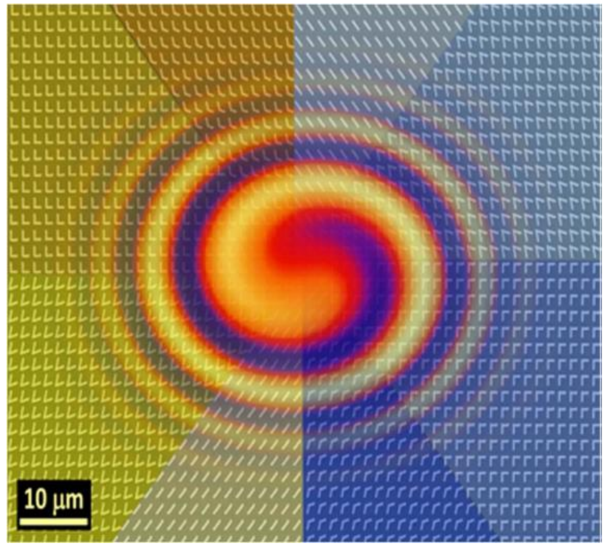
Optical Metasurfaces: Physics & Applications



Patrice Genevet

Centre de Recherche sur l’Hétéro-Epitaxie et ses Applications,

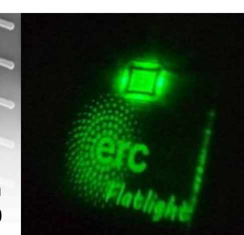
Sophia Antipolis, France

UNIVERSITÉ CÔTE D’AZUR

European Research Council

FLATLIGHT – Grant agreement 639109

Horizon 2020



email: pg@crhea.cnrs.fr

Metasurfaces @ CRHEA Group

Permanents

Dr. Samira Khadir
Maître de conférences UCA

Postdoctoral Fellows

Qinghua Song

Renato Juliano Martins

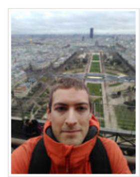
Christina Kyrou

PhD Students

Rajath Sawant

Sandeep Yadav Golla

Fouad Bentata (PhD in co-direction with INL)

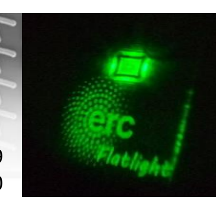


Anthony Gourdin (PhD in co-direction with Université de Montpellier)

Nikita Nikitskiy (PhD in co-direction avec Julien Brault)

FÉDÉRATION DE RECHERCHE "WOLFGANG DÖBLIN"

European Research Council
FLATLIGHT – Grant agreement 639109
Horizon 2020



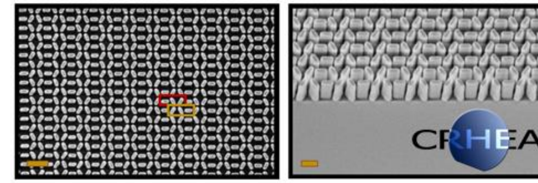
P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

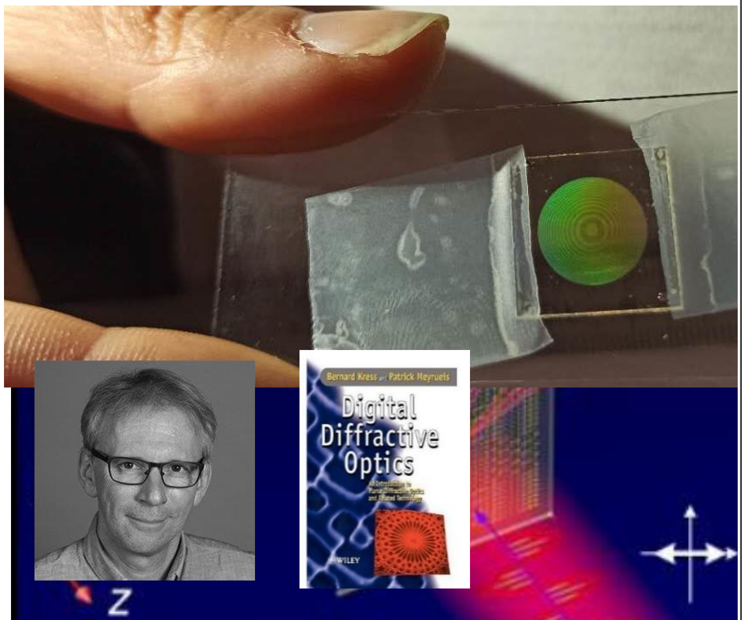
Outline

1. **General introduction**

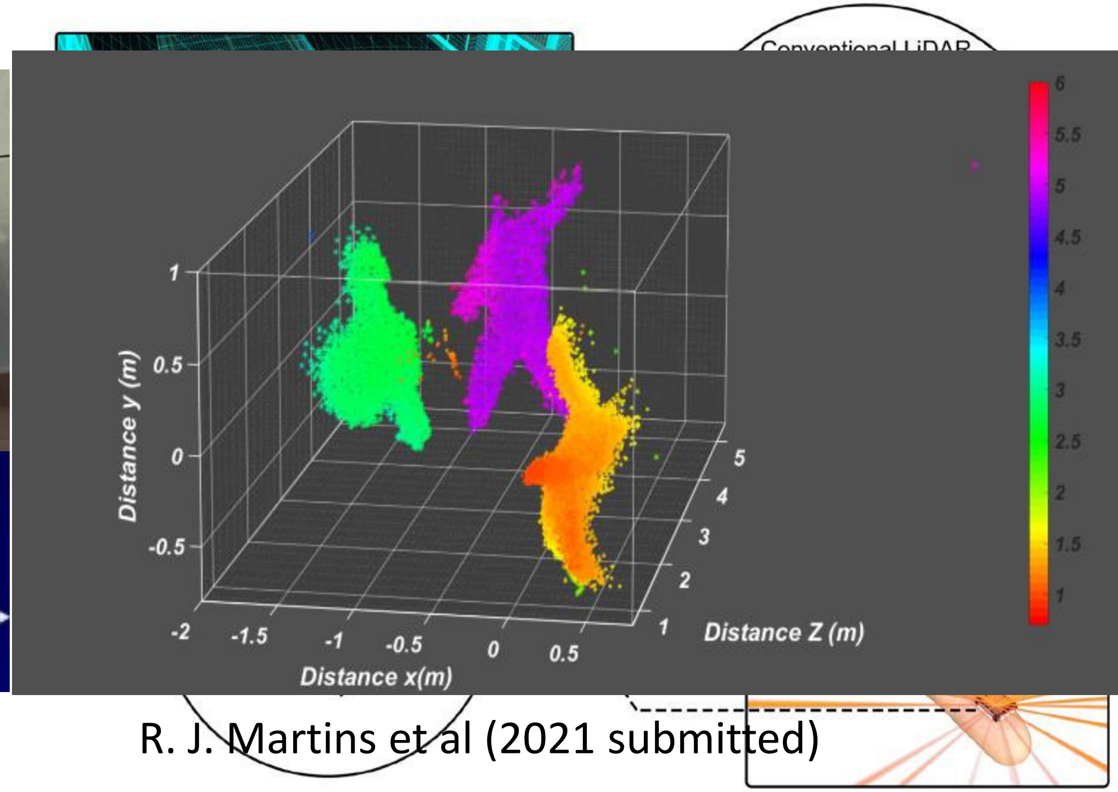
2. **Nanoscale manipulation of the electromagnetic field properties**

3. **Applications and contributions**





Bernard Kress (Microsoft/Hololens)



R. J. Martins et al (2021 submitted)

Technology simplification:
“a single digital pattern (one mask level) can create an arbitrary analog phase profile”

Fermat Principle

"Stationary Phase Principle"

P. Genevet, CRHEA, CNRS, France

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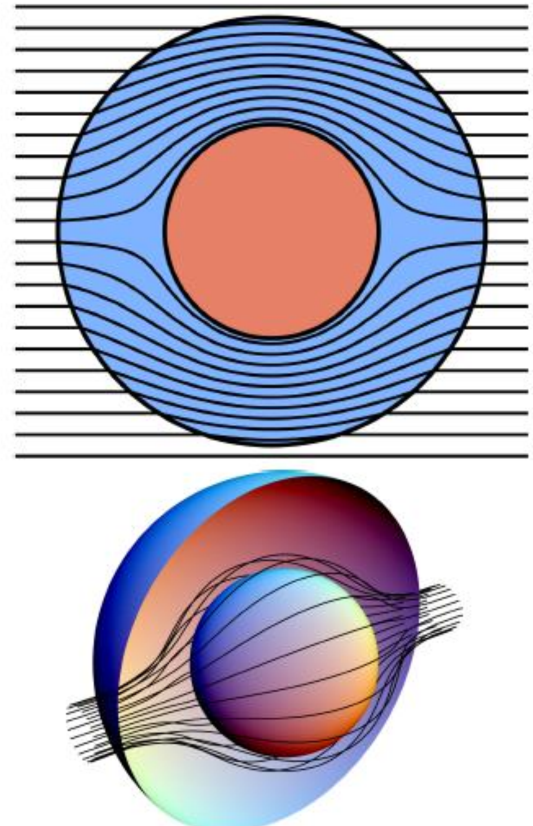
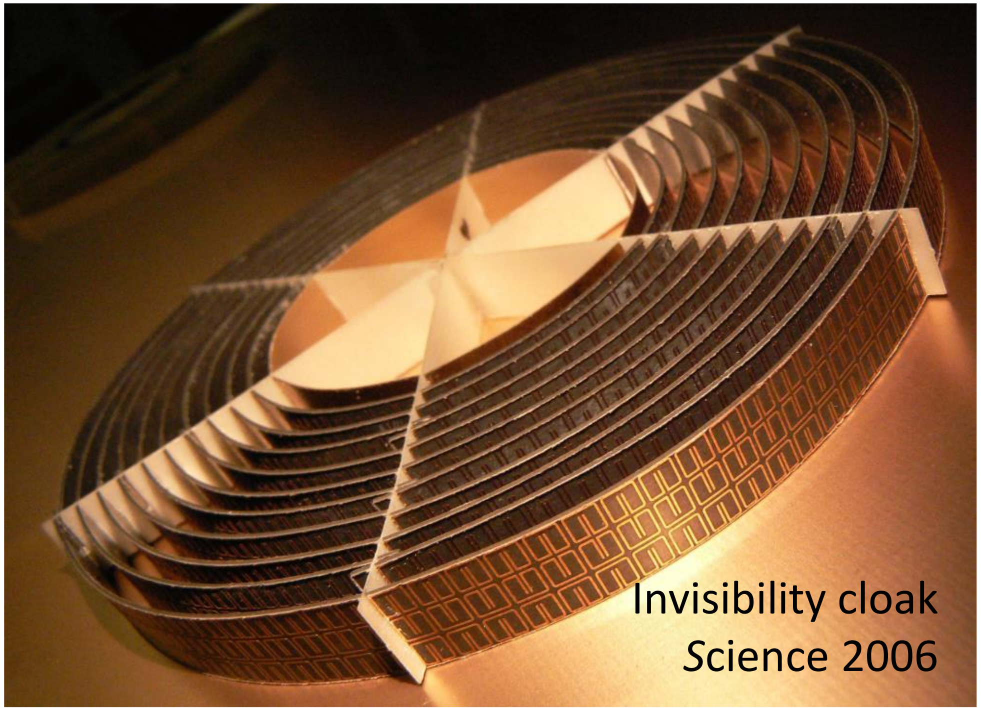
Fermat Principle: conventional optics



Pendry, et. al. 2006

Metamaterials: Controlling light propagation
No reflection and no shadow : cloaking

The 21th century, the era of photonics



Science fiction

Metamaterial
Greek/latin composition

μετά *materia*
«Beyond Matter»

Material engineered to have a property not found in naturally occurring materials

P. Genevet, CRHEA, CNRS, France
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Metasurfaces @ CRHEA

Cars « propagate » at different speed as a function of the length of their trajectory

Cars « propagate » at the same speed

P. Genevet, CRHEA, CNRS, France

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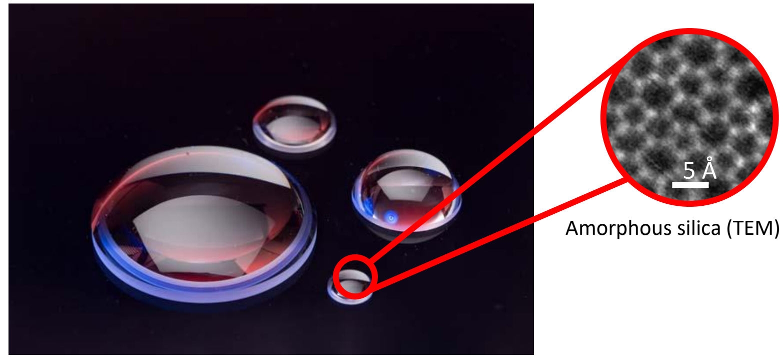
Slide adapted from M. Wegener courses

1. General intro: Optics at interfaces

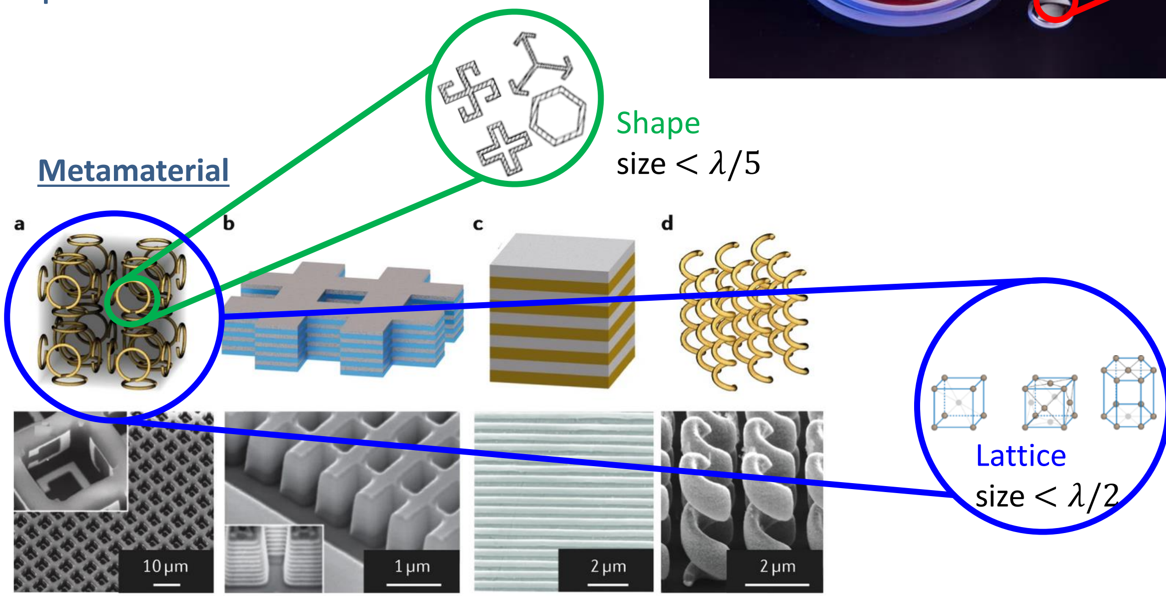
Conventional Material

Ordinary materials are built up from atoms. To reduce the underlying complexity, materials are often treated as fictitious continuous media with associated effective parameters such as the optical refractive index.



Amorphous silica (TEM)

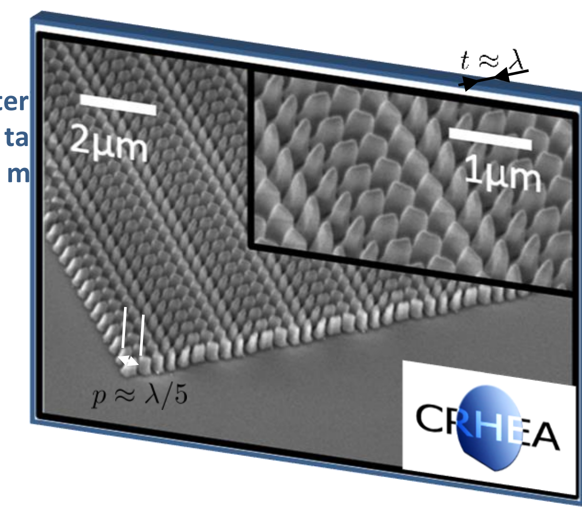
Metamaterial



M. Kadic, G. W. Milton, M. van Hecke and M. Wegener , Nature Reviews Physics 1, 198–210 (2019)

Metasurface

Metamater
made of ta
of one or m



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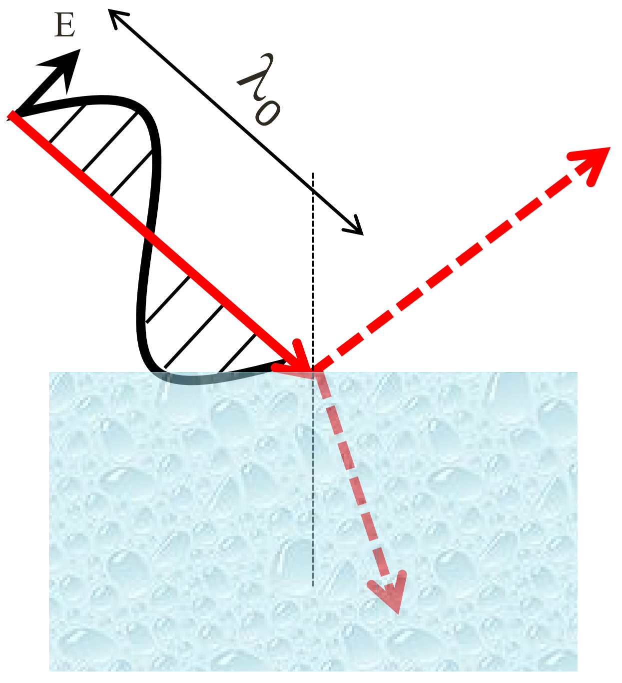
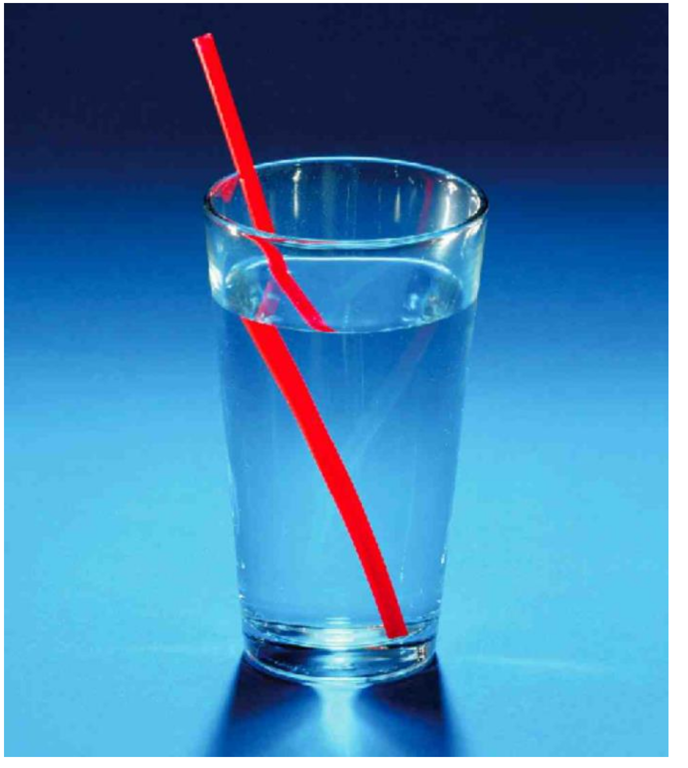
1. General intro: Optics at interfaces

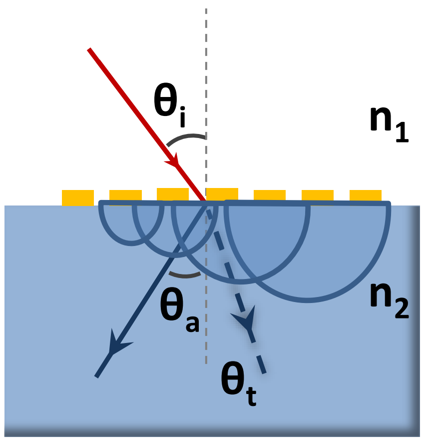




One of the laws of optics, **Snell-Descartes law**, states that a light ray passing from one transparent medium to another is bent at the interface by an amount that depends on the so-called refractive indices of the two media.

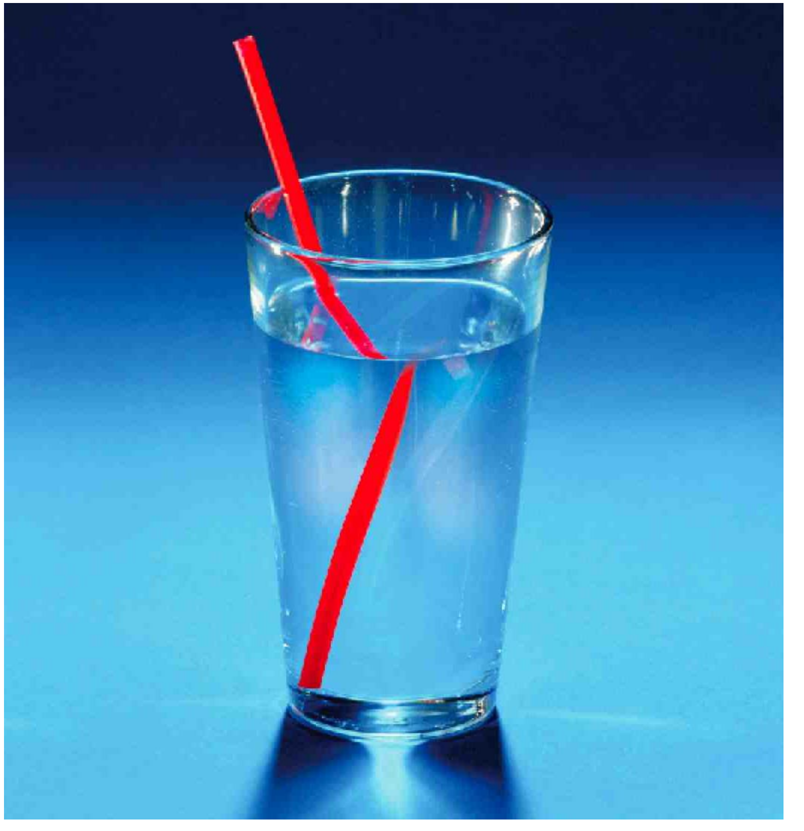
1. General intro for the optics at interfaces

Locally engineering of the surface response



Phase gradient direction

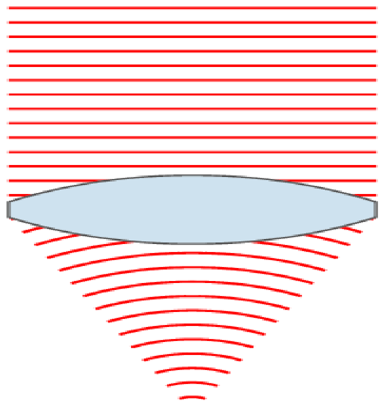
$$\frac{d\varphi}{dx}$$



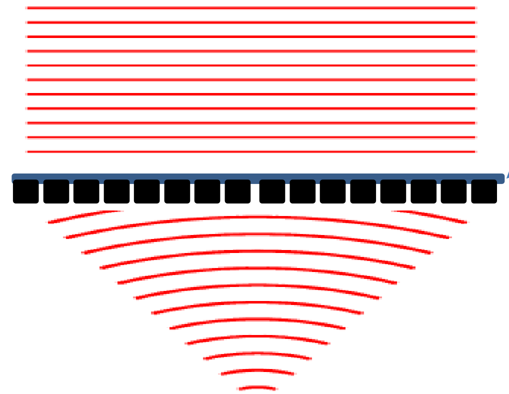
N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.P. Tetienne, F. Capasso and Z. Gaburro, ***Science*** **334**,333 (2011).

1. Generalities

Wavefront control



Classical lens (~ cm)

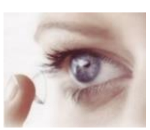


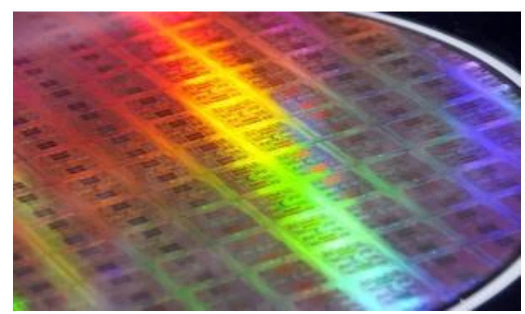
Meta-lens (~nm)

However, it requires nanoscale light manipulation

Engineering of the phase, amplitude, and polarization of light at an interface

Wafer level fabrication of optical components





P. Genevet, CRHEA, CNRS, France

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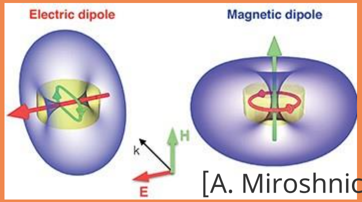
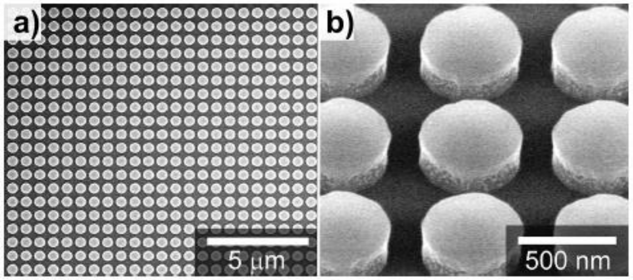
Phase Addressing Mechanisms

Resonant scattering



[A. Miroshnichenko]

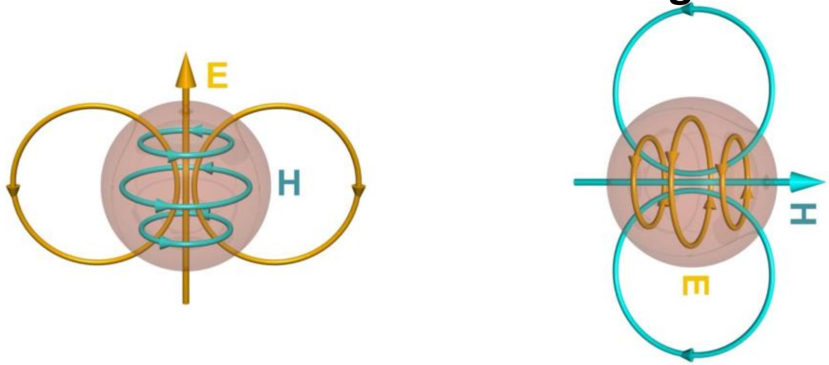
- Plasmonic Resonator (π)
- Dielectric Resonator (2π using Huygens EM design?)



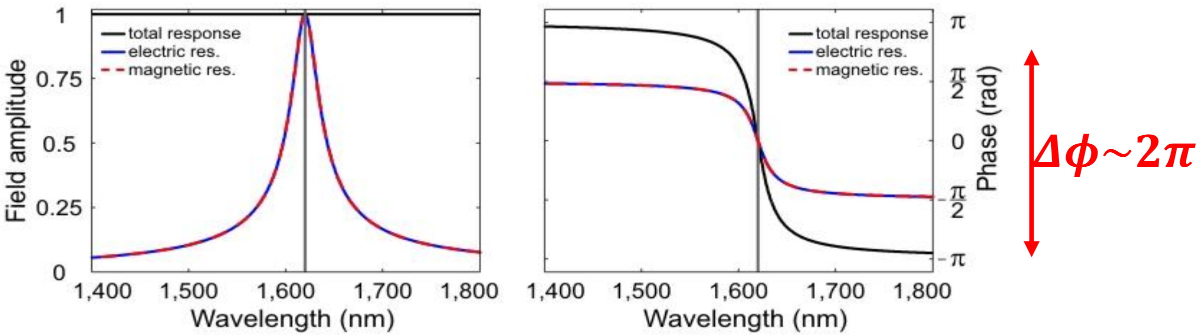
Decker *et al*., Adv. Opt. Mat. **13**, 813 (2015)

Dipoles

Electric **Magnetic**

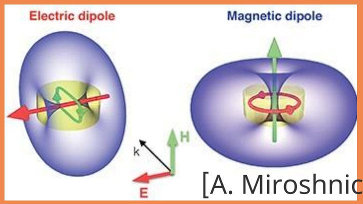


Overlapping e & m resonances

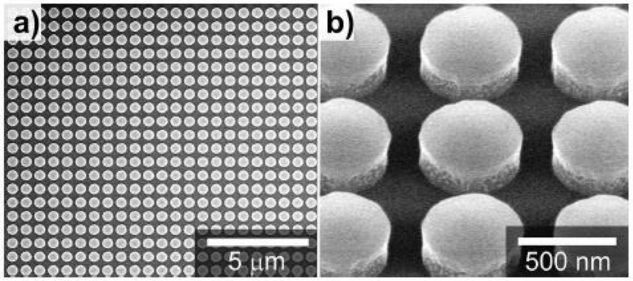


Phase Addressing Mechanisms

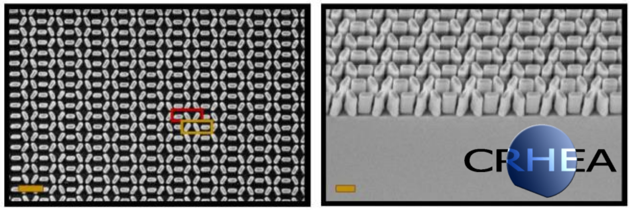
Resonant scattering	Pancharatnam-Berry (PB) Phase
- Plasmonic Resonator (π) - Dielectric Resonator (2π using Huygens EM design?)	-Polarization conversion -Birefringent plasmonic or Dieletrics -full 2π phase coverage



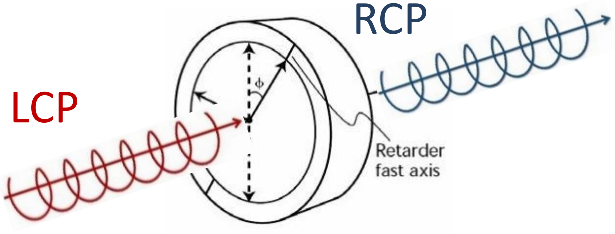
[A. Miroshnichenko]



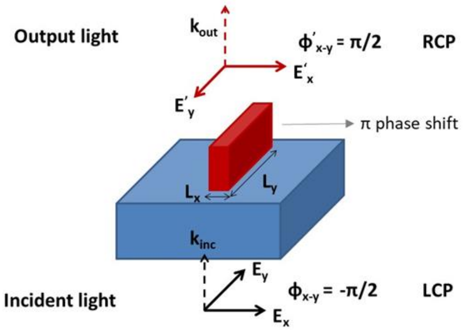
Decker *et al*., Adv. Opt. Mat. **13**, 813 (2015)



Half wave plate



Nanoscale Half wave plate

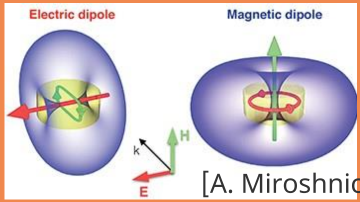


➢ a geometric phase obtained from **anisotropic nanopillars**

$$\Delta\phi = 2\phi$$

Phase Addressing Mechanisms

Resonant scattering



[A. Miroshnichenko]

- Plasmonic Resonator (π)
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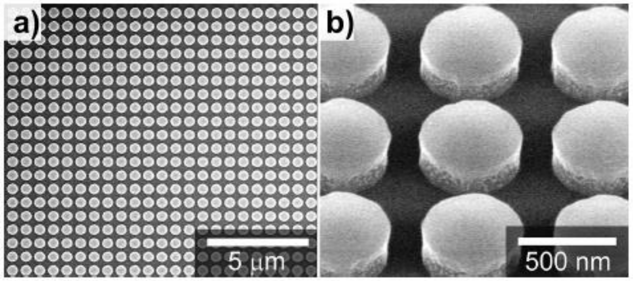
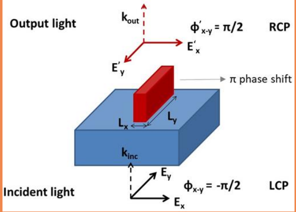
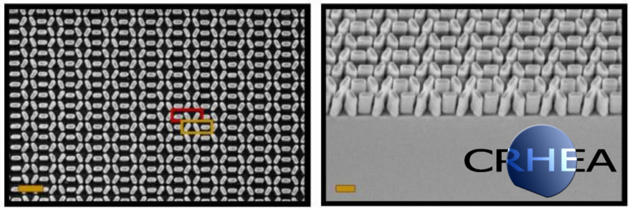


Decker *et al*., Adv. Opt. Mat. **13**, 813 (2015)

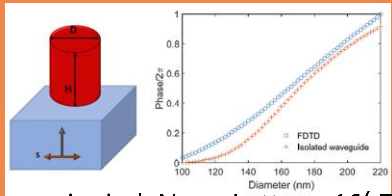
Pancharatnam-Berry (PB) Phase



-Polarization conversion
-Birefringent plasmonic or Dieletrics
-full 2π phase coverage

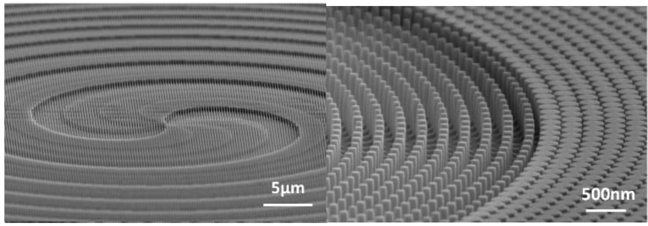


Effective index waveguides



M. Khorasaninejad, Nano Letters, 16(:7229, 2016.

- Not subwavelength in thickness
- Strong NF coupling



Y. Xie et al., Nat. Nanotechnol. **15,** 125–130 (2020)

P Genevet, F Capasso, F Aieta, M Khorasaninejad, R Devlin, **Optica** 4 (1), 139-152 (2017)

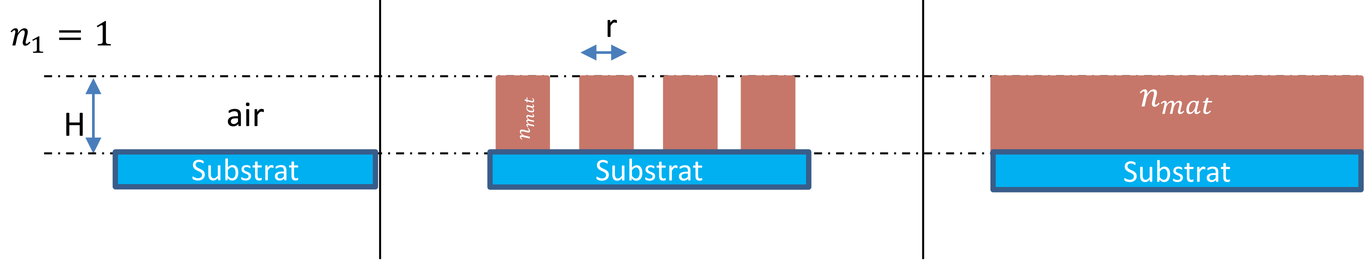
1. Generalities

Effective Index Waveguides

$$\frac{2\pi H}{\lambda} = \phi_{min}$$

$$\phi_{min} < \Delta\Phi(\mathrm{r}) = \frac{2\pi \Delta n(r) H}{\lambda} < \phi_{max}$$

$$\frac{2\pi n_{GaN} H}{\lambda} = \phi_{max}$$

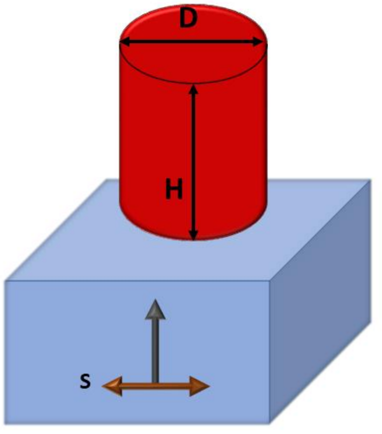


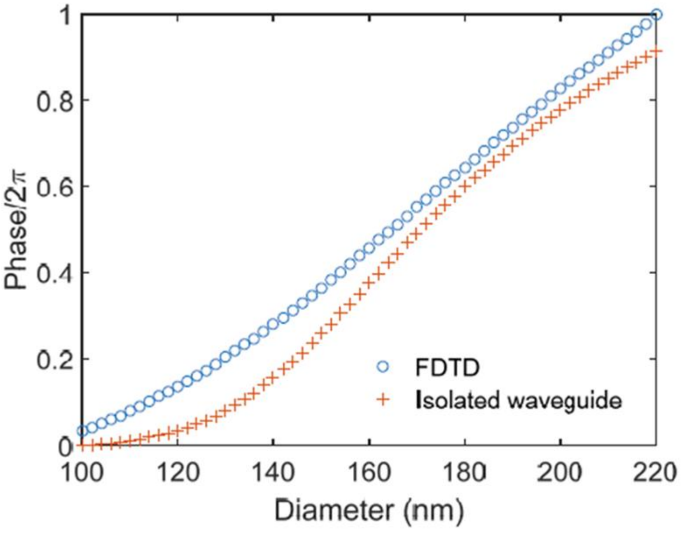
Full wavefront addressing requires phase elements ranging across the 2π phase delay

$$H > \lambda / \Delta n$$

1. Generalities

Effective Index Waveguides



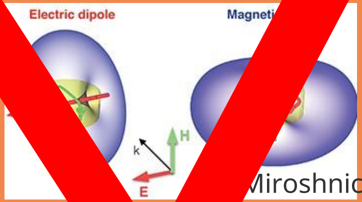
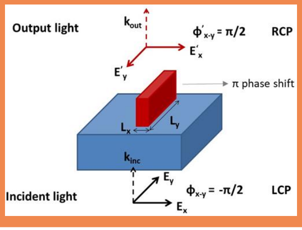
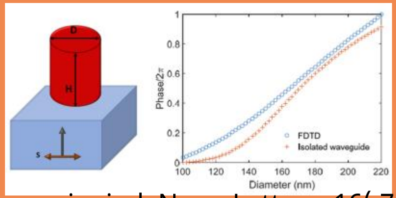


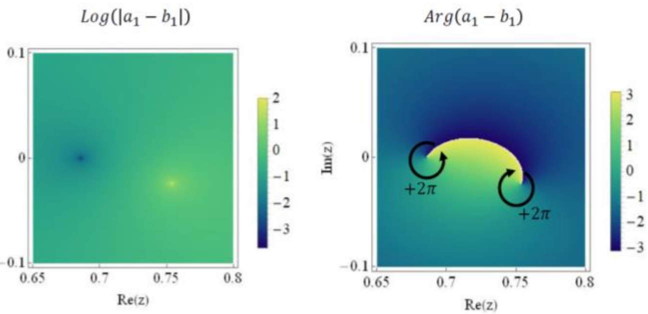
M. Khorasaninejad et. al, Nano Letters, 16(11):7229-7234, 2016.

- Dielectric nanopillars acting as **waveguides** - Controlling phase shift by tuning the **diameter of nanopillars**.

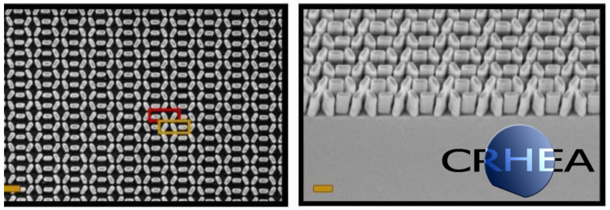
- Agrees with fundamental mode calculation

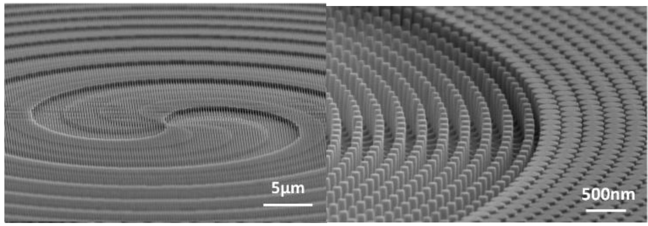
Phase Addressing Mechanisms

SINGULAR SCATTERING	Pancharatnam-Berry (PB) Phase	Effective index waveguides
 [Miroshnichenko]		 M. Khorasaninejad, Nano Letters, 16(:7229, 2016.
2π Topological phase encircling singularities	-Polarization conversion -Birefringent plasmonic or Dieletrics -full 2π phase coverage	- Not subwavelength in thickness - Strong NF coupling



E. Mikheeva, R. Colom et al. (in progress)

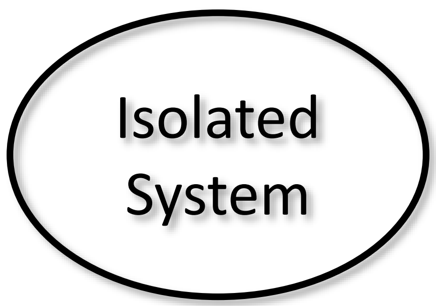


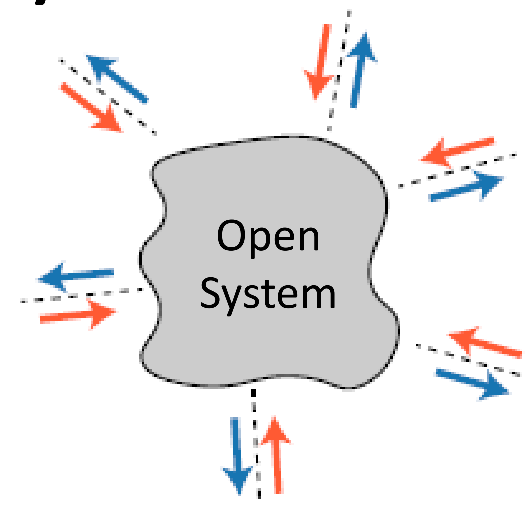


Y. Xie et al., Nat. Nanotechnol. **15,** 125–130 (2020)

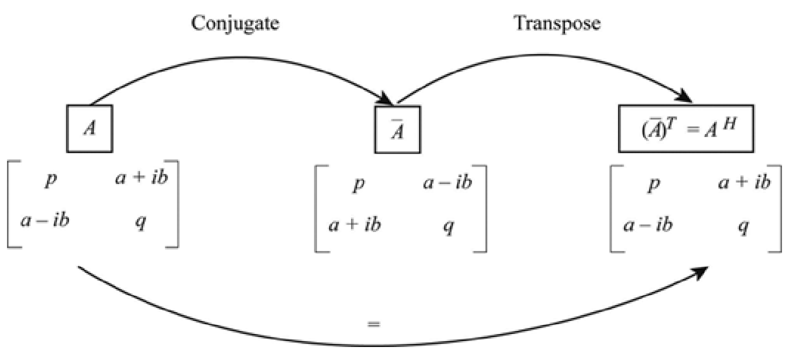
Isolated vs Open System

Environment





Energy is conserved
Hermitian Hamiltonian
Real eigenenergies



Exchange of energy
Gain or loss
Non-Hermitian Hamiltonian
Complex eigenenergies

Scattering: Radiation losses induces non-Hermiticity

P. Genevet, CRHEA, CNRS, France
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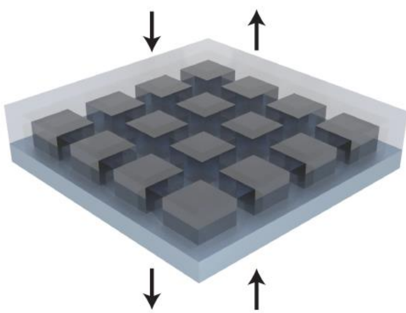
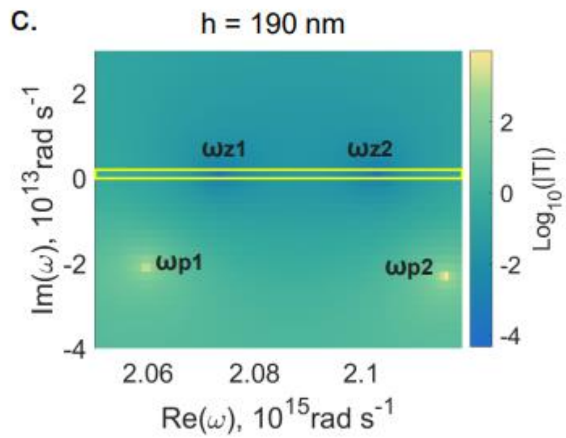
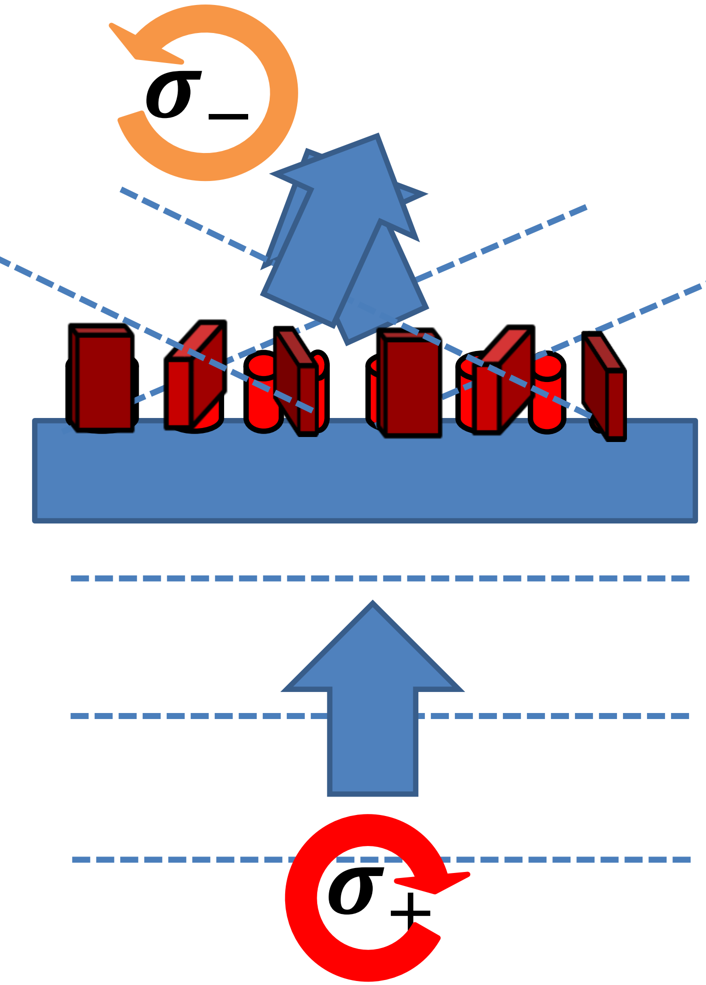
Complex frequency analysis: presence of Singularities

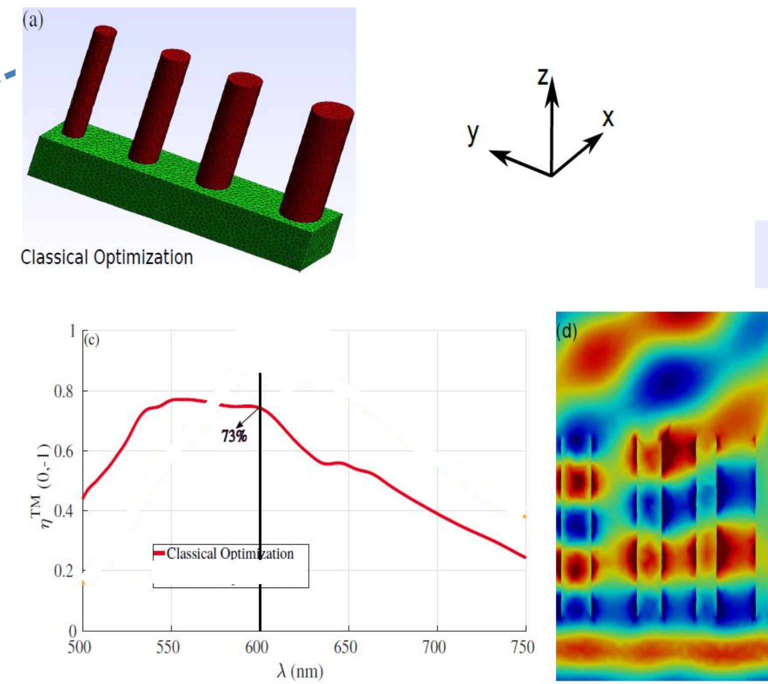




L = 350 nm, period p = 500 nm,
Particles material with pemittivity ε = 8.05,
Substrate & embedding medium ε = 2.25

2. Nanoscale manipulation of the EM field properties





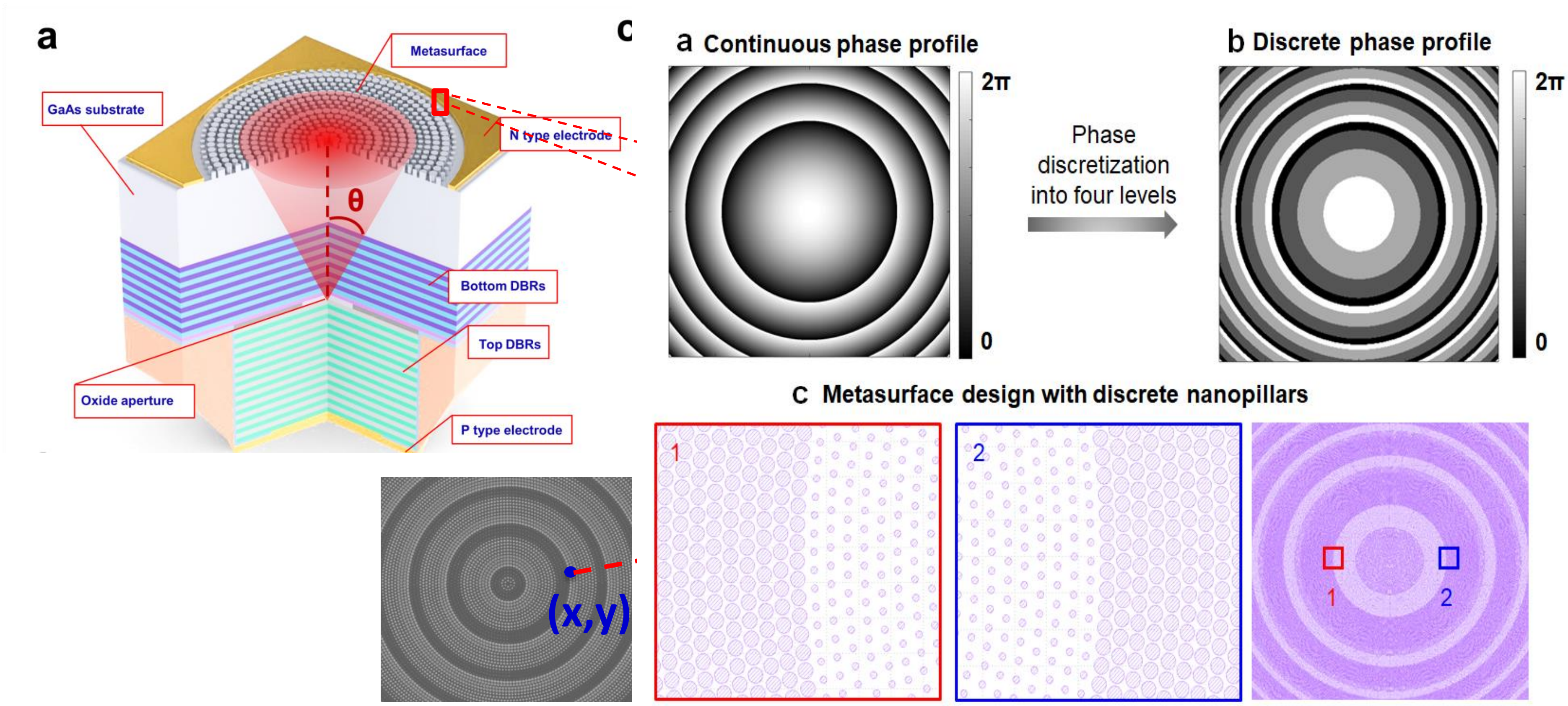
Global optimization

M. Elsawy (INRIA, Lanteri Group)

M Elsawy,et al. , **Scientific Reports** 9 (1), 1-15 (2019)

3. Applications and CRHEA contribution

Integrated Point cloud sources & Laser scanning



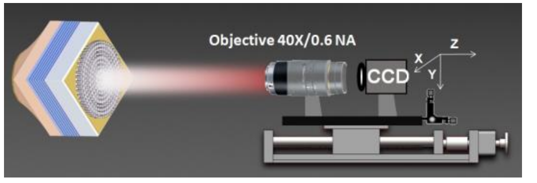
YY Xie, et al., **Nature nanotechnology** 15 (2), 125-130 (2020)

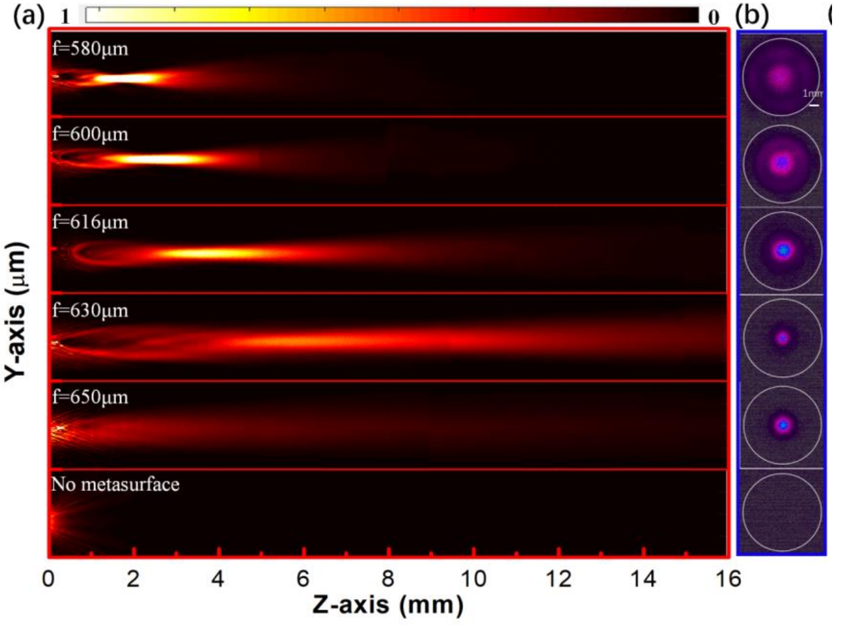
P. Genevet, CRHEA, CNRS, France

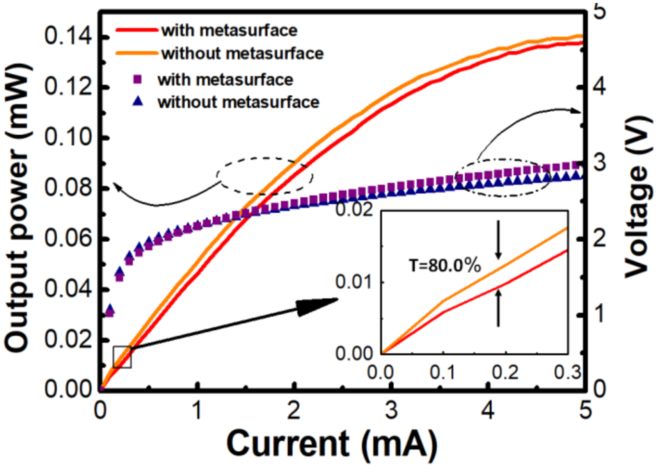
email: pg@crhea.cnrs.fr

3. Applications and CRHEA contribution

Integrated Point cloud sources & Laser scanning







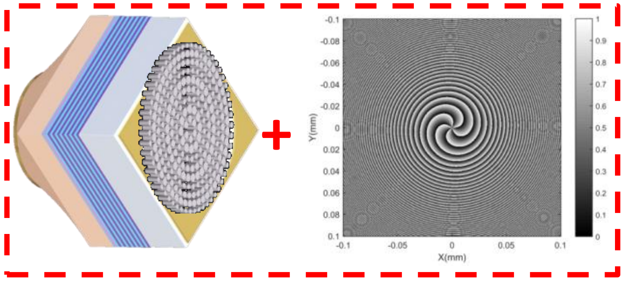
The collimation efficiency of the metasurface is about ***57%.***

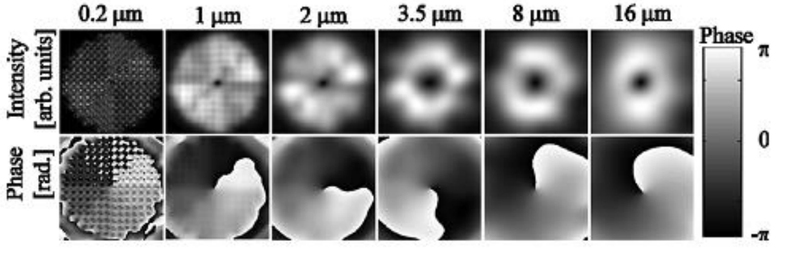
YY Xie, et al., **Nature nanotechnology** 15 (2), 125-130 (2020)

3. Applications and CRHEA contribution

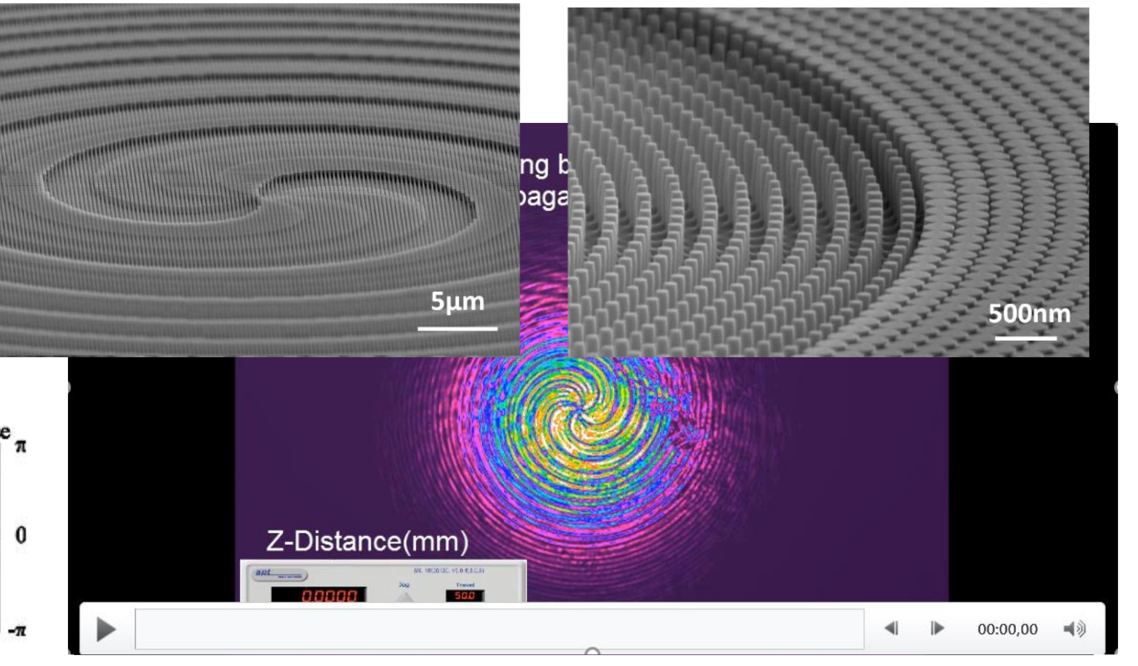
Integrated Point cloud sources & Laser scanning

Vortex VCSEL





P. Genevet etal *Appl. Phys. Lett.* 100, 013101 (2012).



YY Xie, et al., **Nature nanotechnology** 15 (2), 125-130 (2020)

P. Genevet, CRHEA, CNRS, France

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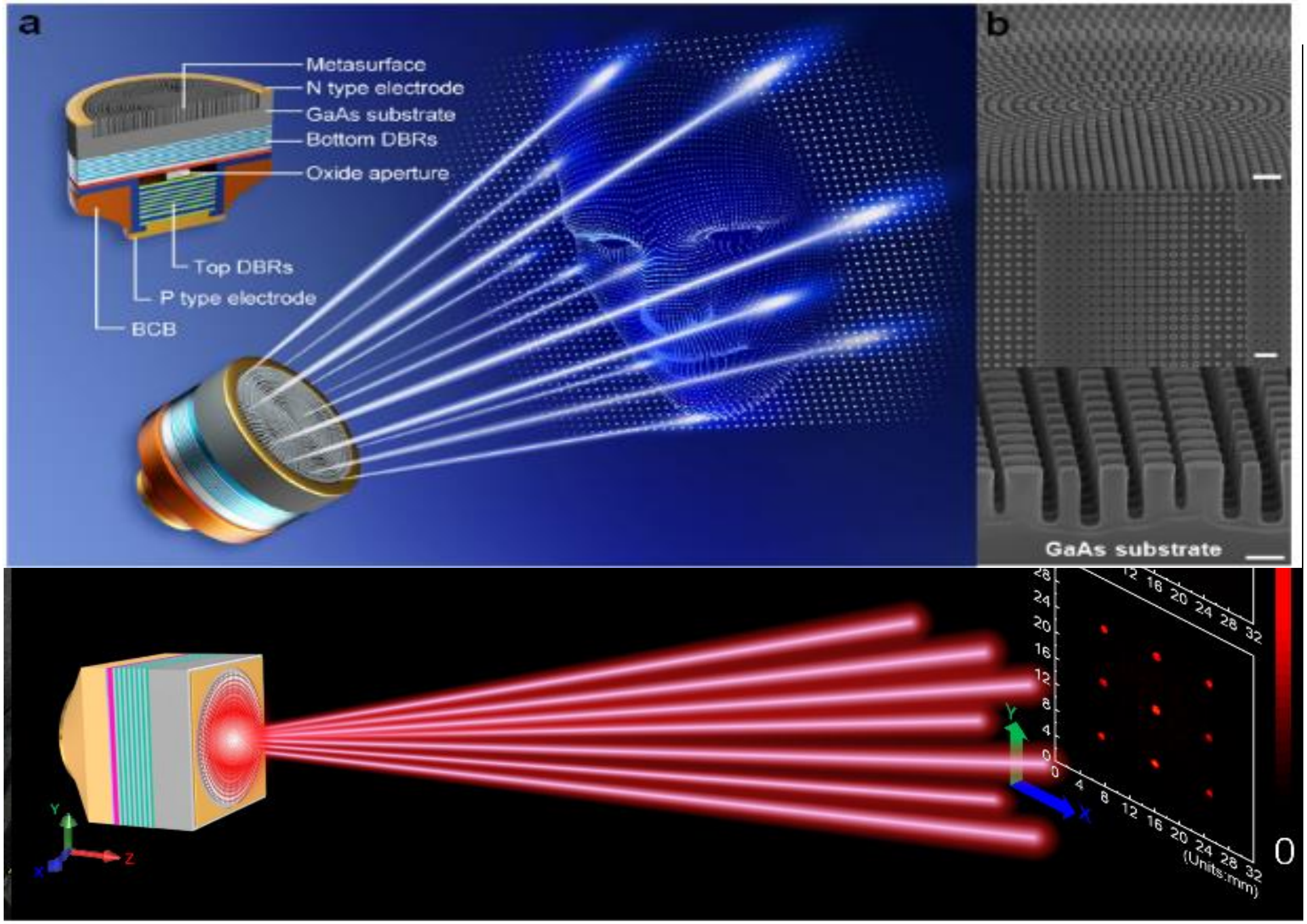
Applications & integration of MS

Integrated Point cloud sources & Laser scanning

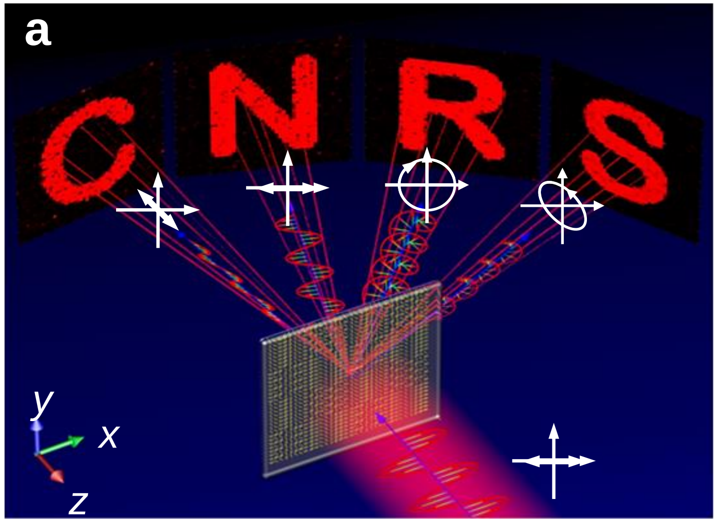


QH Wang et al., **Laser & Photonics Reviews** 15 (3), 2000385 (2021)

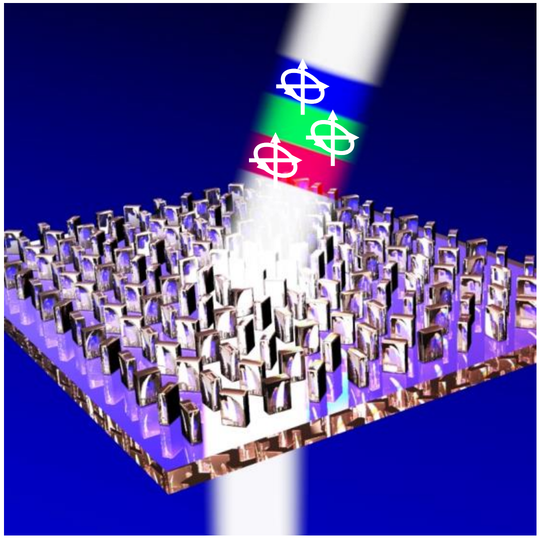
3. Applications and CRHEA contribution

Vectorial wavefront shaping Metasurfaces and holography

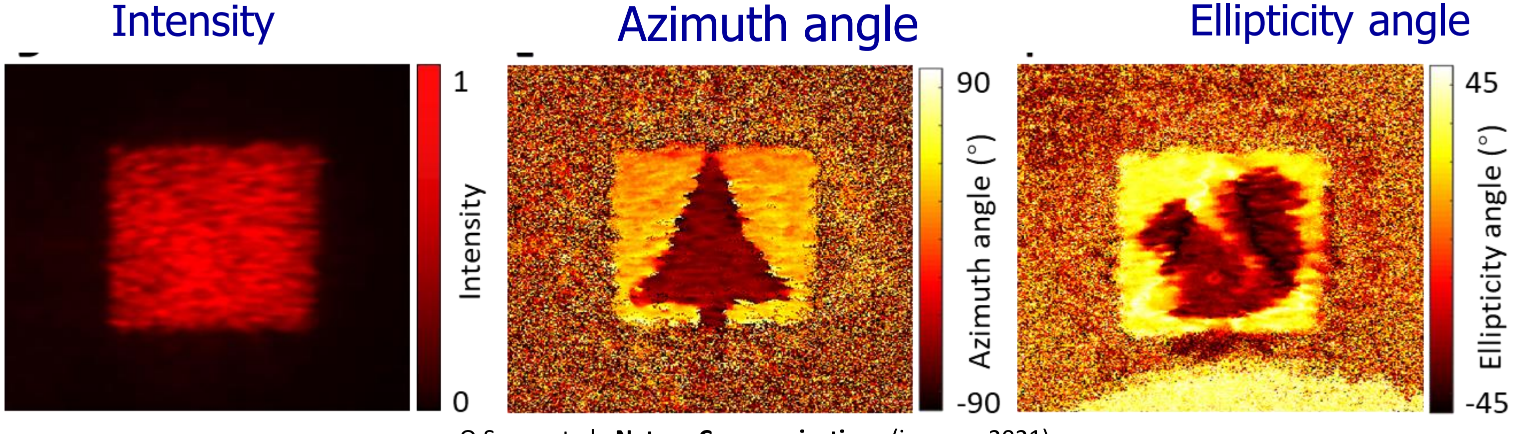
Q. Song



Q Song, et al., **Nature Communications** 11 (1), 1-8 (2020)



Q Song, et al., **Science advances** 7 (5), eabe1112 (2021)



Q Song, et al., **Nature Communications** (in press 2021)

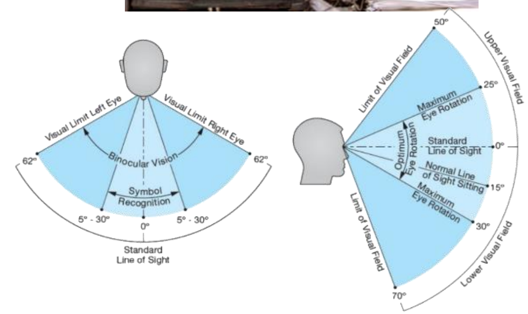
Human perception

<u>Human reaction time (</u>Perceiving and reacting<u>)</u>

- Frame rate around 150 fps
- Response times ~273 ms $(\sim 4Hz)$

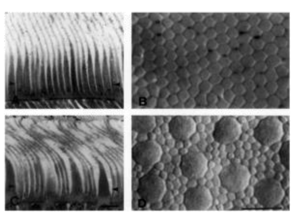
<u>Field of view with variable resolution ~120°</u>

- Binocular vision (focusing on an area of interest)
- Powered by brain interpolation



<u>Resolution: number of pixels (?)</u>

Human eye
90M rods + 4.5M cones



THE JOURNAL OF COMPARATIVE NEUROLOGY 292:497-523 (1990)

Human Photoreceptor Topography

CHRISTINE A. CURCIO, KENNETH R. SLOAN, ROBERT E. KALINA, AND ANITA E. HENDRICKSON
Departments of Biological Structure (C.A.C., A.E.H.), Ophthalmology (C.A.C., R.E.K., A.E.H.), and Computer Science (K.R.S.), University of Washington, Seattle, Washington 98195

Motivation:

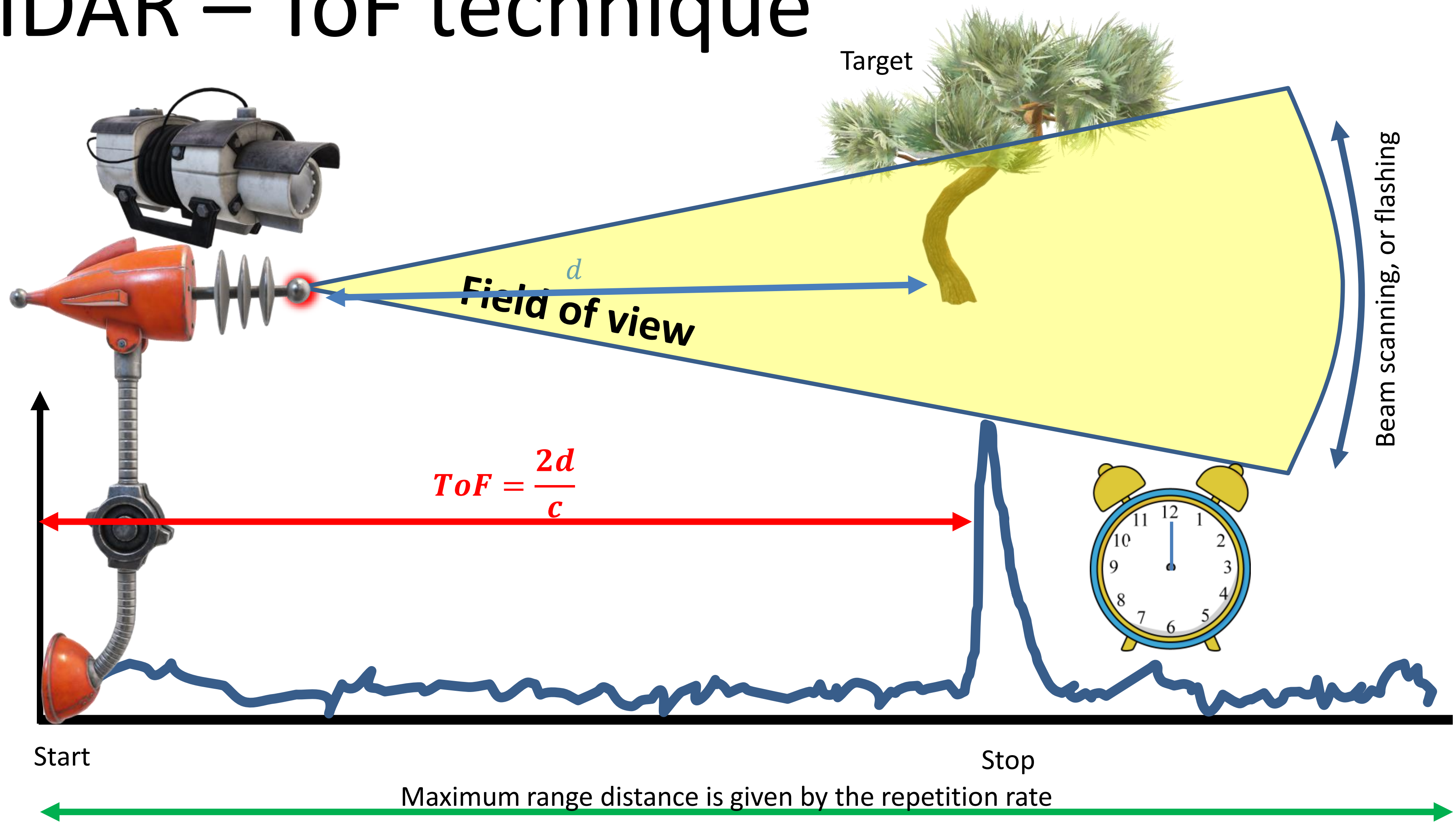
Provide tools to increase the perception of the environment beyond human capabilities

P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

LiDAR – **L**i**g**ht imaging **A**nd **R**anging

- Allows to sense the space and map the environment
  - Advanced driver-assistance systems – ADAS
  - Industry 4.0
  - Land mapping
  - Virtual reality/Augmented reality

LiDAR – ToF technique



P. Genevet, CRHEA, CNRS, France
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Applications & integration of MS

LiDARs applications

United States
Patent Application Publication
Akselrod et al.

TUNABLE LIQUID CRYSTAL METASURFACES (2021)

Applicant: **Lumotive, LLC**, Bellevue, WA (US) (52

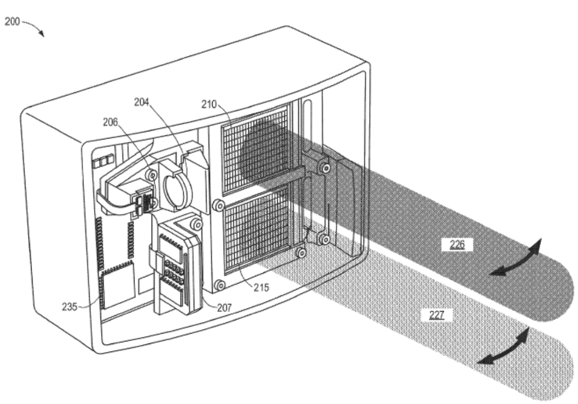
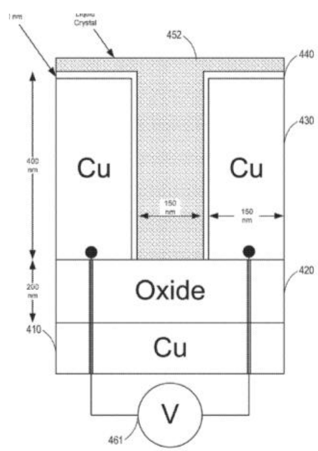


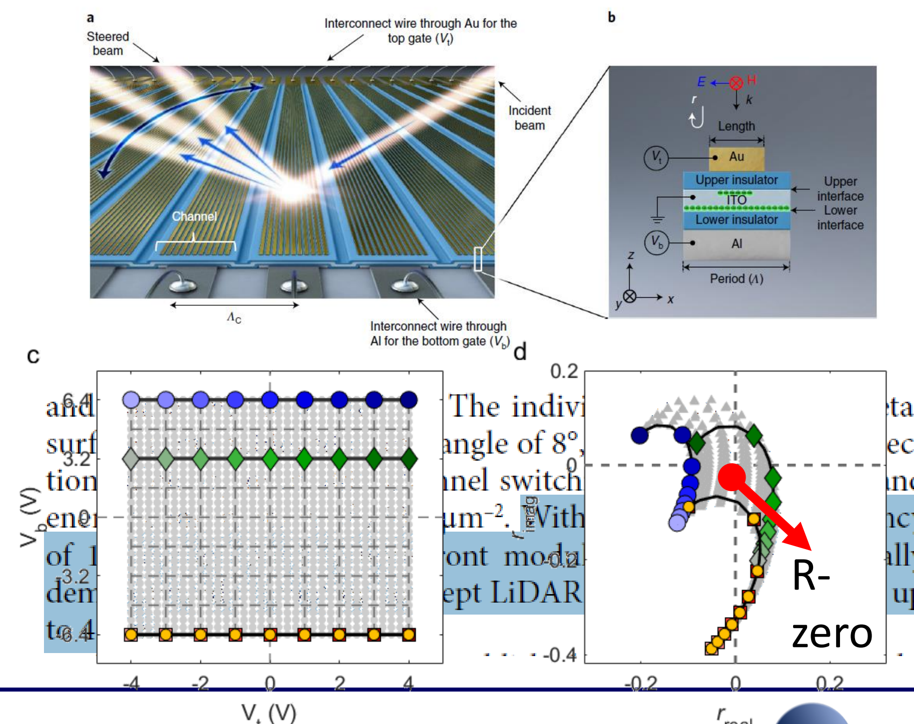
FIG. 2B



nature nanotechnology
ARTICLES
https://doi.org/10.1038/s41565-020-00787-y
Check for updates

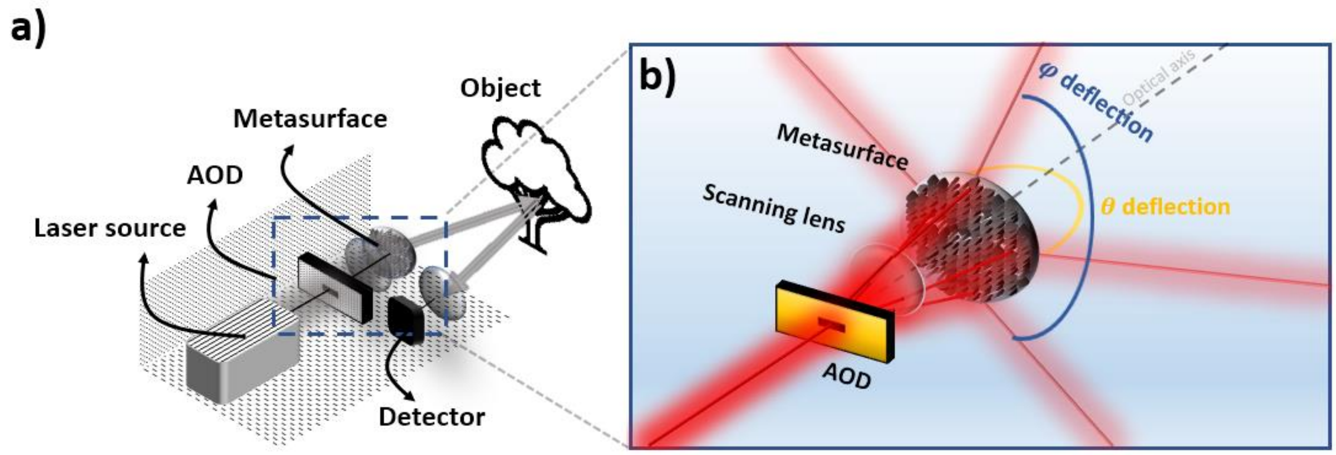
All-solid-state spatial light modulator with independent phase and amplitude control for three-dimensional LiDAR applications (2021)

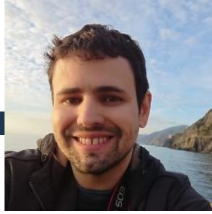
Junghyun Park[1,6], Byung Gil Jeong[1,6], Sun Il Kim[1,6], Duhyun Lee[1], Jungwoo Kim[1], Changgyun Shin[1], Chang Bum Lee[1], Tatsuhiro Otsuka[1], Jisoo Kyoung[1,5], Sangwook Kim[1], Ki-Yeon Yang[1], Yong-Young Park[1], Jisan Lee[1], Inoh Hwang[1], Jaeduck Jang[1], Seok Ho Song[2], Mark L. Brongersma[3], Kyoungho Ha[1], Sung-Woo Hwang[1], Hyuck Choo[1] and Byoung Lyong Choi[4]



Applications & integration of MS

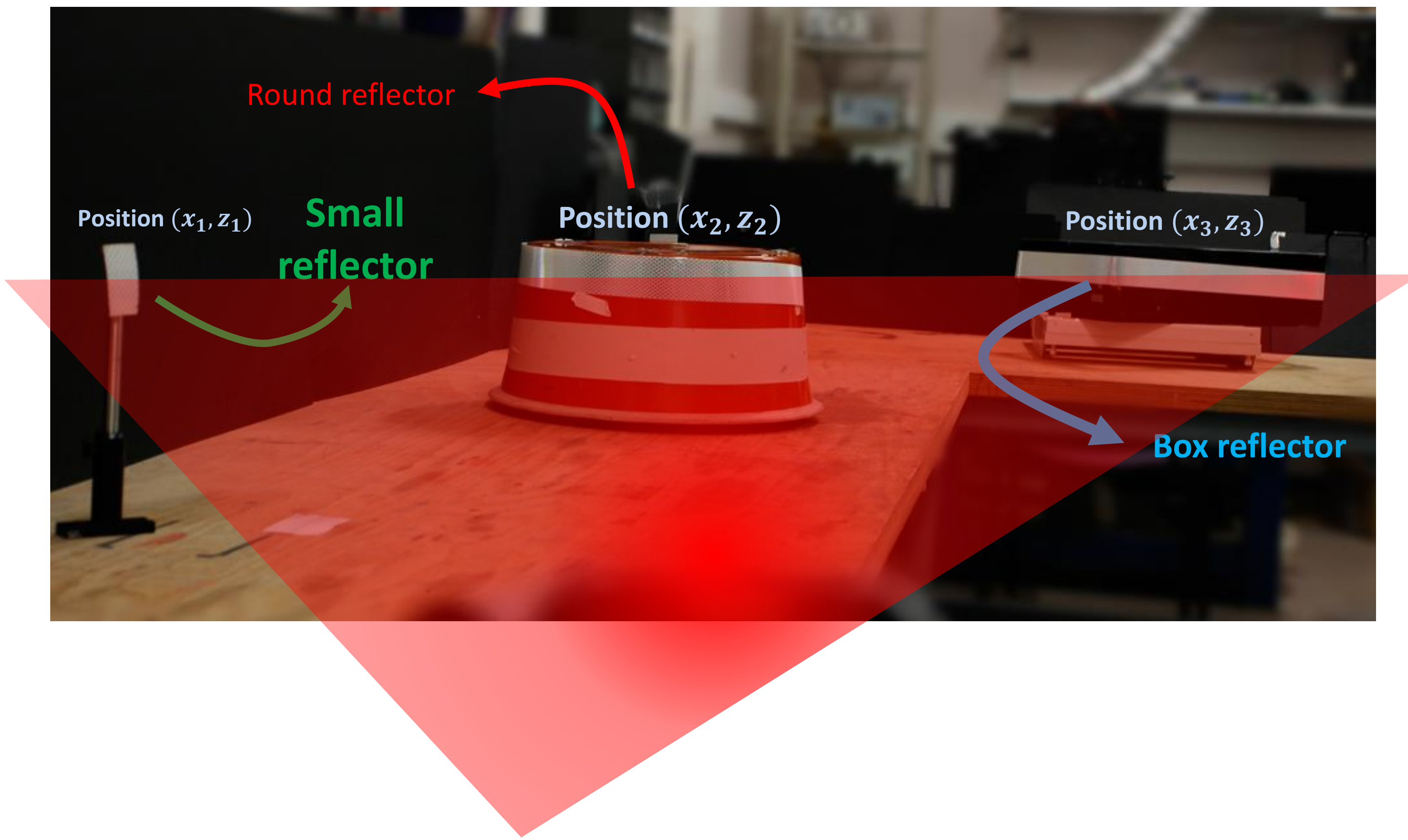
LiDARs applications (MHz beam steering)



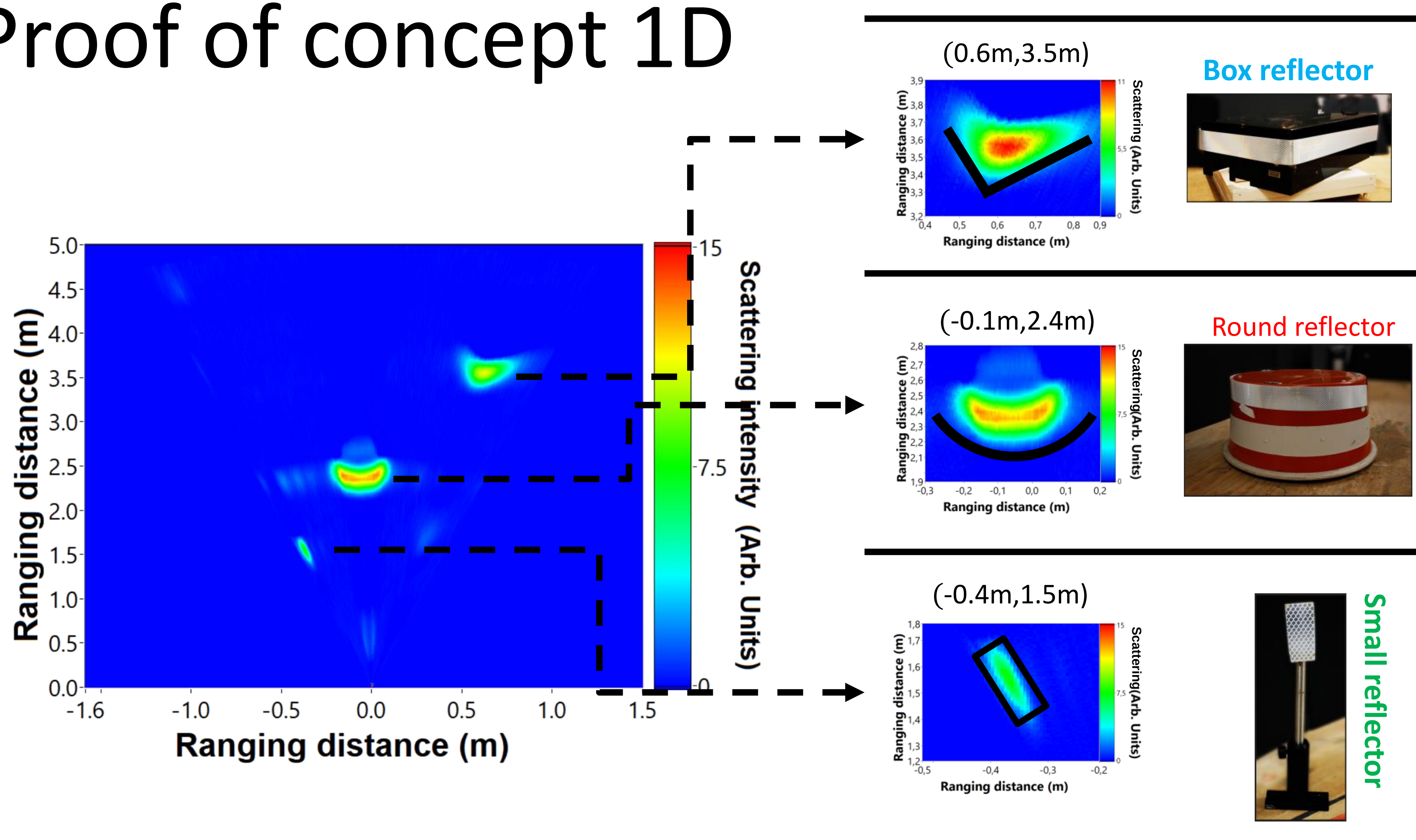


Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

Proof of concept 1D – Simple ToF imaging



Proof of concept 1D



Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

Proof of concept 1D

Image 1 – *60k frames/s*
500 pixels, 100 frames

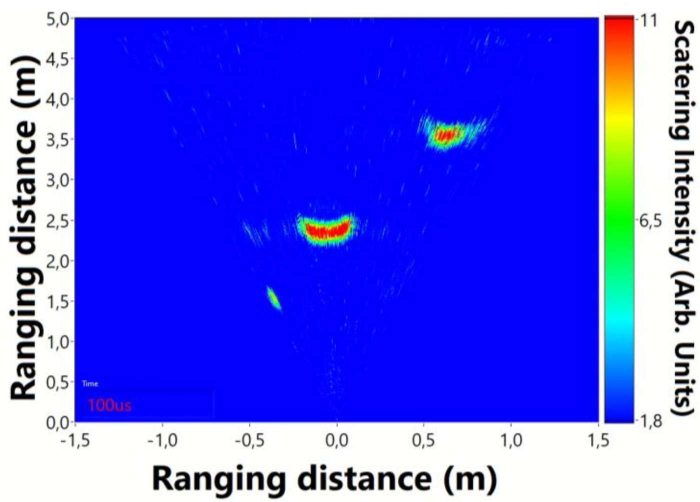
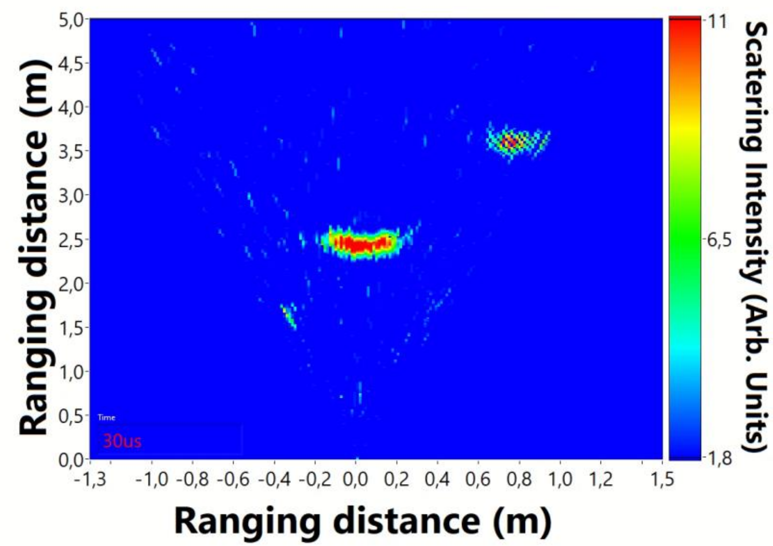


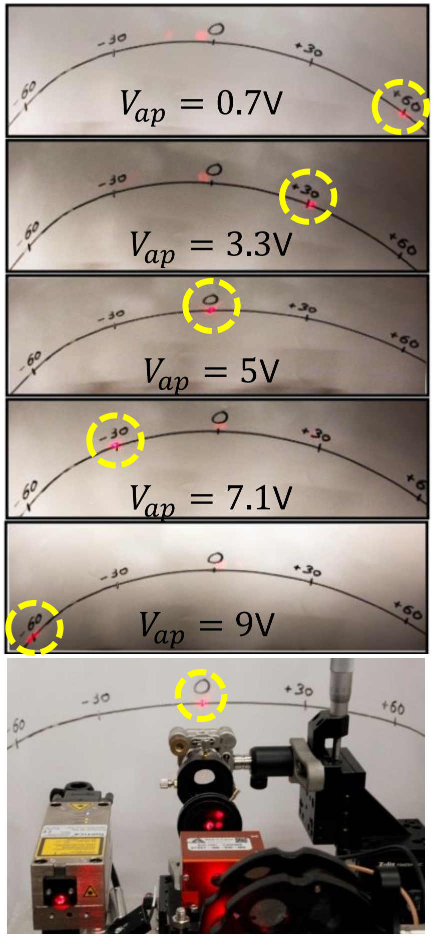
Image 2 – *300k frames/s*
100 pixels, 10 frames



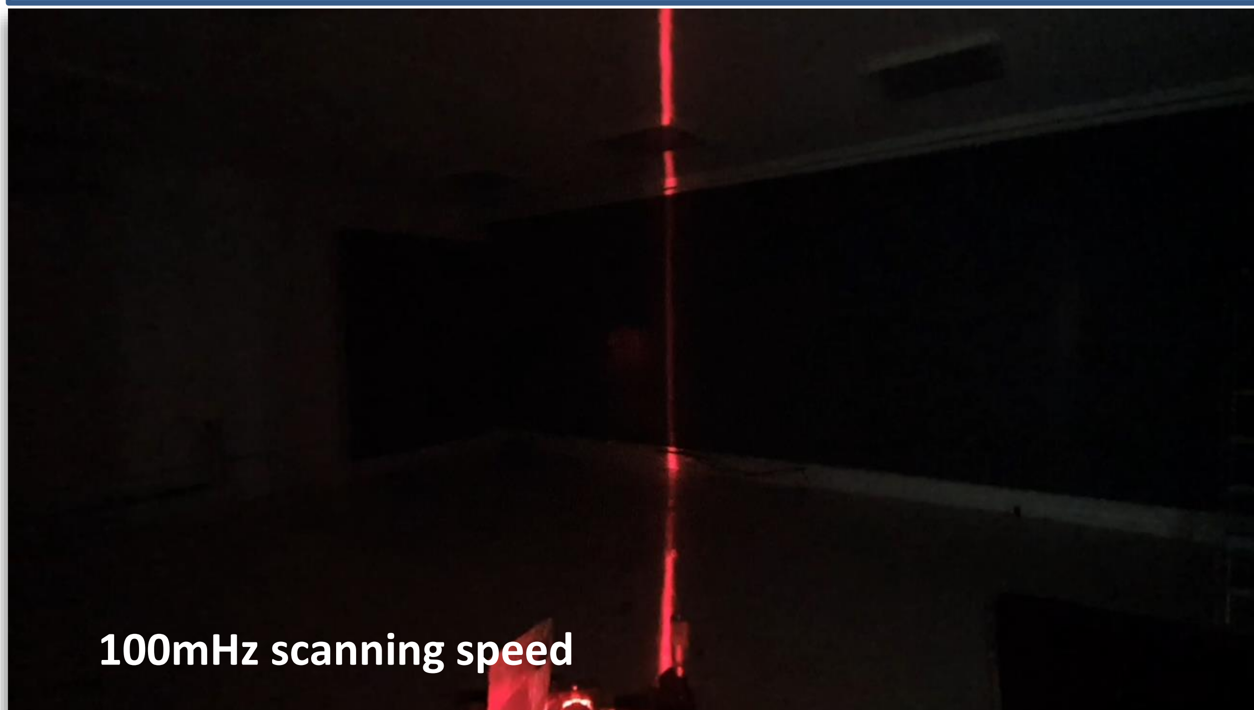
Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

Applications & integration of MS

Voltage applied to the EOD leads to a deflection angle



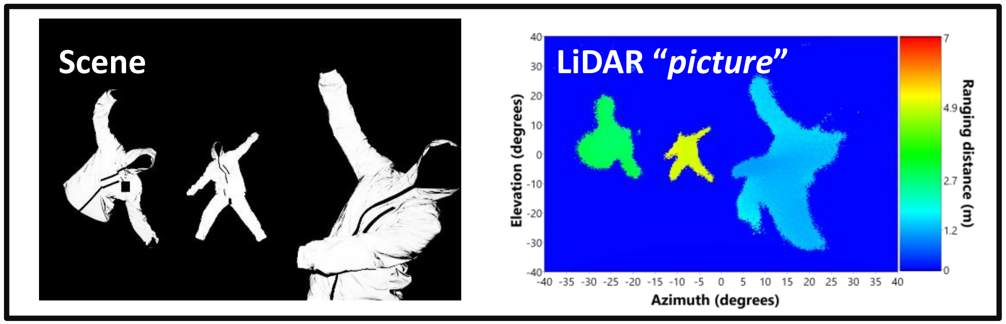
2 axis of scanning is realized by cascading 2 AODs and MS

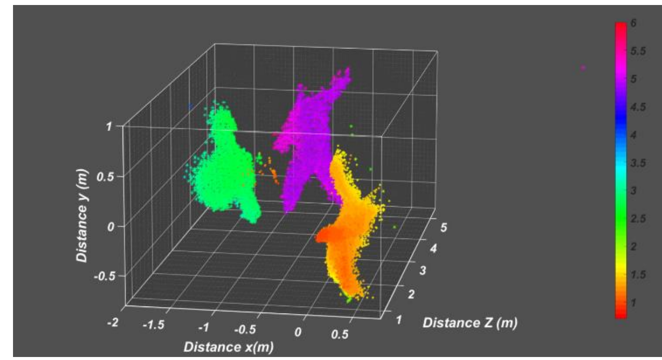


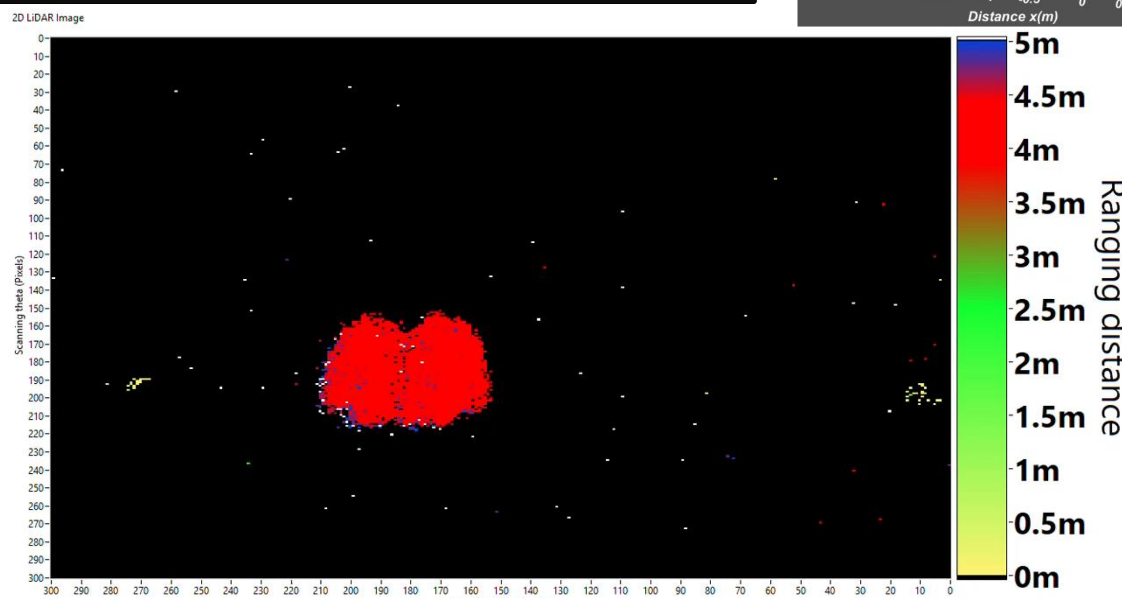
P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

3D LiDAR imaging

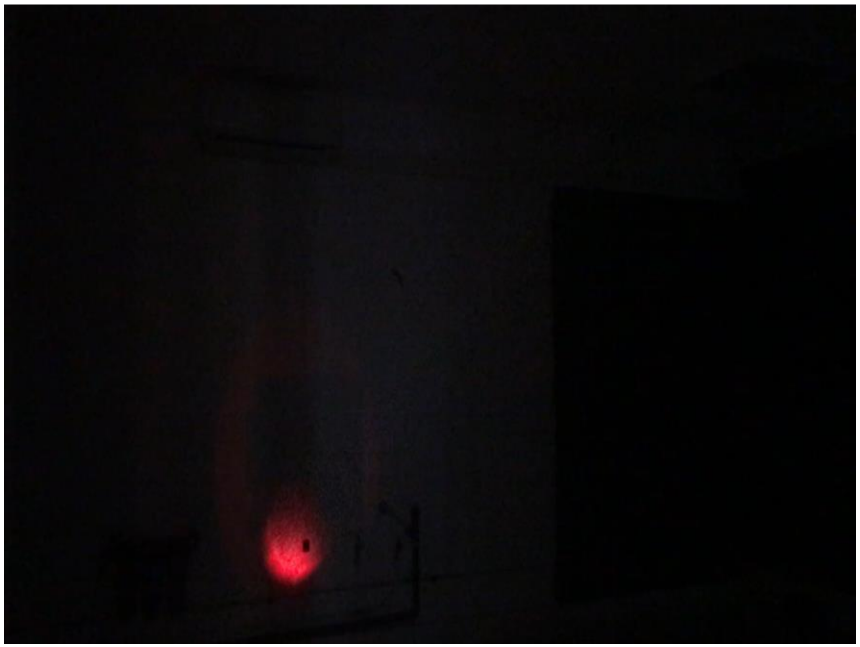


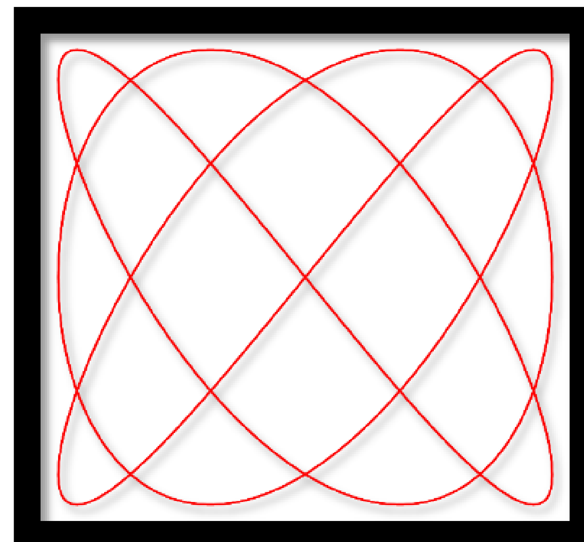




Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

Beam scanning and projection





Any type of random-access scanning can be implemented int the system

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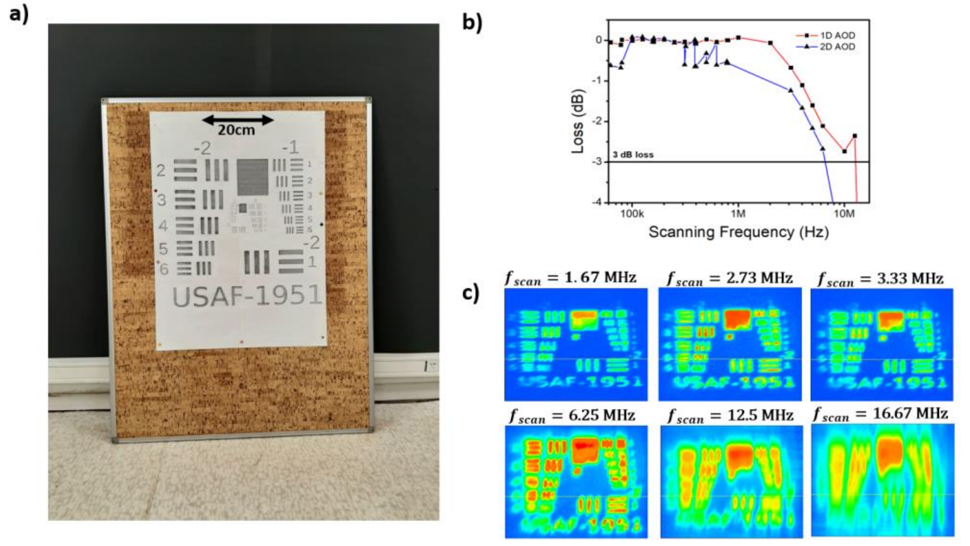
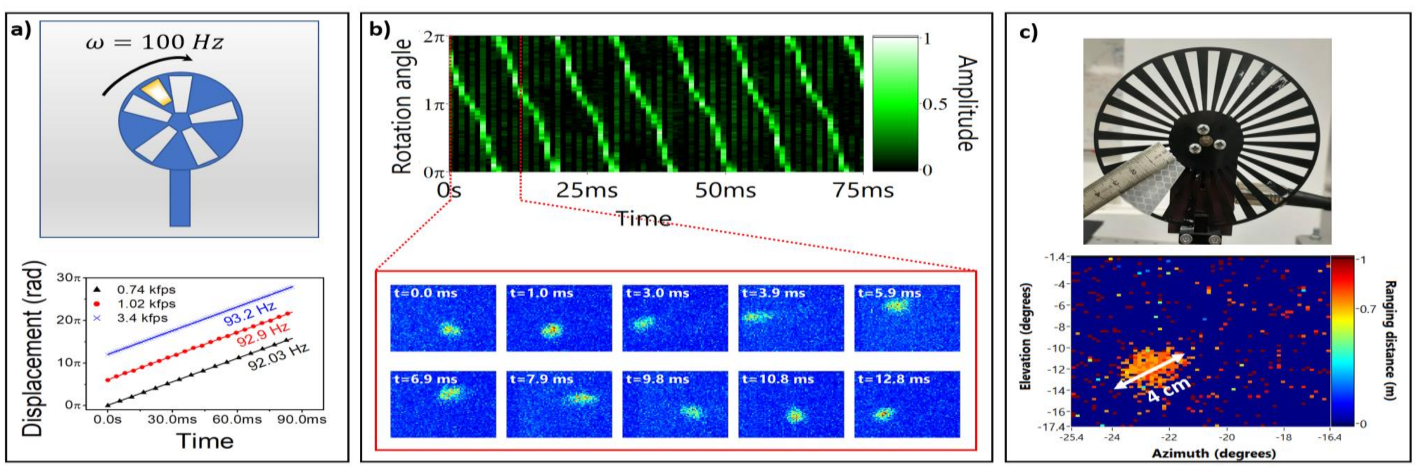
Resolution vs speed





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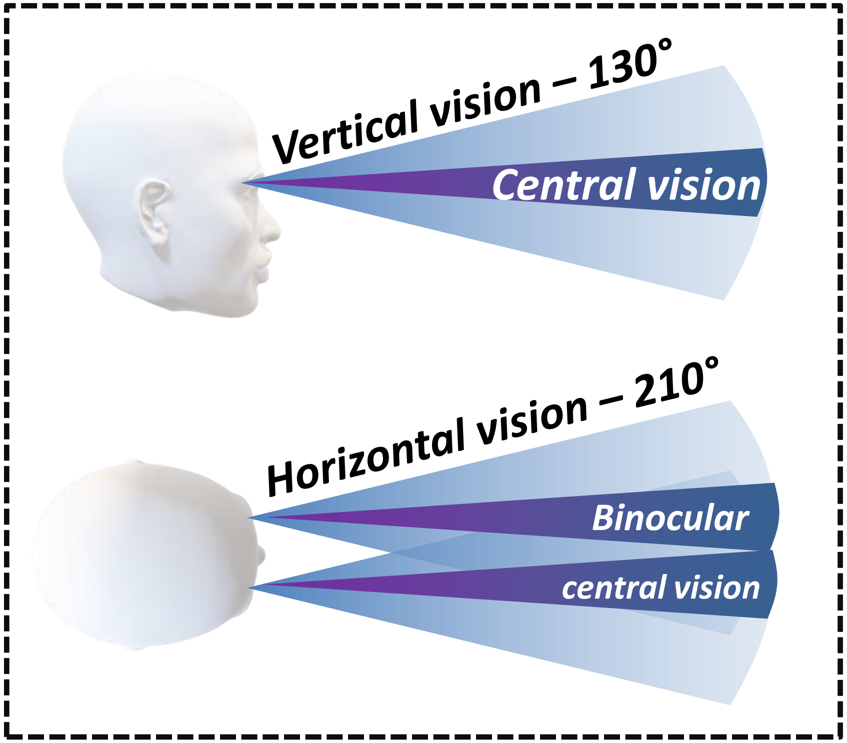
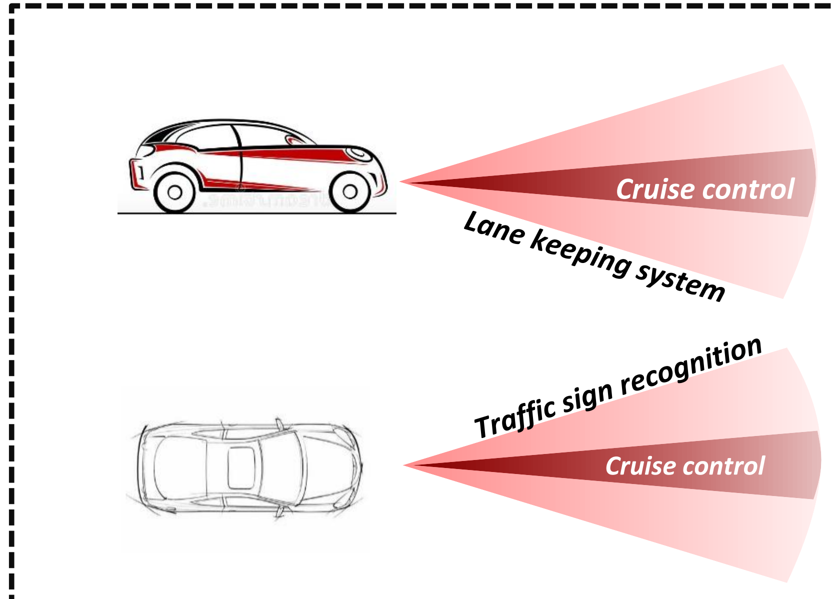
Multi-zones ToF LiDAR

- Human features multi-zone viewing
- Same concept can be adopted on cars carrying LiDAR systems

Human vision



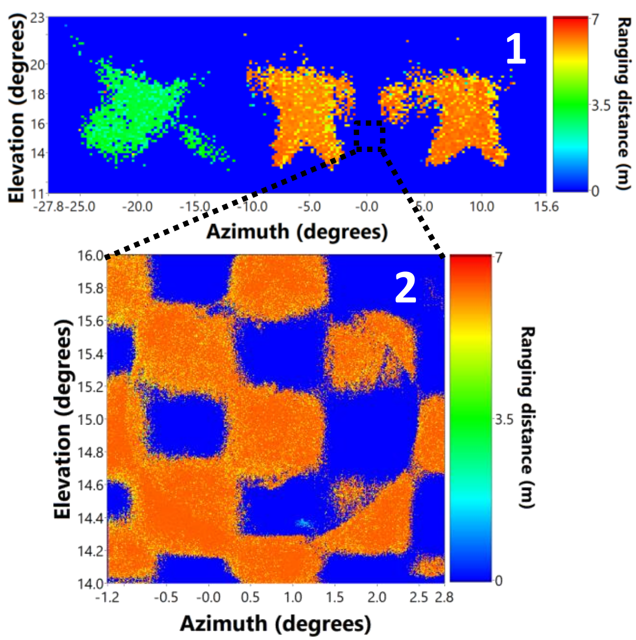
Metasurfaces can be designed to have low efficiency and deflects only a portion of the incoming beam

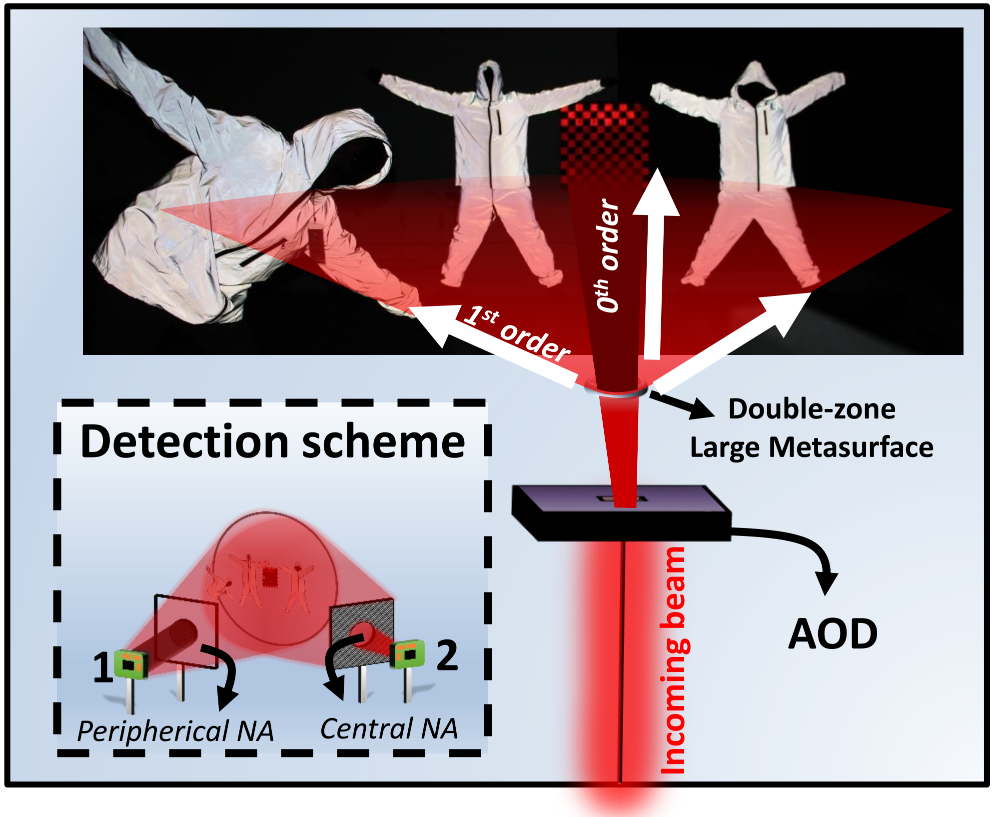


Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

Multi-zones ToF LiDAR



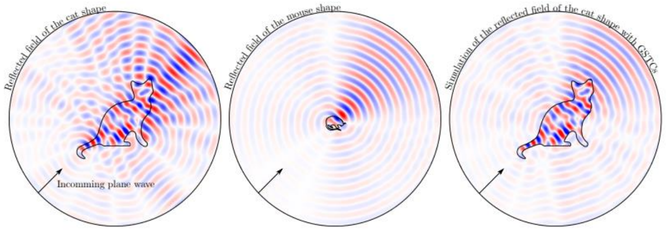


Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021), (paper submitted)

4. Conclusion and Perspectives

Optical metasurfaces, composed of ultrathin subwavelength meta-atoms, have enabled flat-optics such as ultrathin lenses, color filters, polarimeters, holograms and absorbers.
Emerging applications are in the area of imaging systems (LiDAR) and displays (Hologram, AR/VR devices)

- ❖ Metaoptics for imaging
- ❖ Metasurface Holograms for Projective Display Techniques
- ❖ Metasurface Colorations for Reflective Display Techniques
- ❖ Metasurfaces polarimeters
- ❖ Metasurface beam splitters for quantum optics applications
- ❖ Nonlinear metasurfaces
- ❖ Metasurfaces for real time wavefront manipulation
- ❖ Metasurfaces for LiDAR applications
- ❖ Conformal Metasurfaces, …



N. Lebbe, S. Y. Golla, S. Lanteri, P Genevet (submitted)

Collaboration with Lanteri group (INRIA)

Metasurfaces and their integration into systems offer unlimited perspectives of industrial applications

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