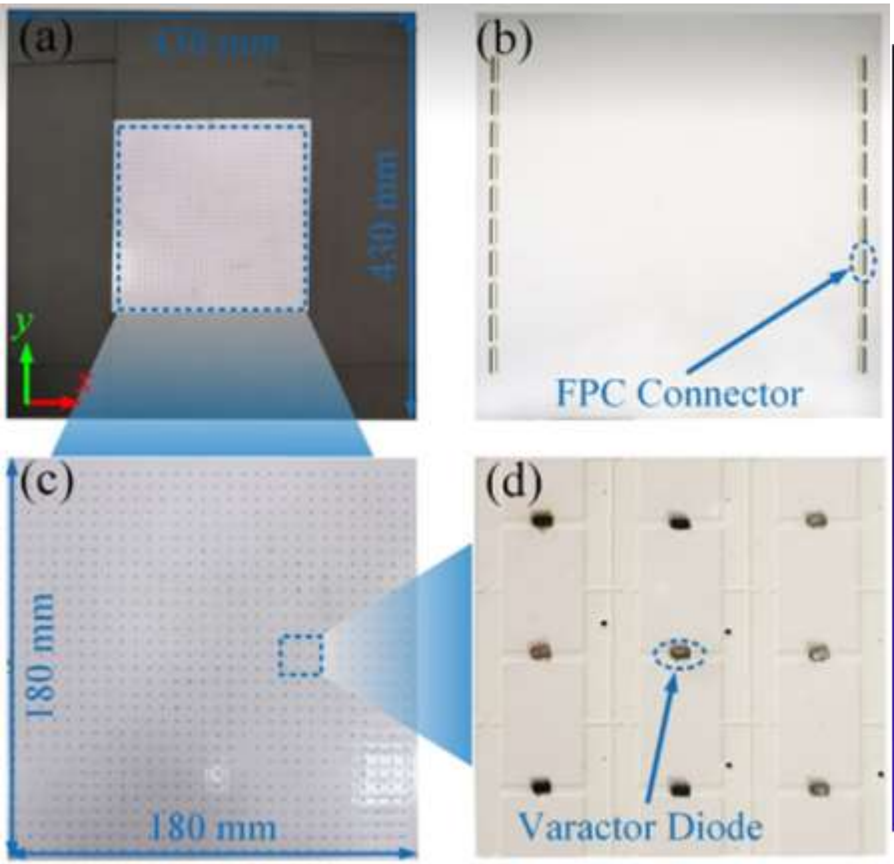

1650 Vol. 9, No. 9 / September 2021 / Photonics Research Research Article

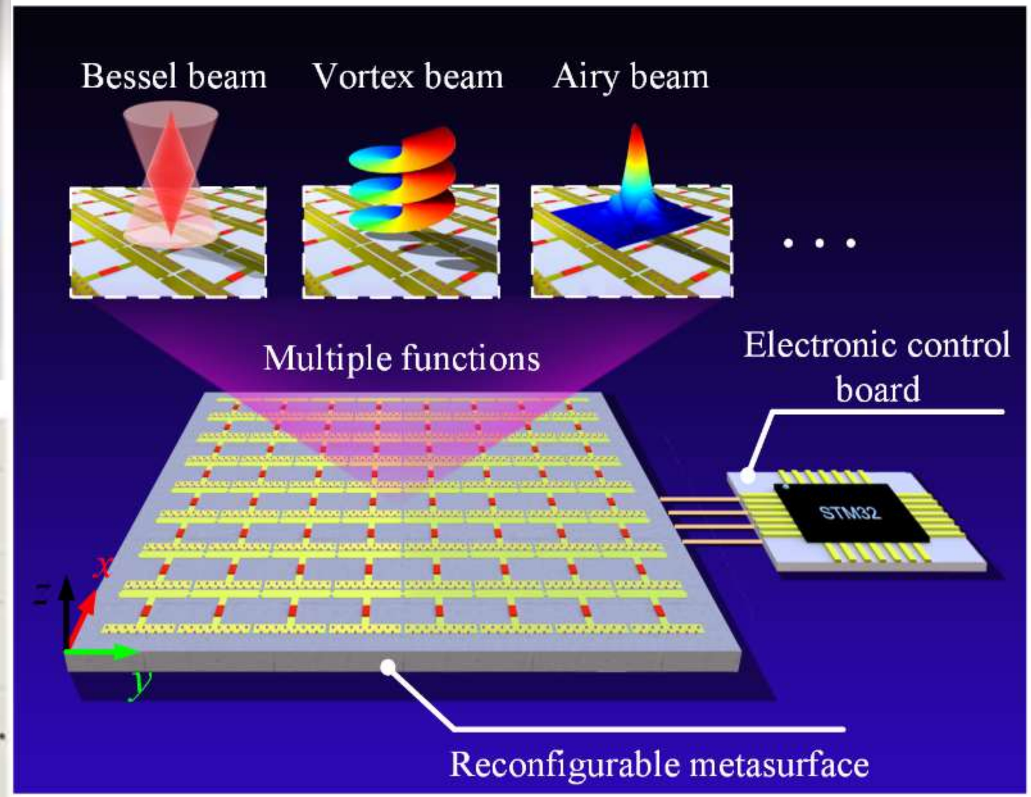
PHOTONICS Research

Versatile metasurface platform for electromagnetic wave tailoring

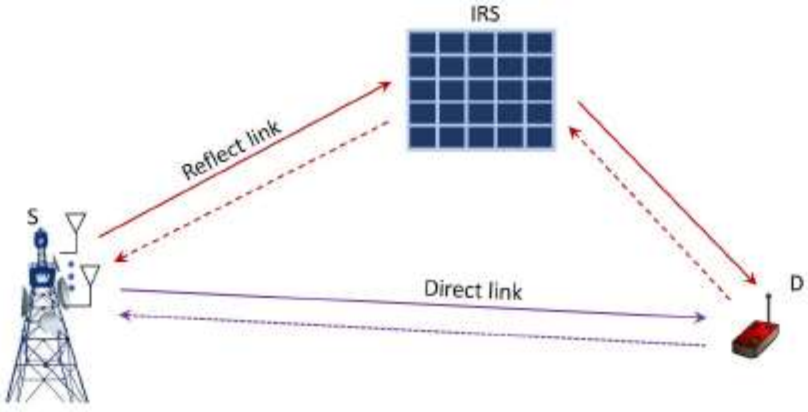
Rui Feng,[1,2] Badreddine Ratni,[2] Jianjia Yi,[4,6] Hailin Zhang,[1] André de Lustrac,[2,5] and Shah Nawaz Burokur[3,*]





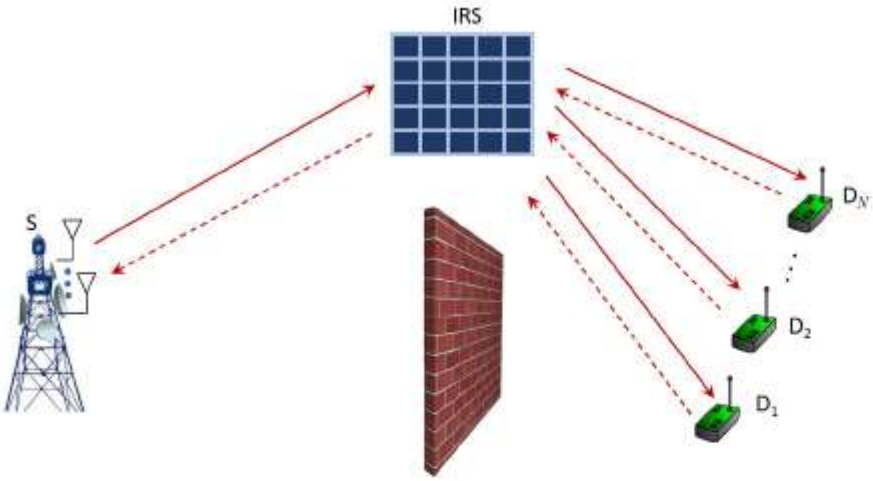


FD transmission: diversity gains to improve the received SNR at D and S



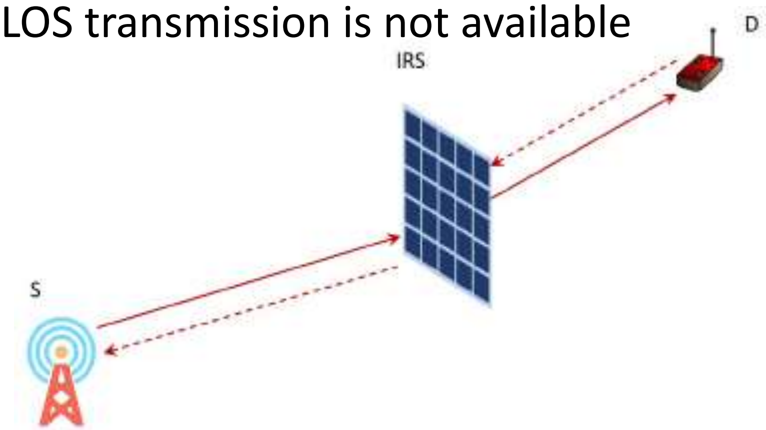
(a) LOS scenarios

FD transmission: communicating with multiple terminals through reflection



(b) NLOS scenarios with reflect waves

FD transmission: S and D located at each side of a RIS and LOS transmission is not available



(c) NLOS scenarios with transmission waves

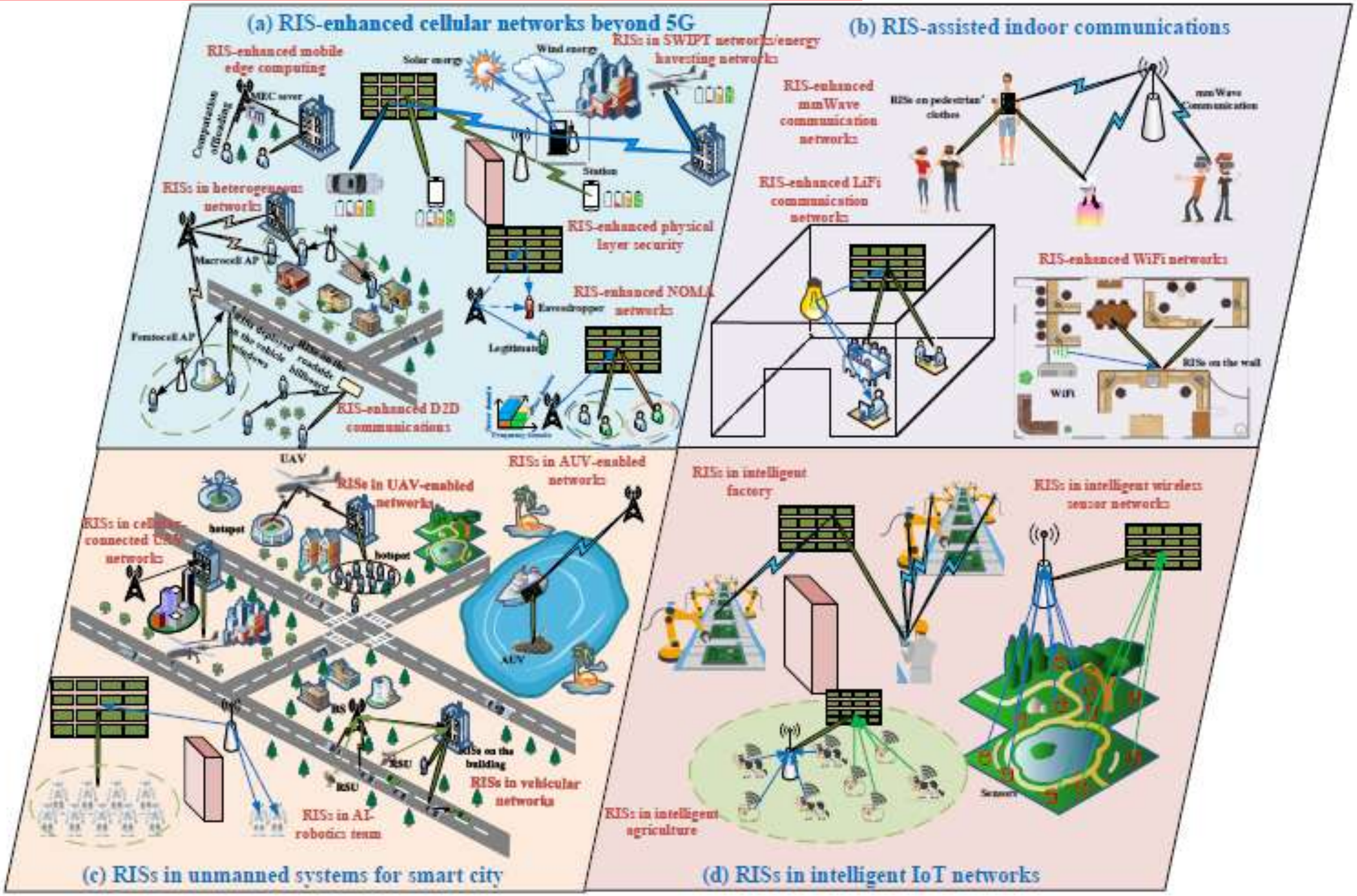
3. Metasurface applications: RIS

Journals & Magazines > IEEE Communications Surveys &... > Volume: 23 Issue: 3

Reconfigurable Intelligent Surfaces: Principles and Opportunities

Publisher: IEEE Cite This PDF

Yuanwei Liu ; Xiao Liu ; Xidong Mu ; Tianwei Hou ; Jiaqi Xu ; Marco Di Renzo **All Authors**



3. Metasurface applications: RIS

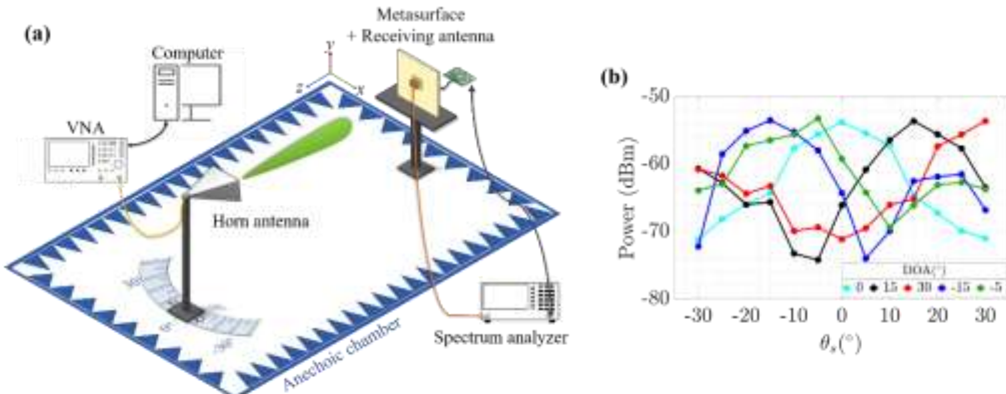
ADVANCED MATERIALS TECHNOLOGIES

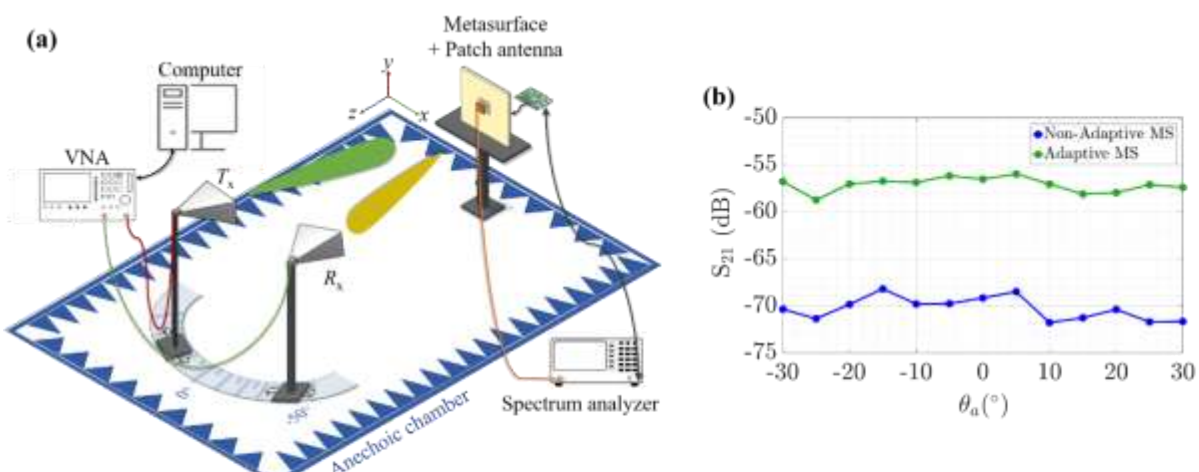
Research Article

Programmable Meta-Reflector for Multiple Tasks in Intelligent Connected Environments

Nawel Meftah, Badreddine Ratni, Mohammed Nabil El Korso, Shah Nawaz Burokur

First published: 08 April 2024 | https://doi.org/10.1002/admt.202400006

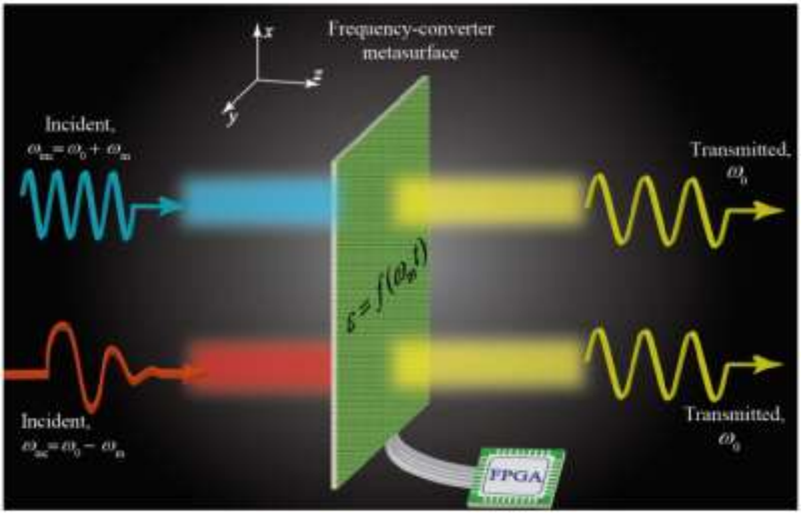




4. Actual trends: Temporal modulation

Pure and Linear Frequency-Conversion Temporal Metasurface

Sajjad Taravati and George V. Eleftheriades
Phys. Rev. Applied **15**, 064011 – Published 4 June 2021

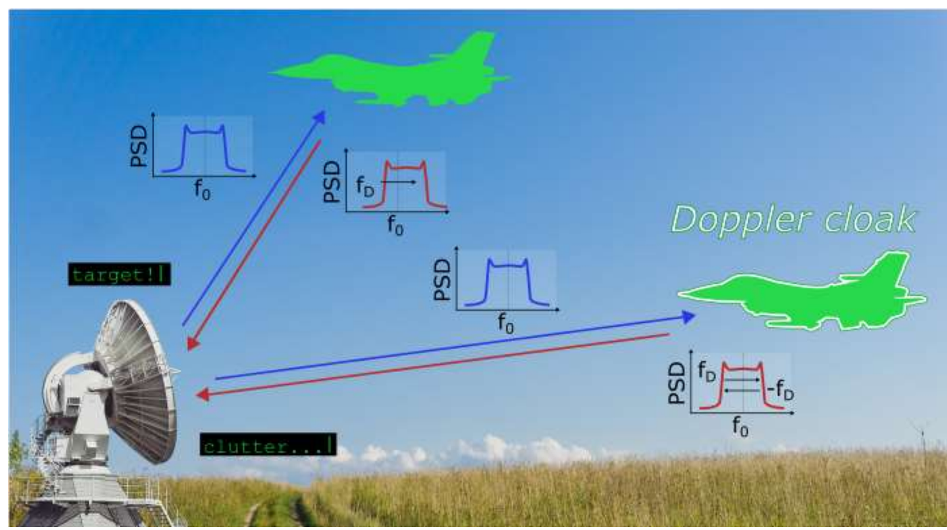


- Transition from the fundamental temporal frequency ω_0 to an infinite number of time frequency harmonics $\omega_0 \pm n\omega_m$.
- Hence, the output wave includes time harmonics of the modulation wave

Tanguy Lopez

Metasurface-based radar stealth solutions over VHF-UHF bands: Tunable absorption and Doppler cloaking

Thèse présentée et soutenue publiquement le 09/10/2024



4. Actual trends: Temporal modulation

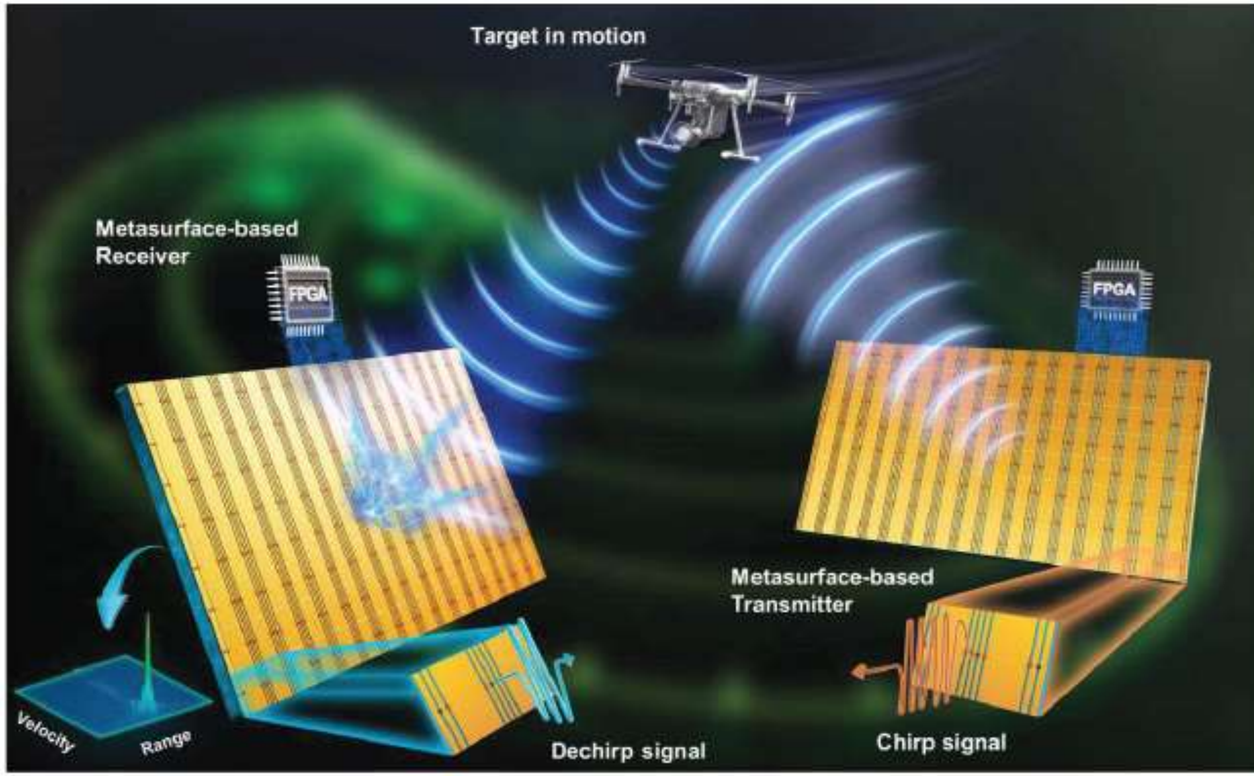
Research Square | Search preprints

Article

Simplified radar architecture based on information metasurface

Tie Jun Cui, Si Ran Wang, Zhan Ye Chen, Shao Nan Chen, Jun Yan Dai, and 8 more

This is a preprint; it has not been peer reviewed by a journal.



At transmitting end:
- Beamforming
- radar-signal generation (no active RF devices)

At receiving end:
- capturing the echo waves
- transforming the broadband chirp signals into narrowband signals (avoiding the conventional RF hardware), lowering prohibitively high AD sampling rates

4. Actual trends: Mathematical operations


nature COMMUNICATIONS

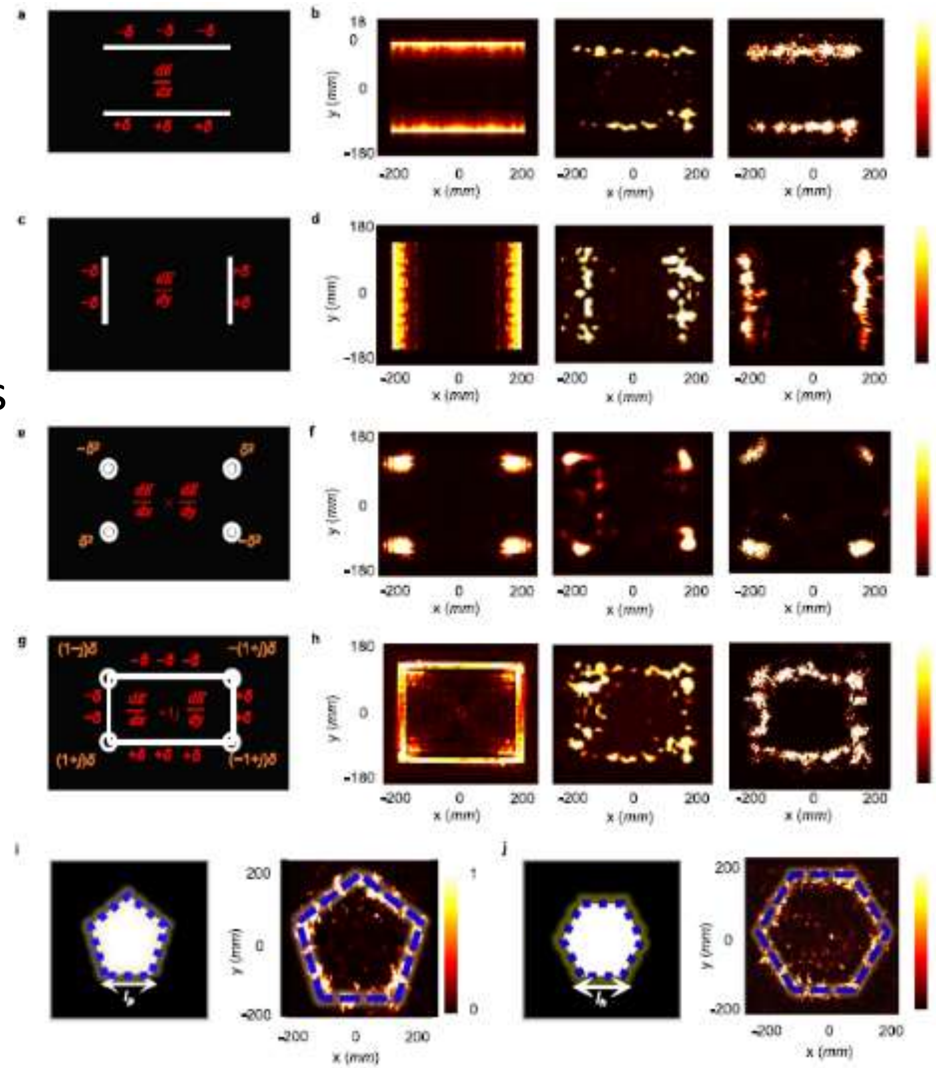
ARTICLE

https://doi.org/10.1038/s41467-022-29732-4 OPEN

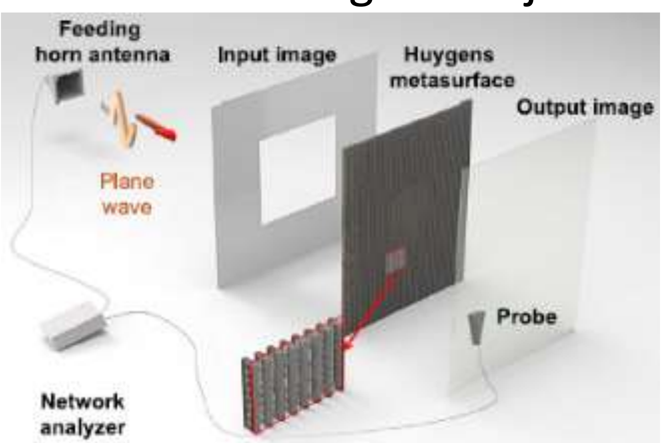
Check for updates

Single-layer spatial analog meta-processor for imaging processing

Zhuochao Wang[1,8], Guangwei Hu[7,8], Xinwei Wang[1,8], Xumin Ding[1,3,4,5✉], Kuang Zhang[6✉], Haoyu Li[1✉], Shah Nawaz Burokur[7✉], Qun Wu[6], Jian Liu[1,3,4,5], Jiubin Tan[1,3] & Cheng-Wei Qiu[2✉]



- performing analog optical computations based on Fourier transform
- Edge detection operation: dramatic change of the derivatives of signals due to the sudden change of objects



4. Actual trends: Multiplexing

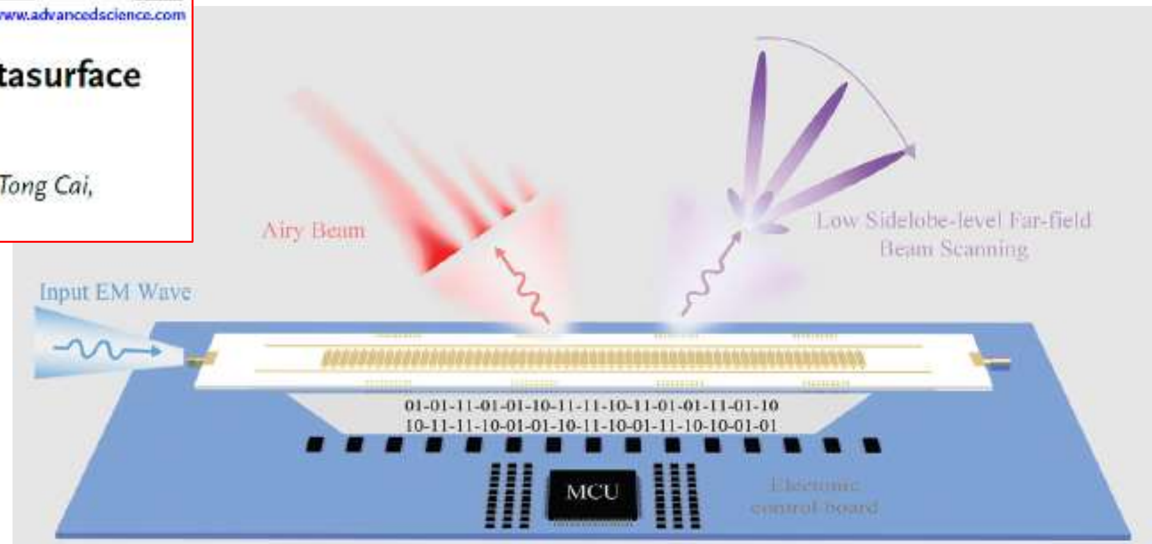
RESEARCH ARTICLE

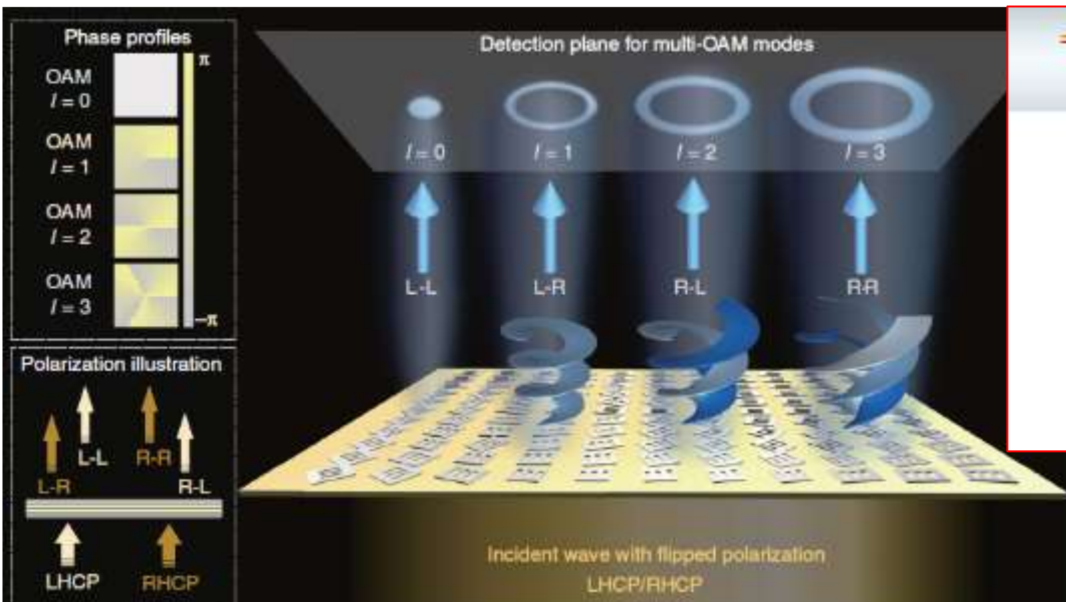
ADVANCED SCIENCE

www.advancedscience.com

Complex-Amplitude Programmable Versatile Metasurface Platform Driven by Guided Wave

Jian-Qiao Han, Fan-Yi Meng, Chunsheng Guan,* Cong Wang, Tao Jin, Tong Cai, Chang Ding,* Shah Nawaz Burokur, Qun Wu, and Xumin Ding**





nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-17773-6 OPEN

Independent phase modulation for quadruplex polarization channels enabled by chirality-assisted geometric-phase metasurfaces

Yueyi Yuan[1], Kuang Zhang[1✉], Badreddine Ratni[2], Qinghua Song[3], Xumin Ding[1✉], Qun Wu[1], Shah Nawaz Burokur[2✉] & Patrice Genevet[3✉]

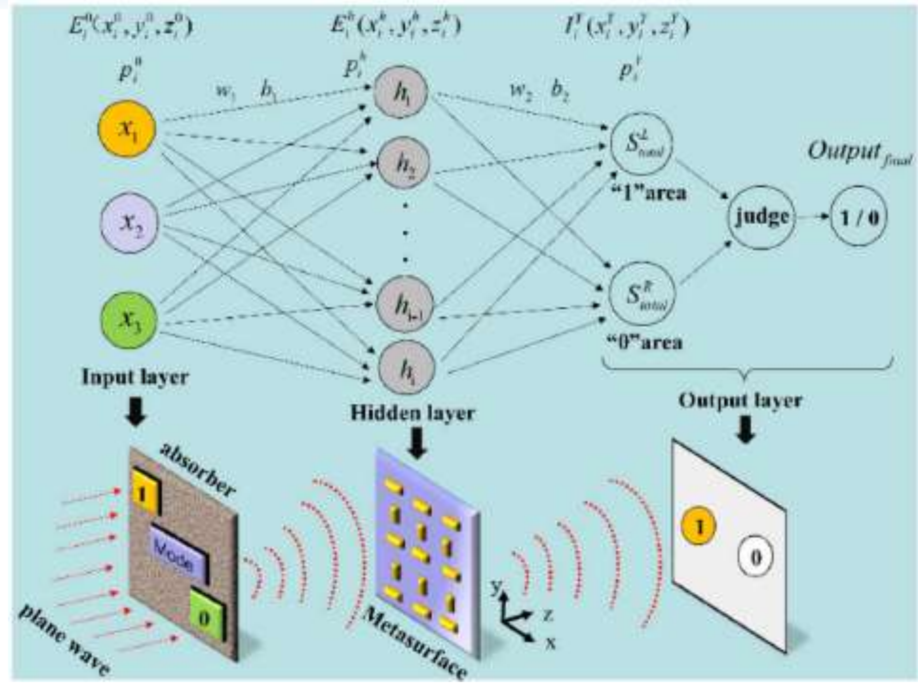
4. Actual trends: Learning-based metasurfaces

316 Vol. 10, No. 2 / February 2022 / Photonics Research — Research Article

PHOTONICS Research

Compact logic operator utilizing a single-layer metasurface

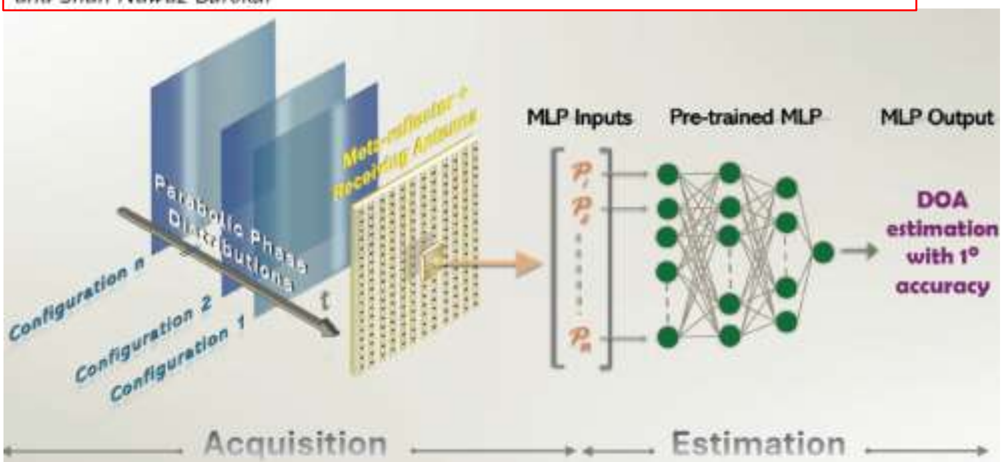
Zihan Zhao,[1,2,†] Yue Wang,[1,†] Xumin Ding,[1,4] Haoyu Li,[1,5] Jiahui Fu,[2] Kuang Zhang,[2,6] Shah Nawaz Burokur,[3,7] and Qun Wu[2]

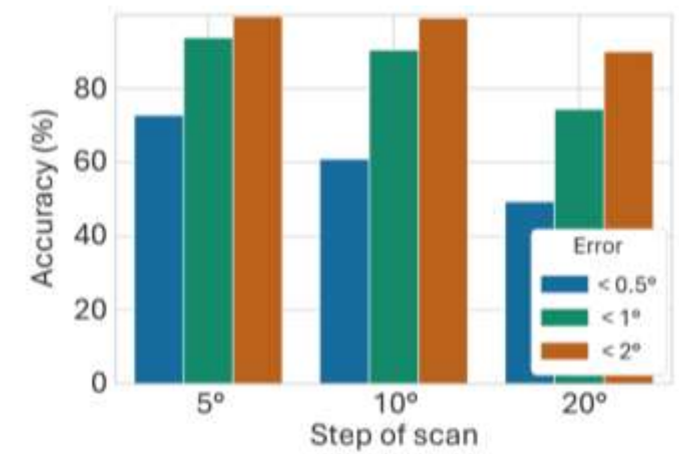


RESEARCH ARTICLE — ADVANCED ELECTRONIC MATERIALS — www.advelectronicmat.de

Enhanced-Resolution Learning-Based Direction of Arrival Estimation by Programmable Metasurface

Nawel Meftah, Badreddine Ratni, Mohammed Nabil El Korso, and Shah Nawaz Burokur**





5. Summary

- Various designs
- Various technologies/process
- Revisiting traditional architectures
- Novel designs with additional degrees of freedom
- Performances of metasurfaces v/s traditional devices ???

Thanks for your attention!