# Metasurface Holograms

Presented by:

OSA Holography and Diffractive Optics Technical Group

# OSA Holography and Diffractive Optics Technical Group Webinar Event

25 January 2018, 19:00 EST

# TG Executive members

| | |
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| Chair | • Yunlong Sheng<br>• Laval University, Canada |
| Vice Chair | • Pascal Picart<br>• LAUM CNRS Université du Maine, France |
| Social Media Officer | • Liangcai Cao<br>• Tsinghua University, China |
| Events Officer | • Guoqiang Li<br>• The Ohio State University, USA |
| Other Officer | • Jae-Hyeung Park<br>• Inha University, South-Korea |

It is a pleasure for us to serve the community

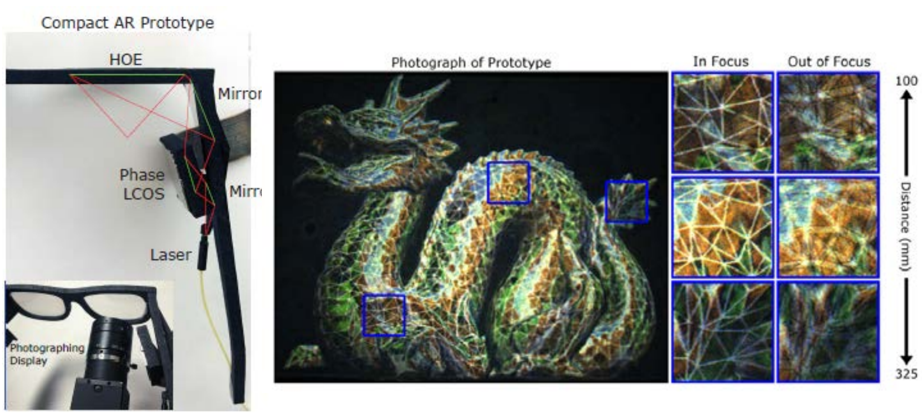
# Holography and Diffractive Optics (FH)

- Our TG focuses on the design and implementation of holographic and diffractive-optic devices and systems for scientific, commercial, and other applications.
- The scope of our TG covers holography technology, holographic materials, digital holographic imaging, holographic microscope, computer-generated holograms, diffractive optical elements, holographic nano-fabrication methods, diffractive-optic micro-manipulation, spatial light modulators for phase modulation, 3D display using spatial light modulators, holographic measurements of 3D structures, phase unwrapping, and other related topics.

# Holography and Diffractive Optics (FH)

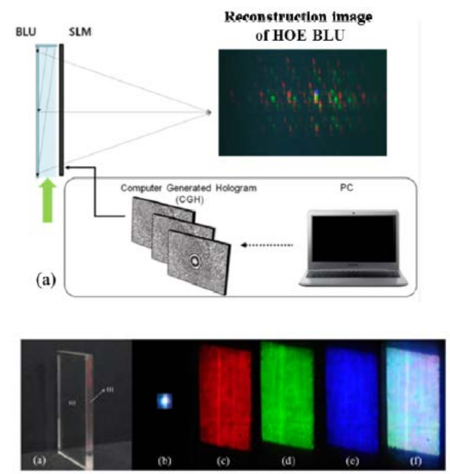
- Research progress on holographic material / CGH / SLM is one of the key issues of holographic displays (for AR / VR), closely related to display industry

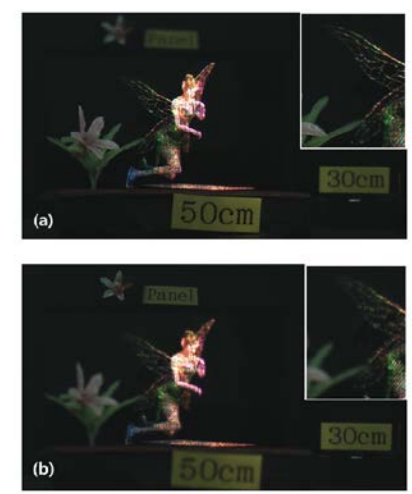
**Holographic 3D Near-to-Eye Display for AR, Microsoft 2017**




A. Maimone et al., ACM Trans. Graphics 36(4), 85, 2017.

**Holographic 3D Display, Samsung 2017**




S. I. Kim et al., Optics Express 25(22), 26781-26791 (2017)

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## Holography and Diffractive Optics (FH)

Get Involved

- Chapters and Sections
- Public Policy
- Diversity & Inclusion in OSA
- Technical Groups –
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation –
    - Fiber Modeling and Fabrication (FF)
    - Gamma, X-Ray and Extreme UV Optics (FX)
    - Holography and Diffractive Optics (FH)
    - Imaging Optical Design (FD)
    - Lasers in Manufacturing (FL)
    - NonImaging Optical Design (FN)
    - Optical Fabrication and Testing (FM)
    - Polarization (FP)
    - Systems and Instrumentation
    - Thin Films (FT)
  - Information Acquisition, Proces
  - Optical Interaction Science
  - Photonics and Opto-Electronics
  - Vision and Color Division
  - Technical Group Webinars
- Local Sections
- Early Career Professionals
- Students
- Professional Development
- Education Outreach
- International Day of Light

### Holography and Diffractive Optics (FH)

This group focuses on the design and implementation of holographic and diffractive-optic devices and systems for scientific, commercial, and other applications. The development of new approaches as well as materials needed to construct both analog and digital holograms are studied. The scope of this technical group covers holography technology, holographic materials, digital holographic imaging, holographic microscope, computer-generated holograms, diffractive optical elements, holographic nano-fabrication methods, diffractive-optic micro-manipulation, spatial light modulators for phase modulation, 3D display using spatial light modulators, holographic measurements of 3D structures, phase unwrapping, and other related topics.

GROUP LEADERSHIP | UPCOMING MEETINGS | RECENTLY PUBLISHED

| Name | Affiliation | Title |
|---|---|---|
| Yunlong Sheng | Universite Laval | Chair |
| Pascal Picart | LAUM CNRS Université du Maine | Vice Chair |

### Announcements

If you are a member of the Holography and Diffractive Optics Technical Group and have ideas for activities that may be of interest to your fellow members, please share them with the group's leader, Yunlong Sheng.

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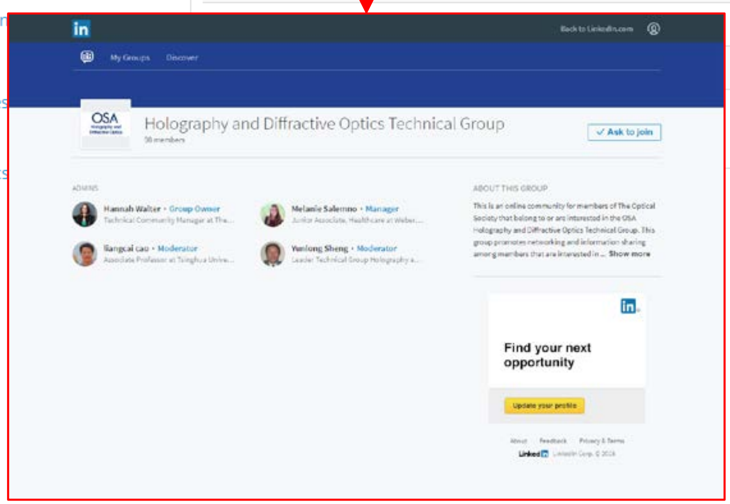
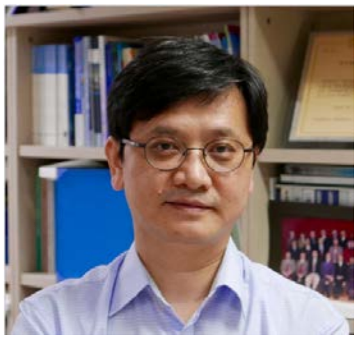
### Work in Optics

As a niche online job board, WORKinOPTICS.com more efficiently connects employers, job seekers and consultants within the optics and photonics community compared to broader job boards







Professor Byoungho Lee
Seoul National University, Korea

- Ph.D. in EECS from UC Berkeley (1993)
- Fellow of *OSA*, *SPIE*, and *IEEE*
- Member of *Korean Academy of Science and Technology* and *National Academy of Engineering of Korea*
- Former Director-at-Large of OSA, former chair of the Member and Education Services Council of OSA
- Former chair of Fabrication, Design & Instrumentation Technical Division
- Vice-President of Optical Society of Korea and the Korean Information Display Society
- Research fields: digital holography and 3D imaging, plasmonics and metasurfaces

# Metasurface Holograms

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*Seoul National University, Republic of Korea*

January 25, 2018

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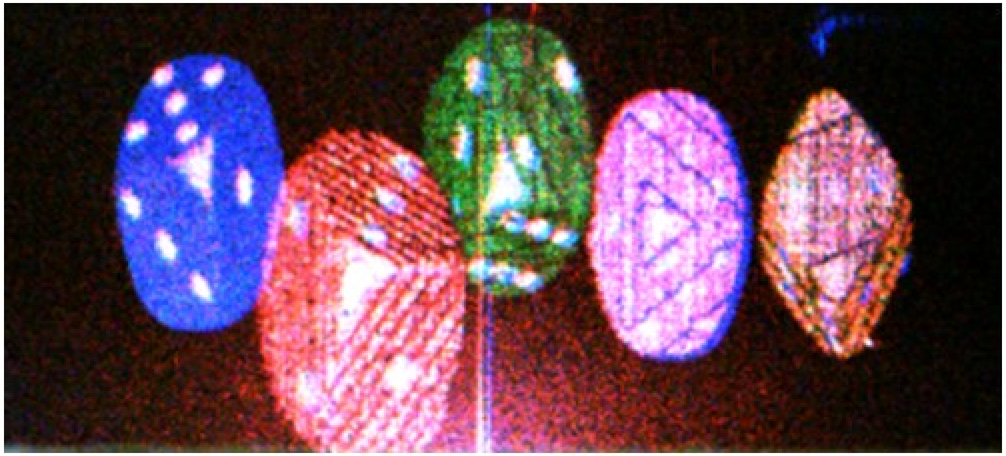
## Holography

- Holography reconstructs wavefront of light with amplitude and phase information the same as the original wave or as desired.


G. Li et al, *Opt. Lett.* **41**, 11 (2016).

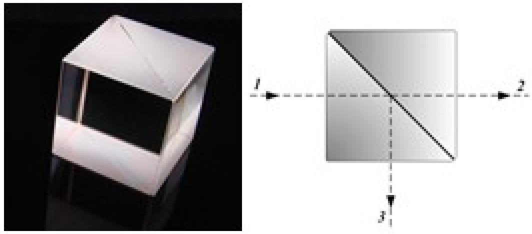


Examples: reconstructed red and full-color holograms using holographic optical element in our lab.

## Optic components for light control

### Directivity

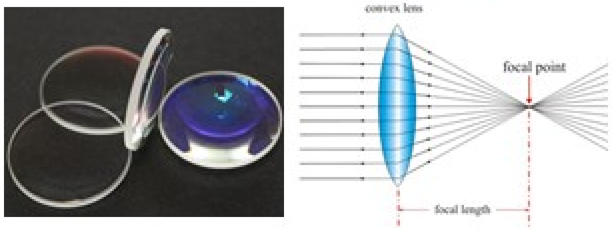
**Beam splitter**



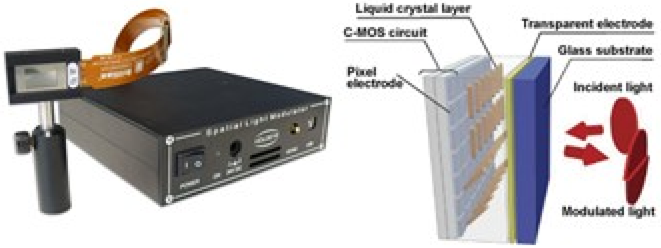

**Mirror**

### Phase or amplitude

**Lens**

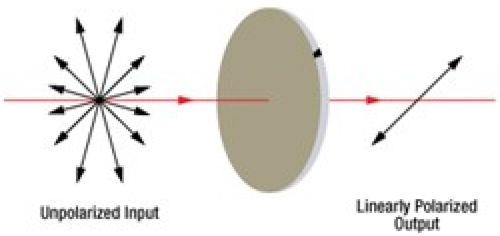



**Spatial light modulator**

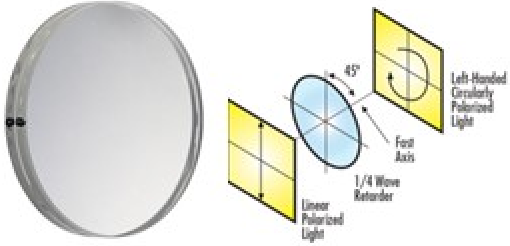



### Polarization

**Polarizer**




**Waveplate**

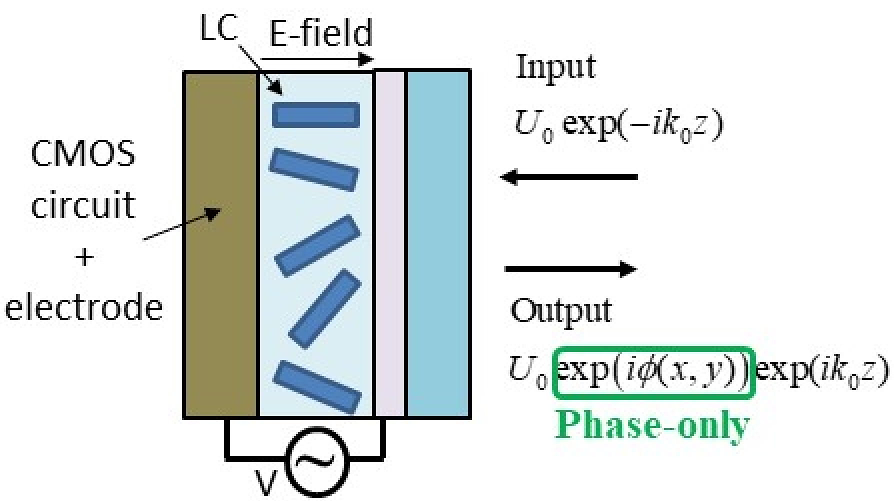


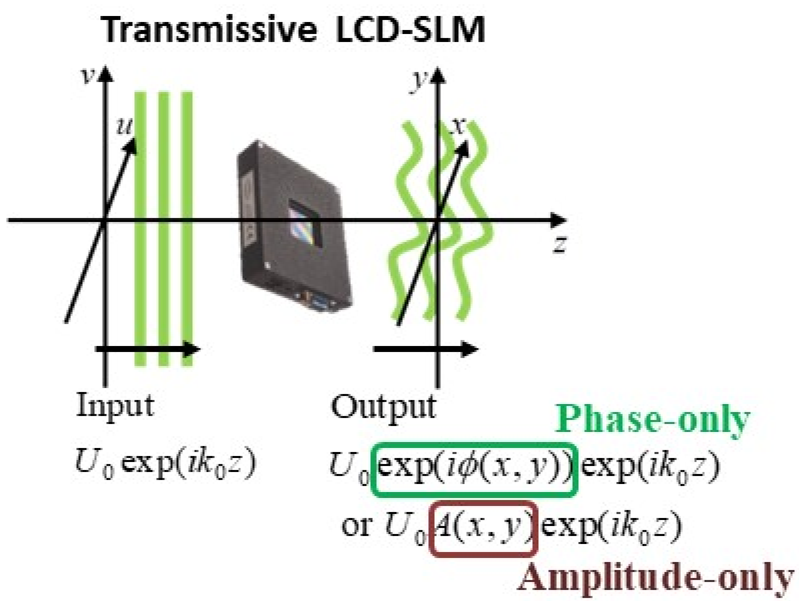

➢ **Some limitations: large form factor, low resolution (SLM), narrow bandwidth**

## Spatial modulation of light

- Wavefront modulations for holography

→ Spatial light modulators (SLMs) for **phase-only** / **amplitude-only** modulations




**Limitations**

- Phase **or** amplitude only modulation
- Large pixel pitch / grating period (> λ): low resolution, high diffraction order, narrow viewing angle in 3D hologram

**Why metasurfaces?**

→ **Improved characteristics**

**+**

**Miniaturization**

# Introduction

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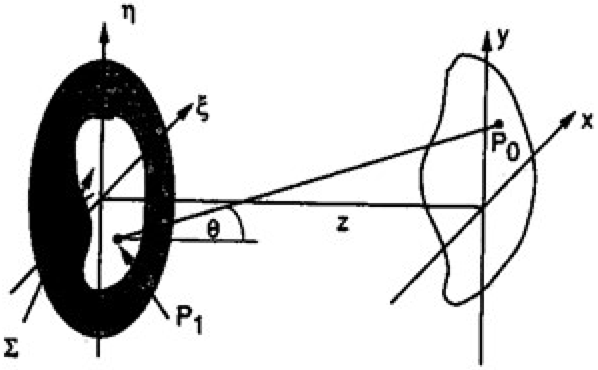
## Hologram generation: Fresnel wavefront calculation

- Fresnel diffraction theory: approximated scalar wave diffraction




Assuming $z^3$ ? $\frac{\pi}{4\lambda}[(x-\xi)^2+(y-\eta)^2]^2_{max}$

→ Fresnel approximation

### Fresnel diffraction integral

$$U(x,y)=\frac{e^{ikz}}{i\lambda z}\int\int_{-\infty}^{\infty}U(\xi,\eta)\exp\left\{i\frac{k}{2z}\left[(x-\xi)^2+(y-\eta)^2\right]\right\}d\xi d\eta$$

$$U(x,y)=\int\int_{-\infty}^{\infty}U(\xi,\eta)h(x-\xi,y-\eta)d\xi d\eta \qquad h(x,y)=\frac{e^{ikz}}{i\lambda z}\exp\left[\frac{ik}{2z}\left(x^2+y^2\right)\right]$$

$$U(x,y)=\frac{e^{ikz}}{i\lambda z}e^{i\frac{k}{2z}\left(x^2+y^2\right)}\mathcal{F}\left\{U(\xi,\eta)e^{i\frac{k}{2z}\left(\xi^2+\eta^2\right)}\right\}\Bigg|_{f_X=x/\lambda z,\,f_Y=y/\lambda z}$$

J. W. Goodman, Introduction to Fourier Optics, 4th ed., Freeman, 2017.

# Introduction

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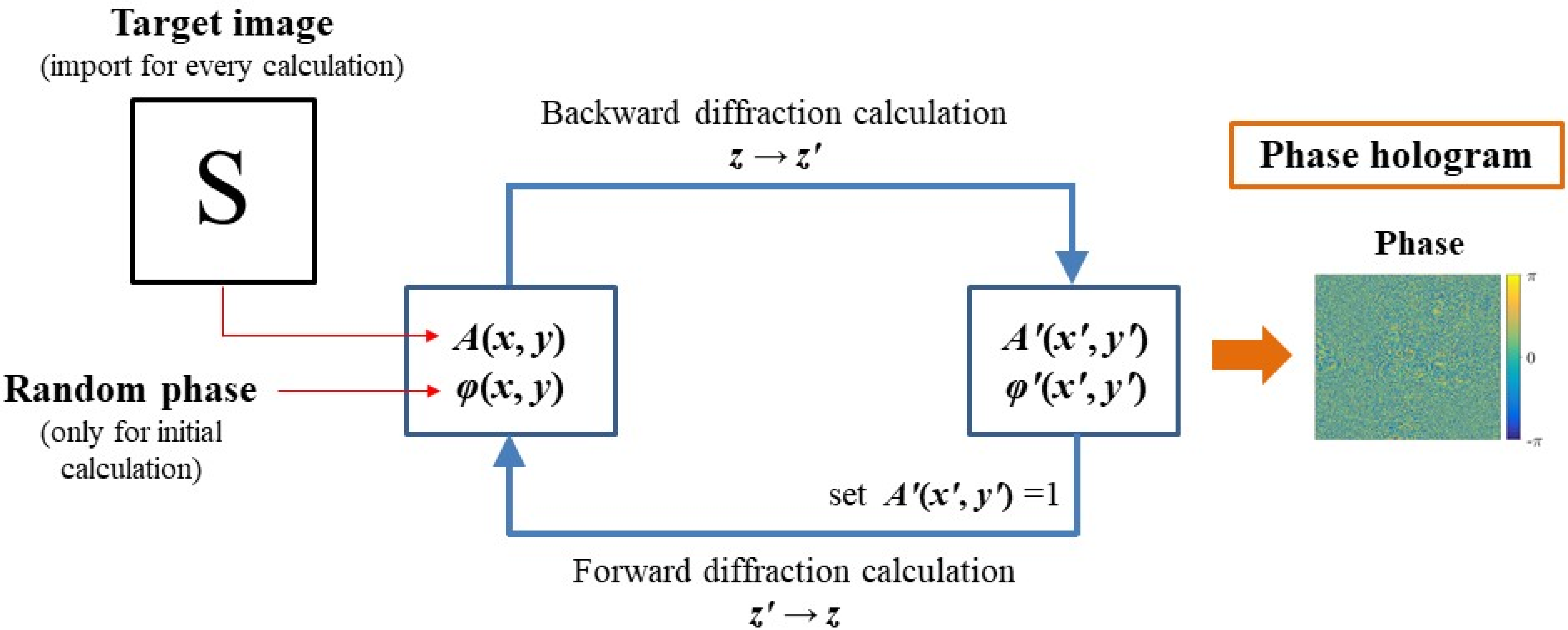
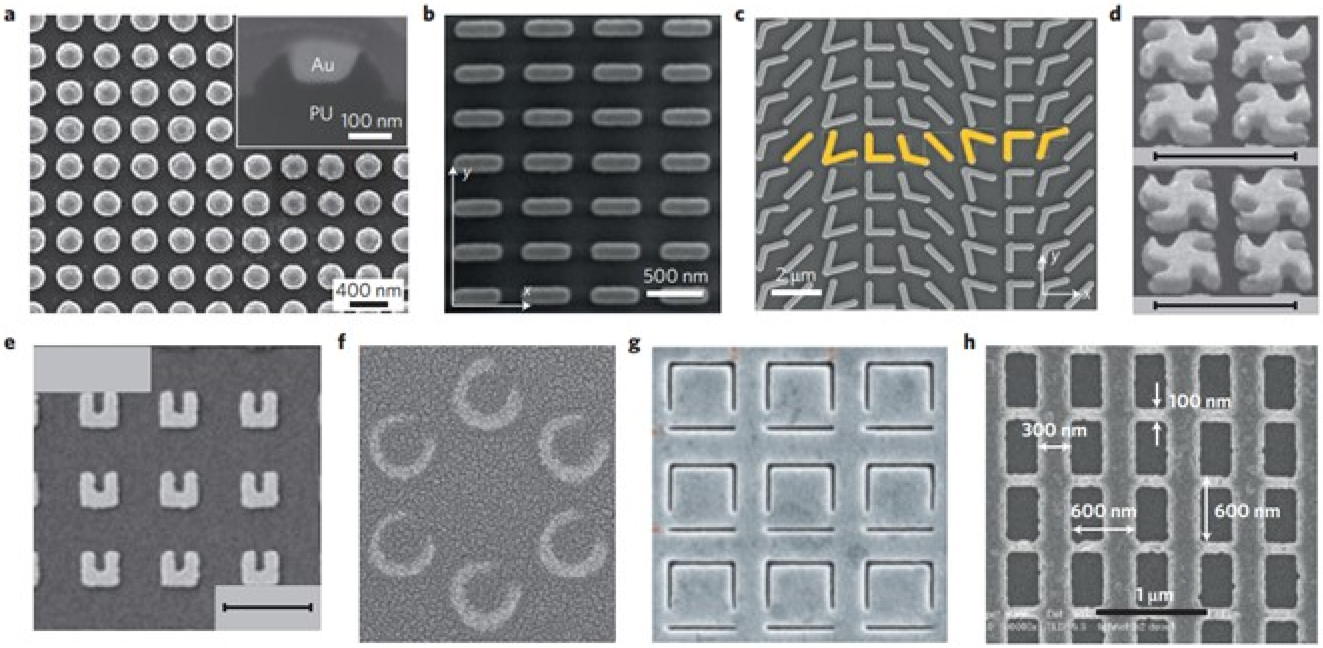
## Hologram generation: Phase-only holograms (with GS algorithm)




- Phase-only holograms require proper approximations due to the absence of amplitude information (In general, both amplitude and phase information are required.)
- The Gerchberg-Saxton (GS) algorithm is a method to increase the image quality of phase-only holograms by sacrificing the phase information at the image plane.

## Metasurfaces: periodically arranged meta-atoms

- Artificially fabricated ultrathin-film structure for controlling light




N. Meinzer et al., *Nat. Photon.* **8**, 891 (2014).

- Applications: **flat optic devices**, super-lensing, optical magnetism, nonlinear effects etc.

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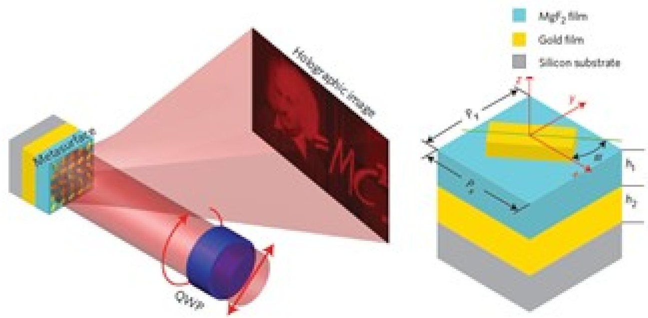
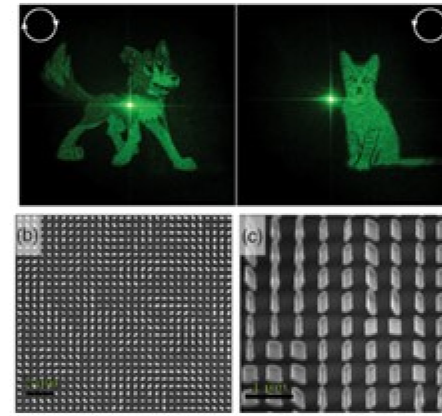
# Metasurface holograms




X. Ni et al., *Nat. Comm.* 4, 2807 (2013).

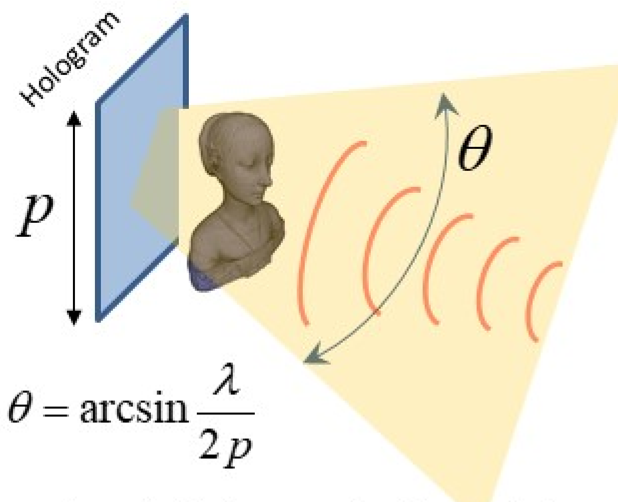



G. Zheng et al., *Nat. Nanotech.* 10, 308–312 (2015).




J. P. B. Muller et al., *Phys. Rev. Lett.* 118, 113901 (2017).

- **Why metasurface holograms?**
  - Subwavelength resolutions (~350 nm)
  - Large viewing angle and higher information density
  - Suppressed high-order diffraction cross-talk
  - Ultracompact (thickness $\leq \lambda$)



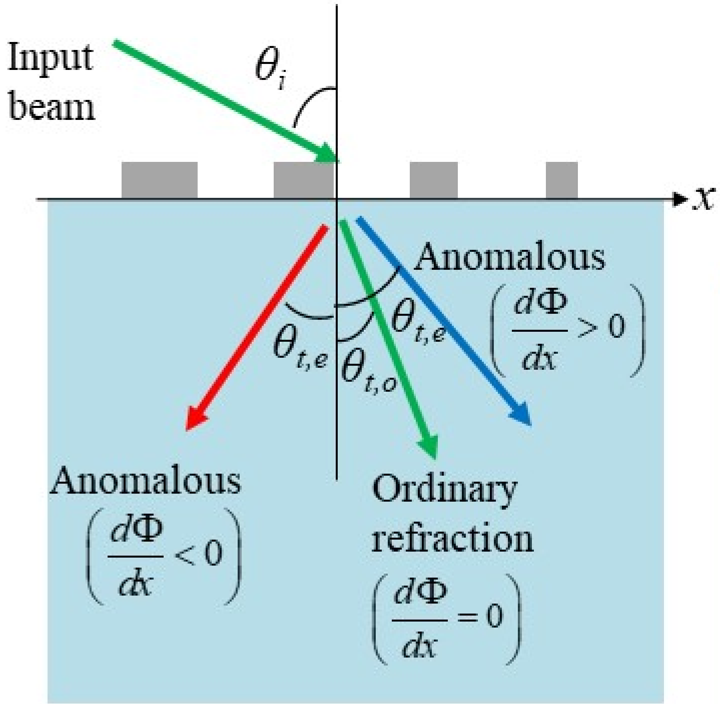

$$\theta = \arcsin \frac{\lambda}{2p}$$

( $p$: pixel size, $\theta$: viewing angle)

## Abrupt phase modulation of wave by metasurface

0. **Breaking the Snell's law**: abrupt phase modulation by ultrathin metasurface

➢ Generalized Snell's law




N. Yu et al., *Science* 334, 6054 (2011).

$$\sin\theta_t = \frac{n_i}{n_t}\sin\theta_i + \frac{1}{n_t k_0}\boxed{\frac{d\Phi}{dx}}$$

Abrupt phase gradient

- ➢ **Abrupt phase gradient** can be imparted by ultrathin metasurface.
- ➢ Generalized Snell's law enables **anomalous** refraction of light.
- ➢ Spatial arrangement of proper meta-atoms → phase modulating metasurface

**Half-wave plate:** absolute conversion of optical handedness

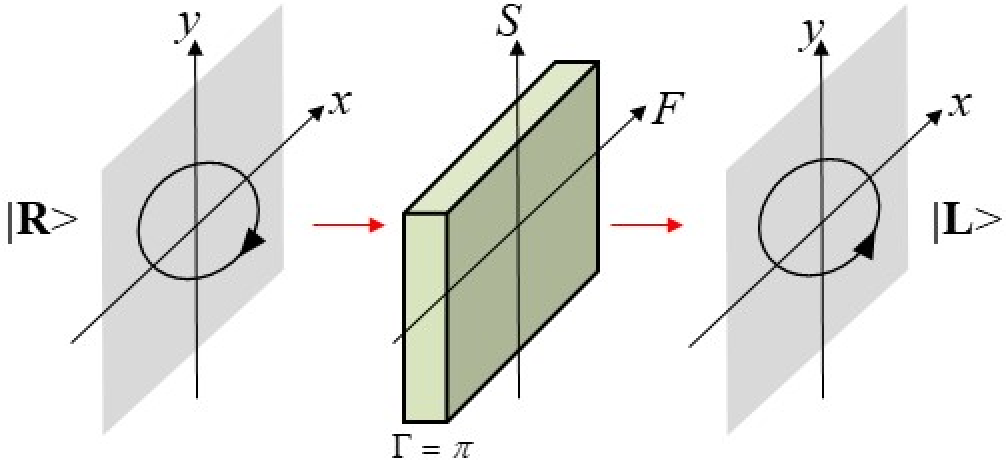
$$\Gamma = \pi$$

$$\mathbf{T} = \begin{pmatrix} 1 & 0 \\ 0 & \exp(-j\Gamma) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$E_t = \mathrm{T}\begin{pmatrix} 1 \\ i\sigma \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \exp(-j\Gamma) \end{pmatrix}\begin{pmatrix} 1 \\ i\sigma \end{pmatrix} = \begin{pmatrix} 1 \\ -i\sigma \end{pmatrix}$$

$\sigma = 1$ **RCP**

$\sigma = -1$ **LCP**



**Rotated half-wave plate**: Pancharatnam-Berry (PB) phase with conversion of handedness

$$\Gamma = \pi$$

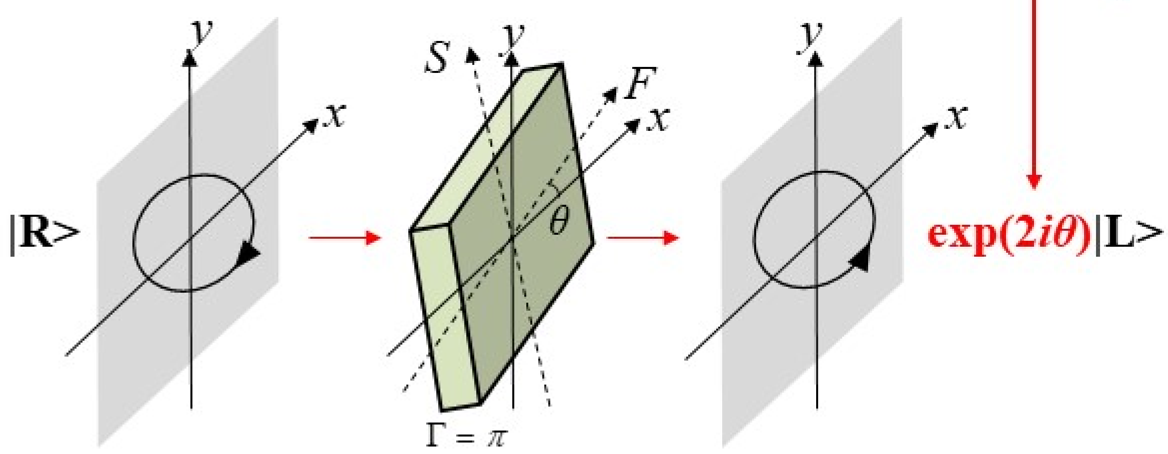
$$\mathbf{T} = R(-\theta)\begin{pmatrix} 1 & 0 \\ 0 & \exp(-j\Gamma) \end{pmatrix} R(\theta)$$

$$= \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$= \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix}$$

$$E_t = \mathrm{T}\begin{pmatrix} 1 \\ i\sigma \end{pmatrix} = \exp(i2\sigma\theta)\begin{pmatrix} 1 \\ -i\sigma \end{pmatrix}$$

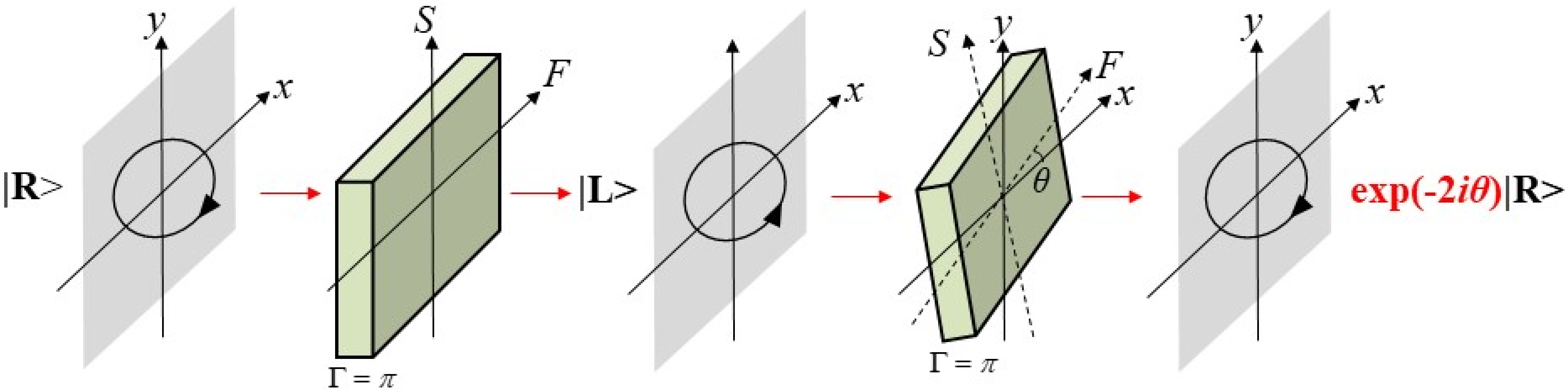
PB phase



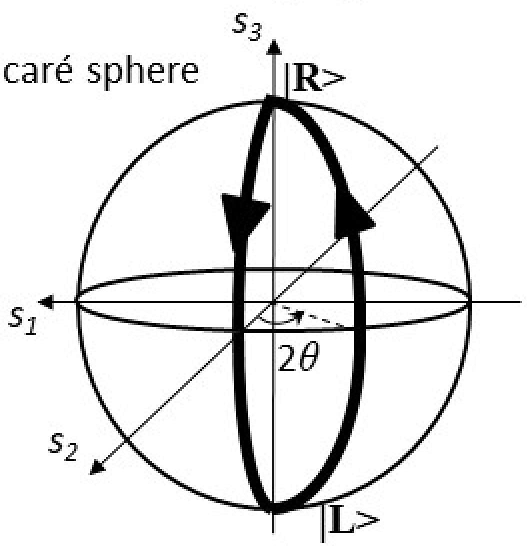
# Metasurface holograms



**Rotated half-wave plate**: Pancharatnam-Berry (PB) phase




- Poincaré sphere




$$\phi_g = \frac{\Omega}{2} = \frac{1}{2}\int_0^{2\theta}\int_0^{\pi} \sin\theta \, d\theta \, d\phi = 2\theta$$

- Phase difference between input RCP light and output RCP light is determined by a rotation angle.
- The traversed surface areas = $\Omega$
- PB phase (geometric phase) = $\phi_g = \Omega/2 = 2\theta$

N. Shitrit et al., *Opt. Lett.* 38, 21 (2013).

# Metasurface holograms

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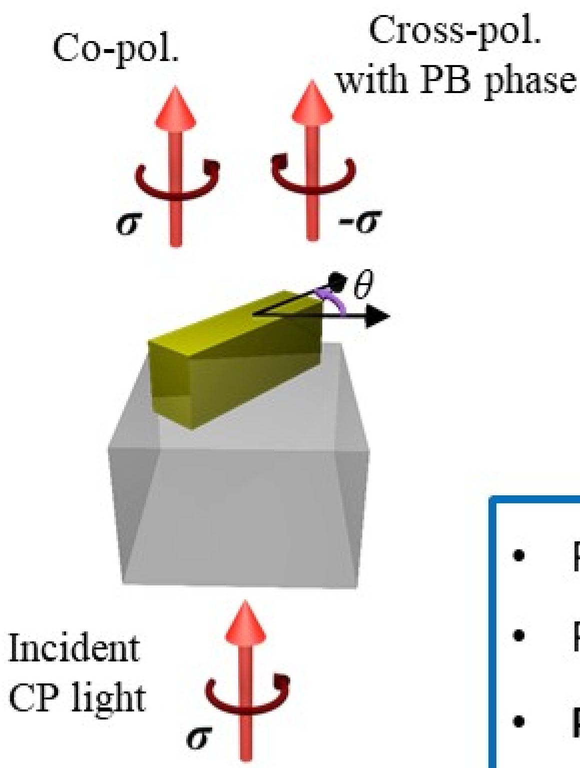
## Methods of abrupt phase modulation by metasurfaces

1. Anisotropic phase modulation: Pancharatnam-Berry (PB) phase

   - A meta-atom acting as a miniature elliptical polarizer




$$E_t = R(-\theta)\begin{pmatrix} t_L & 0 \\ 0 & t_S \end{pmatrix} R(\theta)\begin{pmatrix} 1 \\ i\sigma \end{pmatrix}$$

$$= \frac{t_L + t_S}{2}\begin{pmatrix} 1 \\ i\sigma \end{pmatrix} + \frac{(t_L - t_S)}{2}\exp(2i\sigma\theta)\begin{pmatrix} 1 \\ -i\sigma \end{pmatrix}$$

$$= E_{t,\sigma} + E_{t,-\sigma}$$

PB phase

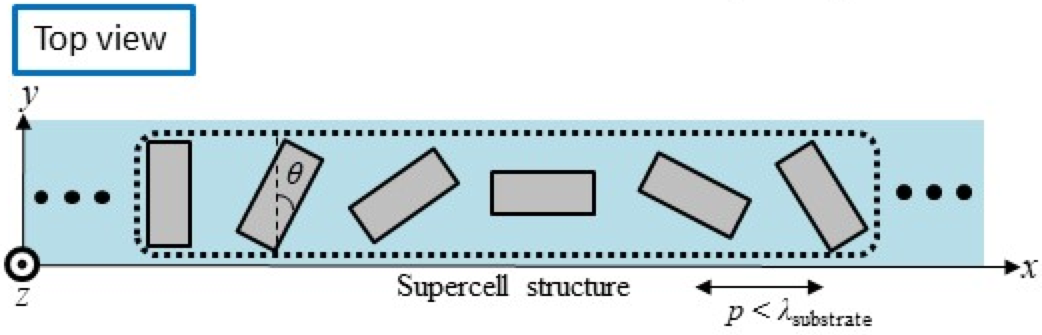
Large anisotropy is required for high cross-pol. modulation efficiency.

- Phase modulation using **circular polarization basis**
- Phase control of **cross-pol.** by **rotation ($\theta$)**
- **PB phase ($2\sigma\theta$)** can cover full 2π phase by rotation of 180˚.
- Wavelength-independent method: **broadband**

## Methods of abrupt phase modulation by metasurfaces

1. Anisotropic phase modulation: Pancharatnam-Berry (PB) phase

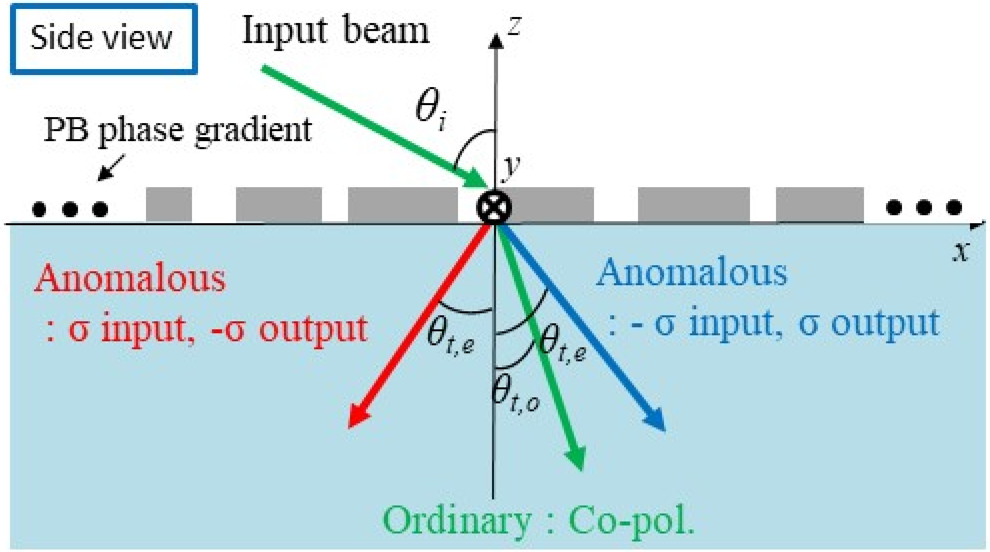
➢ Anomalous refraction by PB phase




$$\Phi = 2\sigma\theta$$

$$\sin\theta_t = \frac{n_i}{n_t}\sin\theta_i + \sigma\frac{\lambda_0}{\pi}\frac{d\theta}{dx}$$

$$\sigma = \begin{cases} 1 & \text{(RCP)} \\ -1 & \text{(LCP)} \end{cases}$$




- PB phase gradient is opposite for two different input circular polarizations.
- Two different anomalous refractions occur **according to input handedness.**
- Regardless of input handedness, co-pol. light is not affected by phase gradient.

L. Huang et al., Nano Lett. 12, 5750-5755 (2012).

# Metasurface holograms

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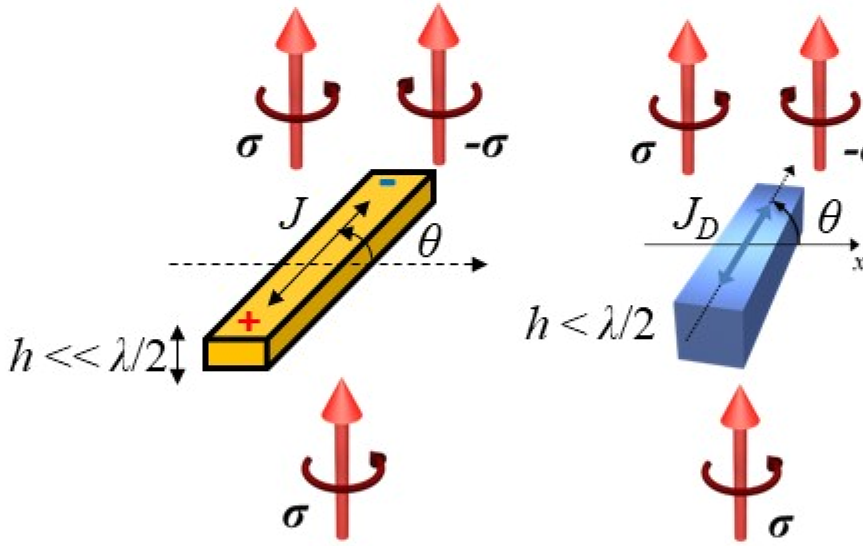
## Methods of abrupt phase modulation by metasurfaces

1. Anisotropic phase modulation: Pancharatnam-Berry (PB) phase

➢ Implementation: metallic / high-index nanorod




$$E_t \approx R(-\theta)\begin{pmatrix} t & 0 \\ 0 & 0 \end{pmatrix} R(\theta)\begin{pmatrix} 1 \\ i\sigma \end{pmatrix}$$

$$\approx \frac{t}{2}\left\{\begin{pmatrix} 1 \\ i\sigma \end{pmatrix} + e^{2i\sigma\theta}\begin{pmatrix} 1 \\ -i\sigma \end{pmatrix}\right\}$$

- Plasmonic / high-index nanorod: large scattering cross-section
- Nearly acting as a miniature linear polarizer
- Ultra-thin thickness of nanorods < λ/2
- Electric dipole is induced along the long axis. → $t_L = t$ and $t_S \approx 0$

# Metasurface holograms

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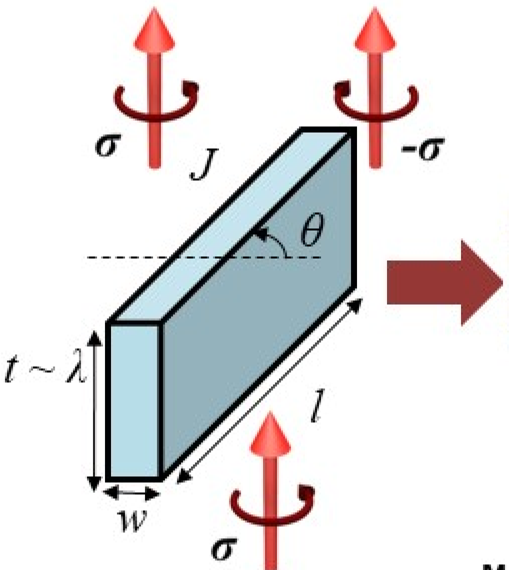
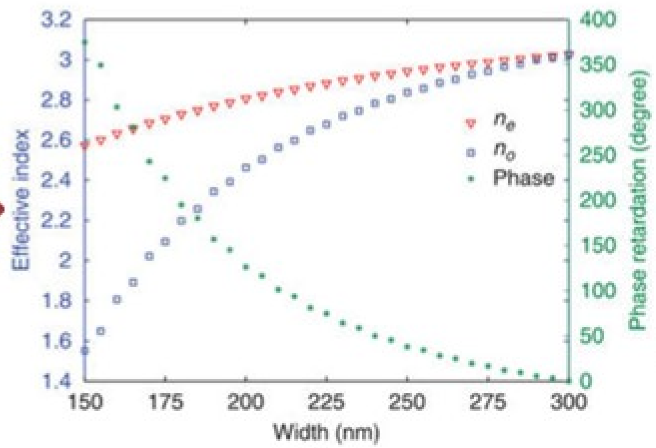
## Methods of abrupt phase modulation by metasurfaces

1. Anisotropic phase modulation: Pancharatnam-Berry (PB) phase

➢ Implementation: low loss moderate-index nanofin (birefringent waveguide)




$$E_t = \frac{t_L + t_S}{2}\begin{pmatrix}1\\ i\sigma\end{pmatrix} + \frac{t_L - t_S}{2} e^{2i\sigma\theta}\begin{pmatrix}1\\ -i\sigma\end{pmatrix}$$

$$t_L \approx a\exp\left(i\frac{2\pi}{\lambda_0}n_e t\right) \text{ and } t_S \approx b\exp\left(i\frac{2\pi}{\lambda_0}n_o t\right)$$

$(a, b$ : real constants)

M. Khorasaninejad et al., *Nat. Commun.* 5, 5386 (2014).

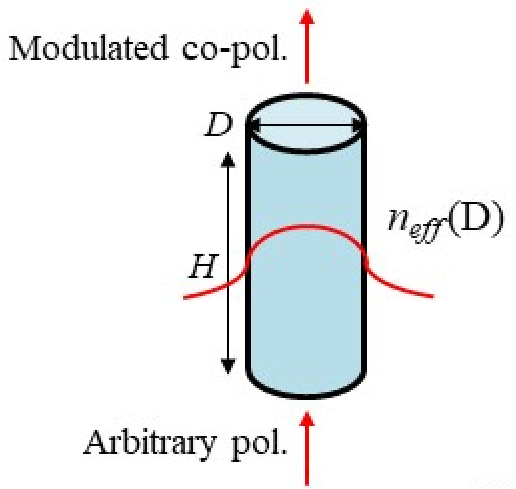
- Dielectric nanofin : short birefringent **dual mode** ($n_e$, $n_o$) waveguide
- Higher-order modes are suppressed by subwavelength thickness and normal incidence.
- Acting as a miniature elliptical polarizer
- Nearly $\lambda$-thick nanofins required for enough phase retardation (difference between $t_e$ and $t_o$)
- Fabry-Perot resonances can be avoided by proper selection of height.

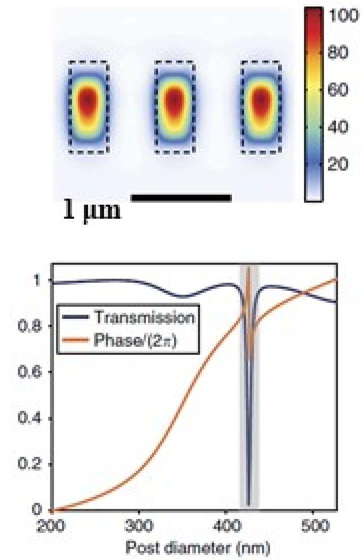
## Methods of abrupt phase modulation by metasurfaces

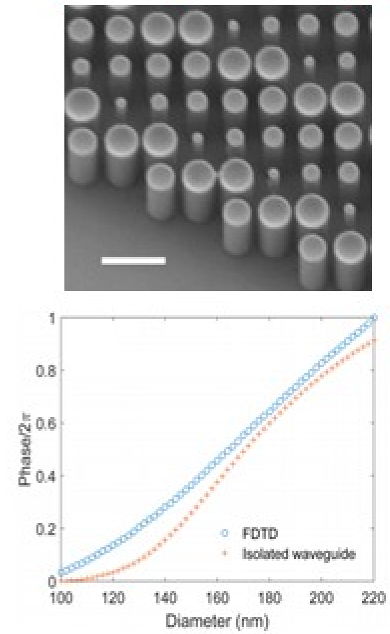
2. Isotropic phase modulation: control of **local meta-atom dimensions**

➢ Implementation: low loss moderate-index dielectric nano-cylinder (isotropic waveguide)

$$E_t \approx t e^{ik_0 n_{eff}(D)H} E_i$$




A. Arbabi et al., *Nat. Commun.* 6, 7069 (2015). M. Khorasaninejad et al., *Nano Lett.* 16, 11 (2016).

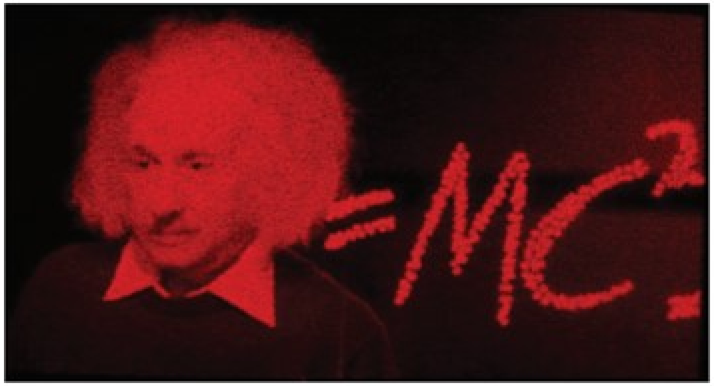
- Dimension of isotropic nano-cylinder is controlled for full 2π phase modulation.
- Dimension determines effective mode index of the fundamental waveguide mode.
- Subwavelength period → Input light is mostly coupled to waveguide mode.
- Multi-wavelength operation is possible by avoiding FP resonant height condition.

# Metasurface holograms

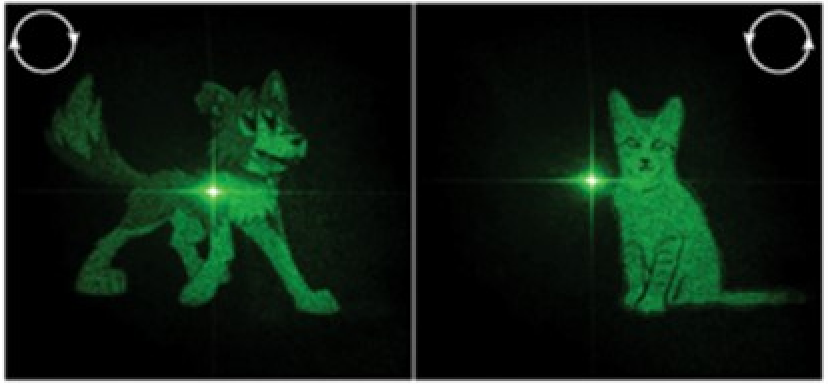


## Recent demonstrations of metasurface holograms

Anisotropic PB phase meta-atom based

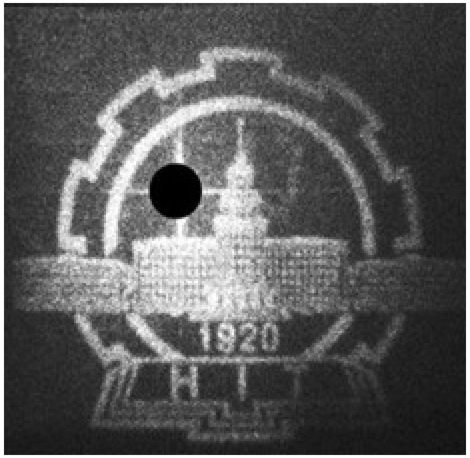


G. Zheng et al., *Nat. Nanotech.* 10, 308–312 (2015).



J. P. B. Muller et al., *Phys. Rev. Lett.* 118, 113901 (2017).

Isotropic dielectric meta-atom based



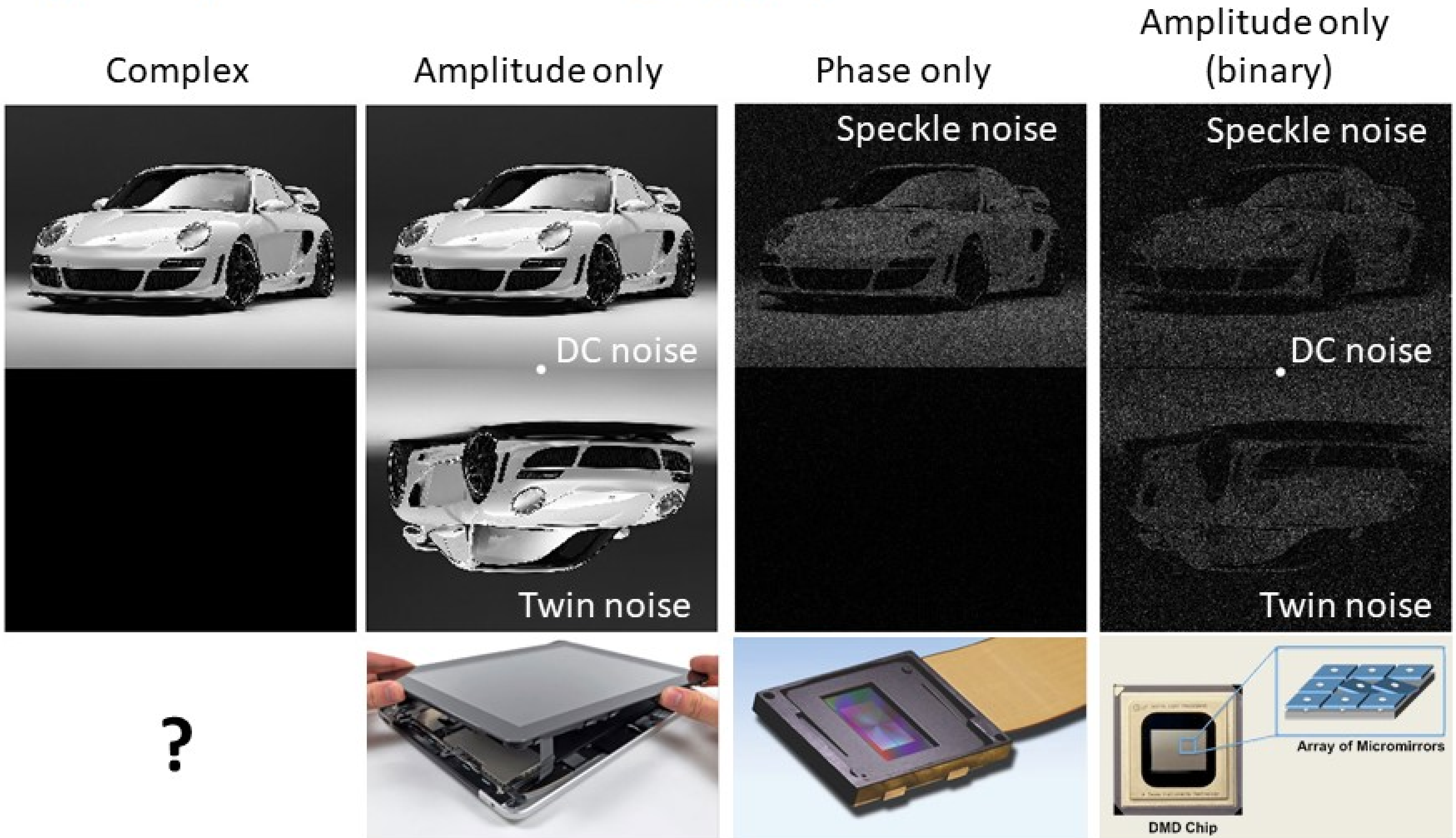

W. Zhao et al., *Sci. Rep.* 6, 30613 (2016).


X. Su et al., *RSC Adv.* 7, 26371 (2017).

# Complex modulation and holograms



## Why is complex modulation in holography important?



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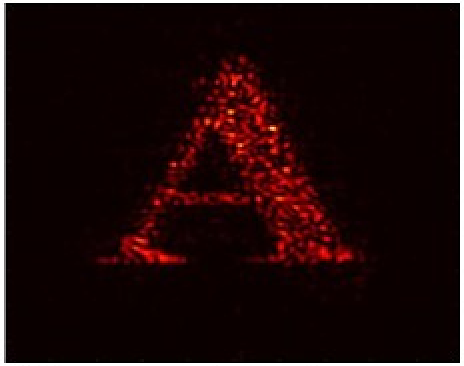
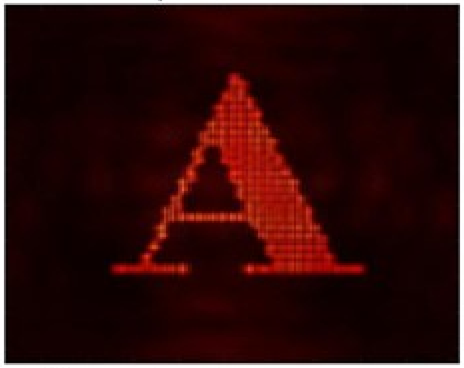
## Metasurface for complex modulation and holograms

**Comparison**

**Dipole modeling metasurface hologram simulations**



Phase-only hologram



Complex hologram

- Conventional methods using phase-only SLM or amplitude-only SLM
  - → Small viewing angle (~5°) and restricted image size
  - → Filtering of twin image is required.
- Complex modulation by metasurface can overcome these limits.

# Complex metasurface holograms

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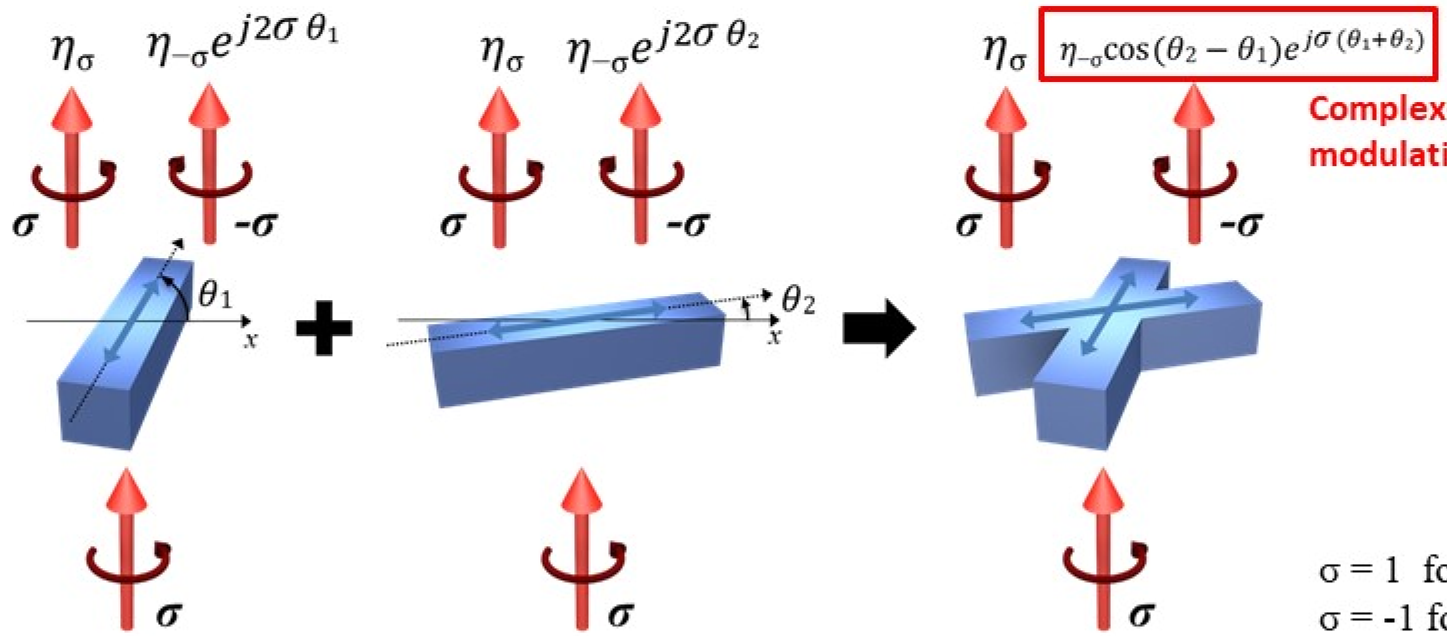
## X-shaped silicon meta-atoms based on the PB phase




σ = 1 for RCP
σ = -1 for LCP

- Two crossed silicon nanorods → crossed nearly-independent electric dipoles

$$E_{-\sigma} \propto e^{j2\sigma\theta_1} + e^{j2\sigma\theta_2} = 2\cos(\theta_2-\theta_1)e^{j\sigma(\theta_1+\theta_2)}$$

Complex-amplitude of cross-polarized transmission

| | |
|---|---|
| $A = \cos(\theta_2-\theta_1)$ | **(amplitude)** |
| $\phi = \theta_2+\theta_1$ | **(phase)** |

- Full ranges of both amplitude and phase can be described.

G.-Y. Lee et al., "Complete amplitude and phase control of light using broadband holographic metasurface," *Nanoscale*, 2018.

# Complex metasurface holograms

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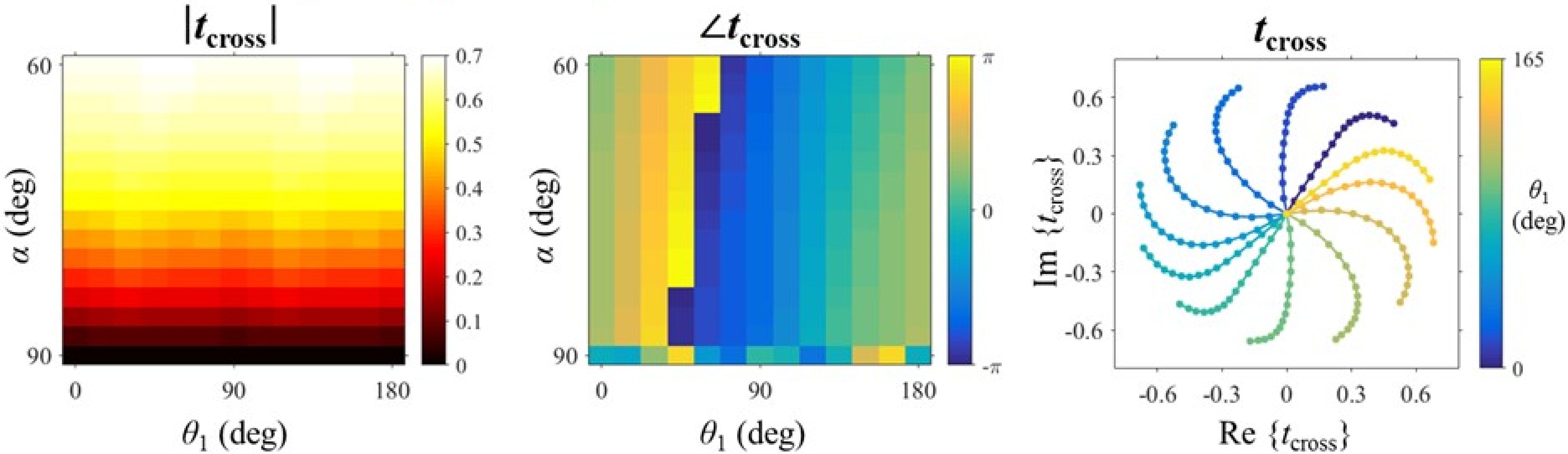
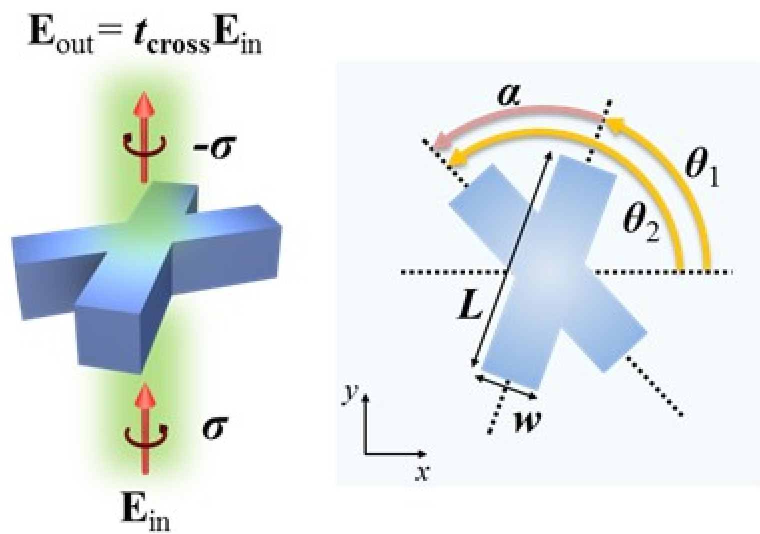
## Modulation capability of X-shaped meta-atoms




- $t_{cross}$ is calculated for various disparity angles ($\alpha$) and orientation angles ($\theta_1$).
- Disparity angle ($\alpha$) controls the amplitude while orientation angle ($\theta_1$) controls the phase.
- A full range of complex-amplitude is continuously covered on complex domain.

# Complex metasurface holograms

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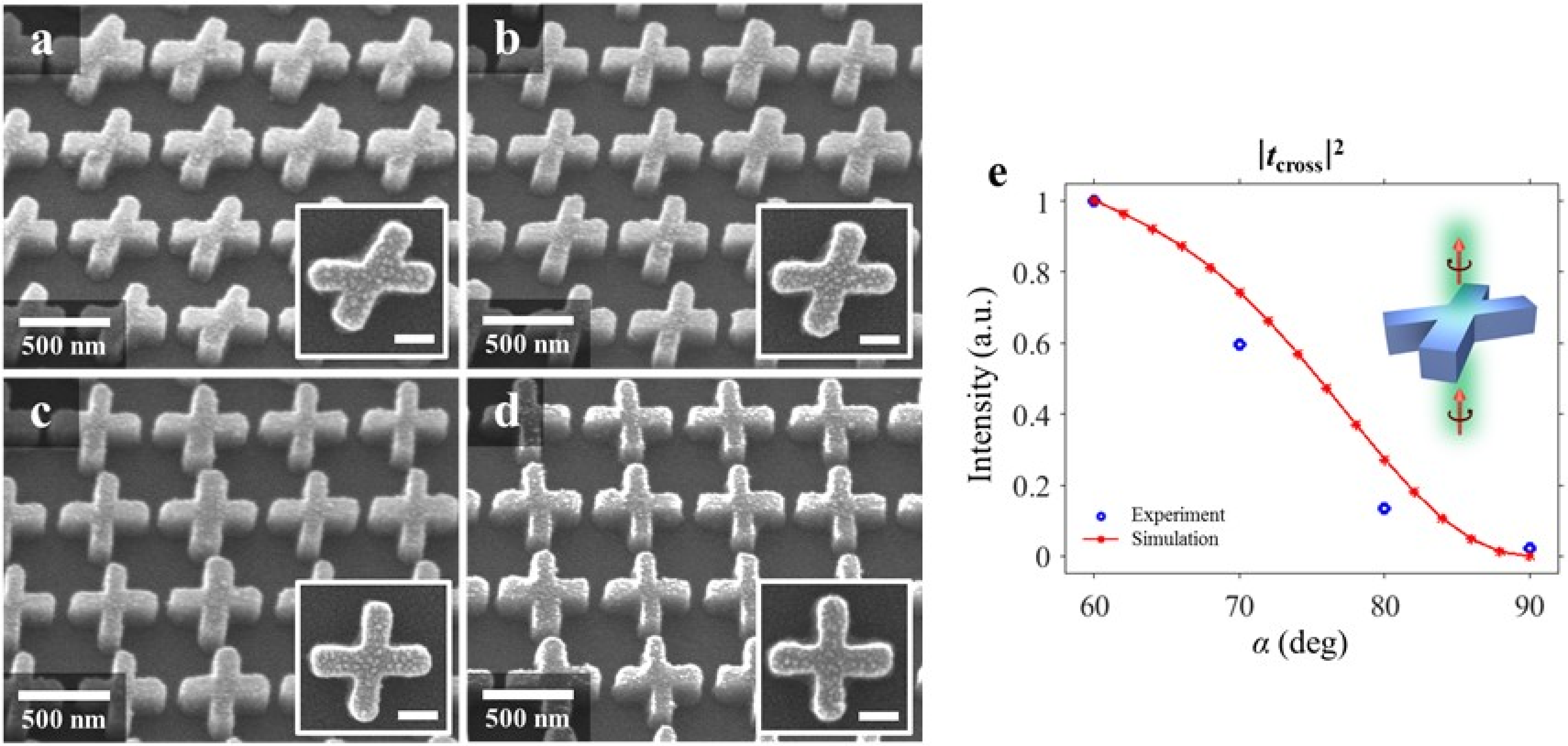
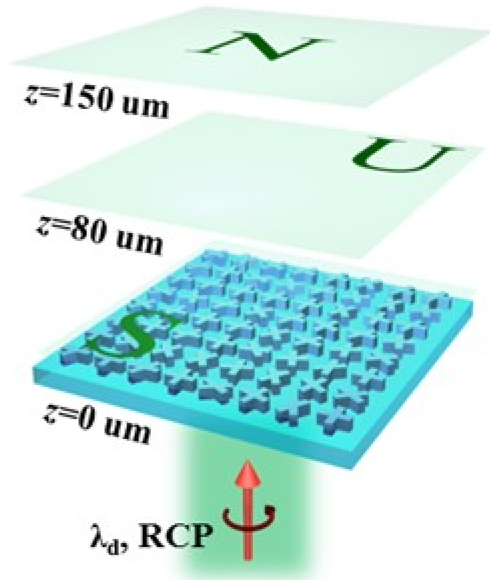
## Experimentally measured cross-polarized transmissions ($t_{cross}$)

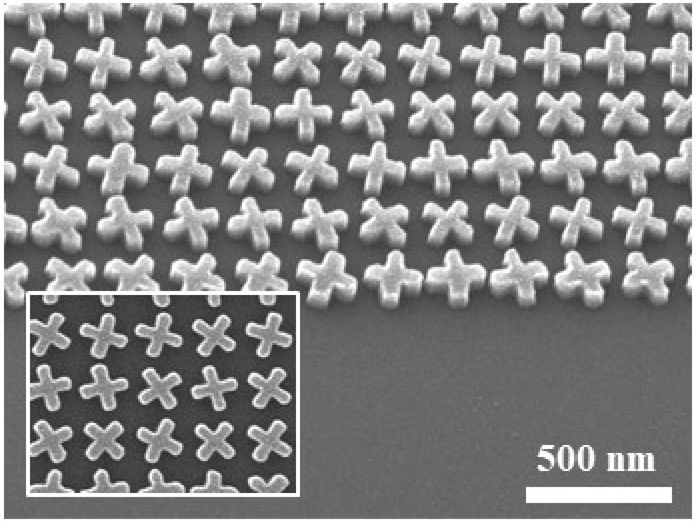


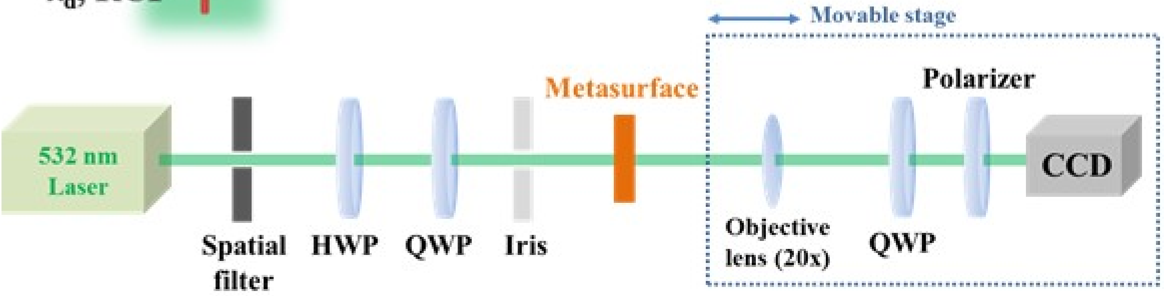

- Standard electron beam lithography process was used.
  (co-work with prof. Junsuk Rho at POSTECH)
- Experimental results show a good agreement with the simulation results.
- As expected, disparity angle ($\alpha$) controls the amplitude components of $t_{cross}$.

# Complex metasurface holograms

## Complex-amplitude metasurface holograms



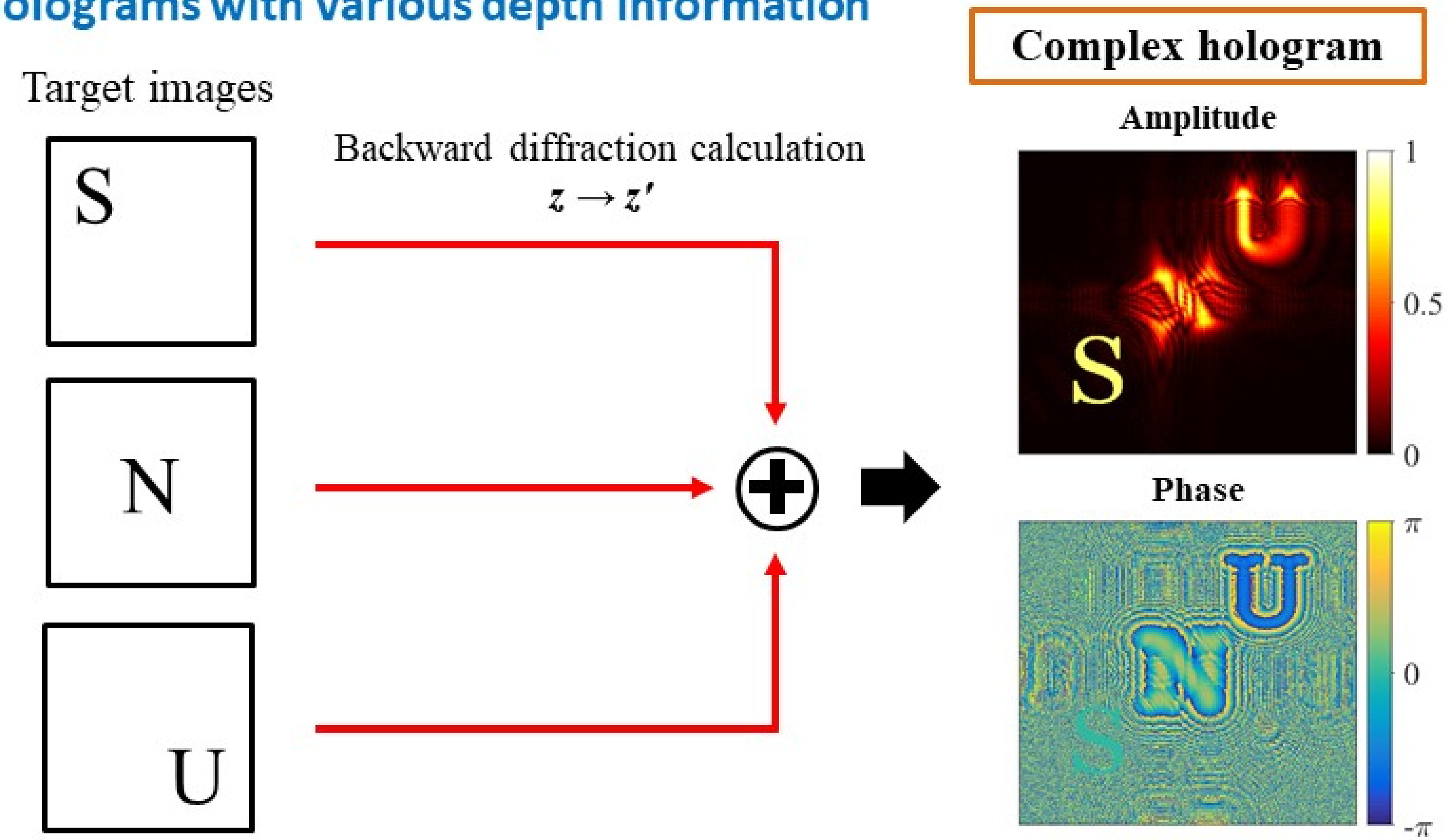




- As an example, hologram with letters of "SNU" is designed without any approximations.
- "S" is at metasurface plane ($z$=0 μm), and "U" and "N" are at z=80 and 150 μm.
- Reconstructed images are measured by using CCD camera with an objective lens.

# Complex metasurface holograms



## Complex holograms with various depth information




- Compared to phase-only holograms, a complex hologram does not need any approximations or scarifications of information on its calculation.
- Angular spectrum method was employed to generate holograms.
- Finally, the complex hologram for the three letters with different depths is calculated by the sum of the holograms of each image (S, N, U).

# Complex metasurface holograms

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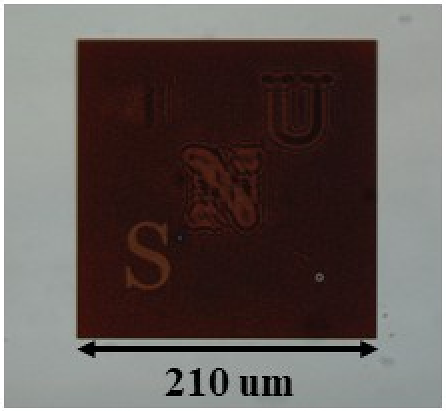
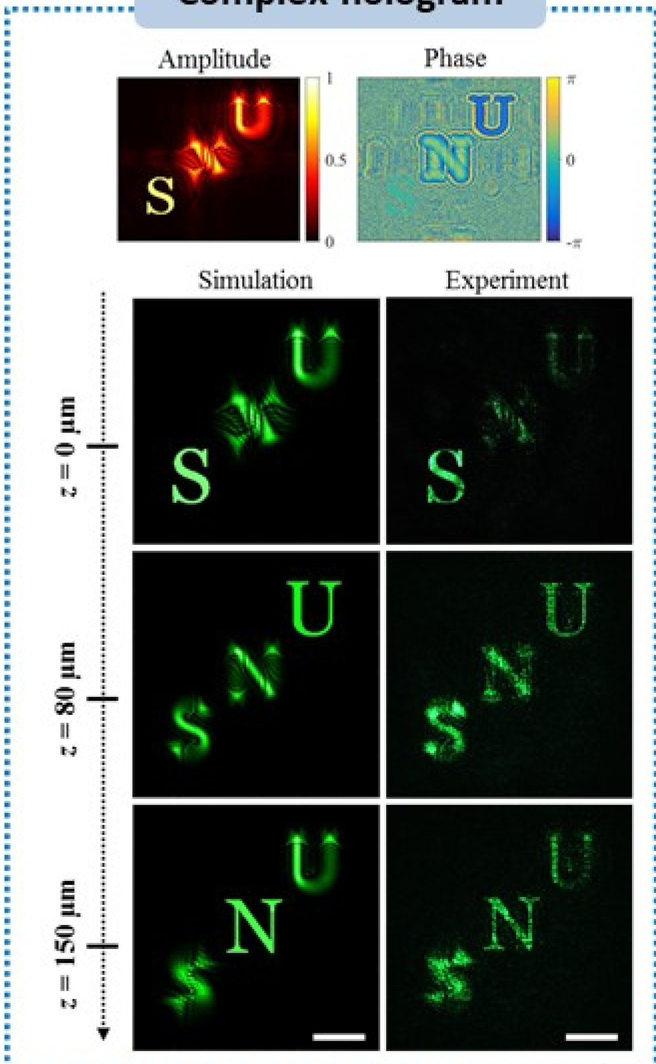
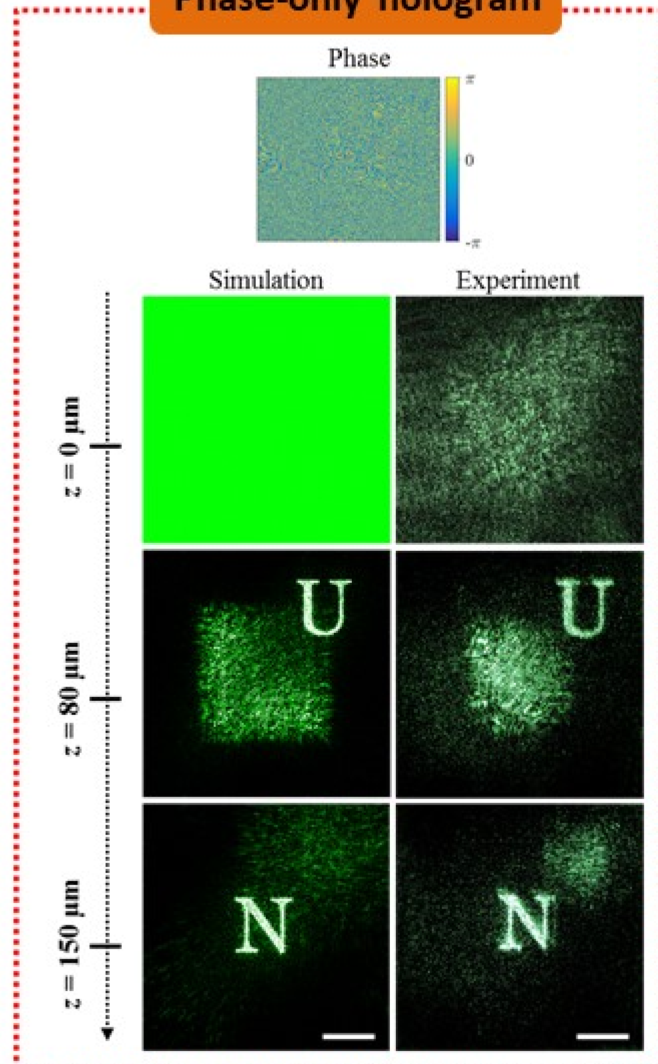
## **Experimental results:** Complex-amplitude hologram vs. phase-only holograms




**Complex hologram**



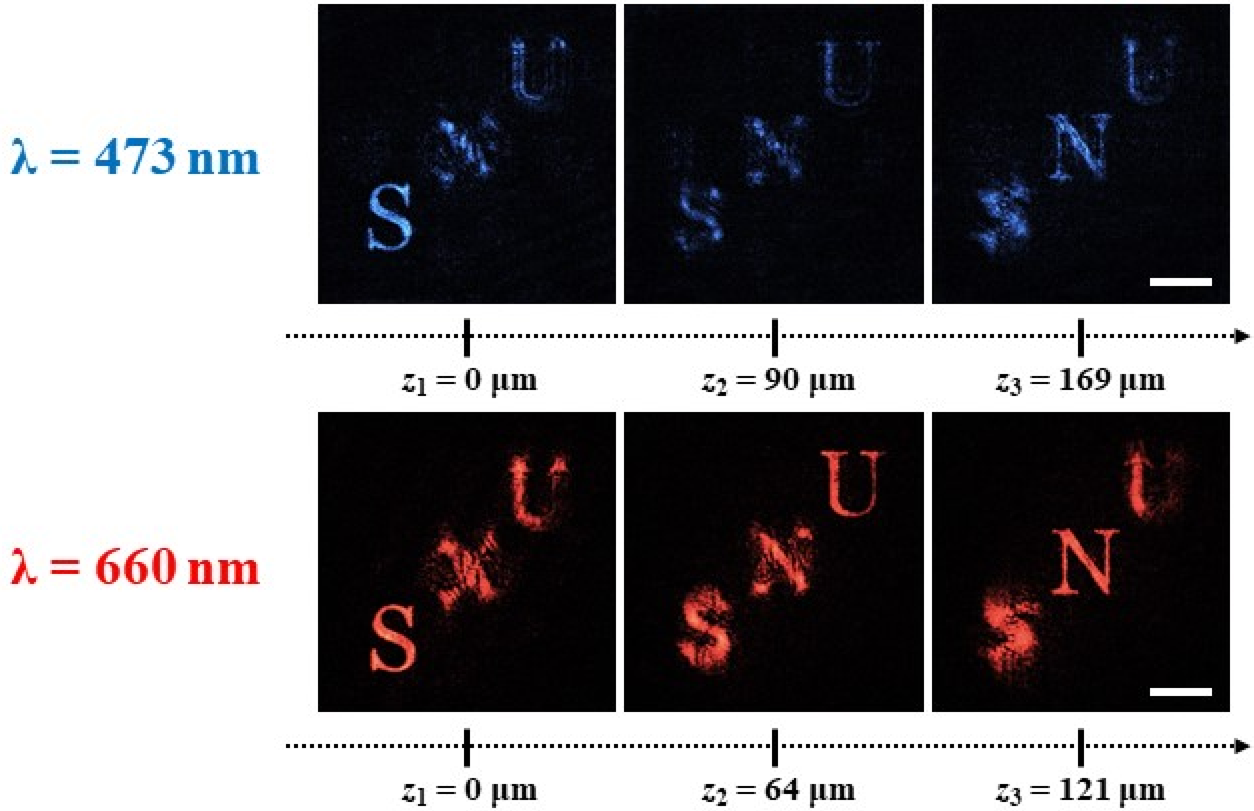

**Phase-only hologram**



# Complex metasurface holograms



## **Experimental results:** Broadband complex-amplitude hologram




- Due to the broadband property of the PB phase, X-shaped meta-atoms well operate in broadband visible region.
- Full complex-amplitude holograms show very clear images with a record-breaking signal-to-noise ratio **(SNR = 211.3)** where previously reported SNR for phase holograms are about 50.

**G.-Y. Lee et al., "Complete amplitude and phase control of light using broadband holographic metasurface,"** ***Nanoscale*****, 2018.**

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# Metalens and prospect of metasurface



## Optical applications & optic components

- Smartphone camera

Samsung Galaxy S8

- Augmented Reality (AR) device

Microsoft Hololens

- Virtual Reality (VR) device

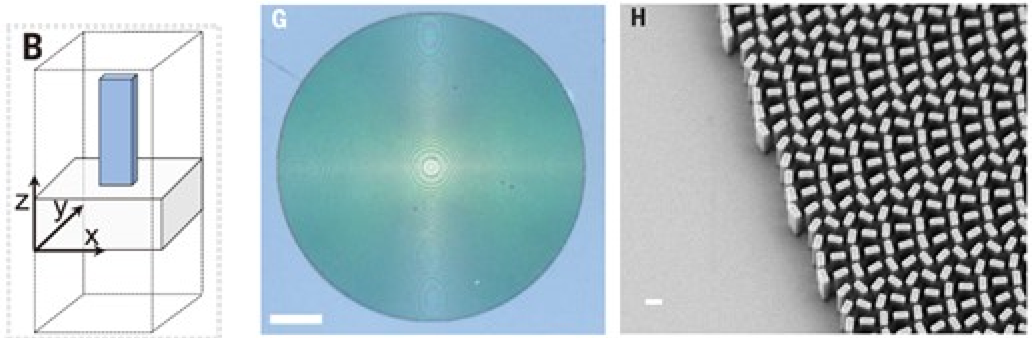
Samsung Gear VR

- There are various mobile optical applications using a series of optic components.
- Miniaturization of optic components is essential for advanced mobile applications.

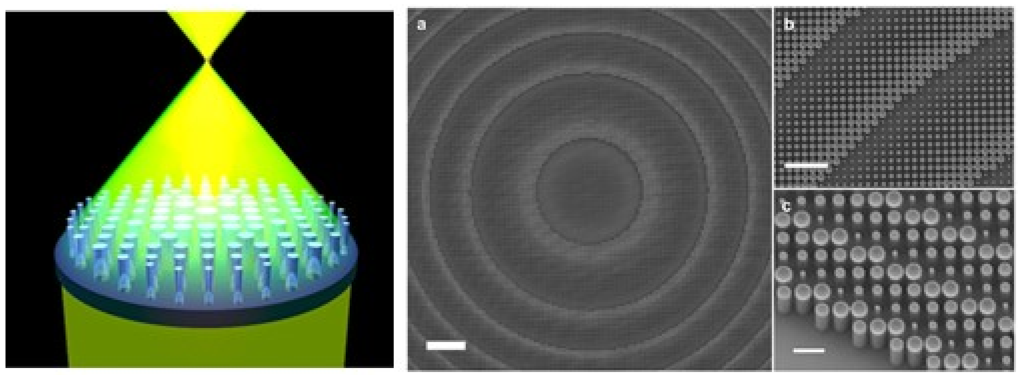
# Metalens and prospect of metasurface



## Metasurface lens (metalens) : overview




M. Khorasaninejad et al., *Science* 352, 6290 (2016).




M. Khorasaninejad et al., *Nano Lett.* 16, 7229–7234 (2016).

- Metalens concept overcomes the limitations of conventional bulk-optic lenses including large form factor and low numerical aperture.
- Recent advances in metalens have shown high efficiency (>80 %) and high NA (NA=0.8) within ultrathin thickness (<500 nm).

# Metalens and prospect of metasurface

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## Study on metalens

| Reference | Efficiency | Polarization | Wavelength (nm) |
|---|---|---|---|
| F. Aieta *et al.*[1] | ~1% | Linear | 1550 |
| X. Ni *et al.*[2] | ~10% | Linear | 476-676 |
| A. Arbabi *et al.*[3] | ~62-74% | Insensitive | 1450-1550 |
| S. Vo *et al.*[4] | ~70% | Insensitive | 850 |
| D. Lin *et al.*[5] | Not reported | Circular | 550 |
| M. Khorasanineja *et al.*[6] | Above 50% | Circular | 405, 532, 660 |
| M. Khorasanineja *et al.*[7] | ~30%, ~70%, ~90%, | Insensitive | 405, 532, 660 |


1. F. Aieta *et al.*, *Nano Lett.* 12, 4932–4936 (2012).
2. X. Ni *et al.*, *Light Sci.* Appl. 2, e72 (2013).
3. A. Arbabi *et al.*, *Nat. Commun.* 6, 7069 (2015).
4. S. Vo *et al.*, *IEEE Photon. Technol. Lett.* 26, 1375–1378 (2014).
5. D. Lin *et al.*, *Science* 345, 298–302 (2014).
6. M. Khorasaninejad *et al.*, *Science* 352, 6290 (2016).
7. M. Khorasaninejad *et al.*, *Nano Lett.* 16, 7229–7234 (2016).

# Metalens and prospect of metasurface

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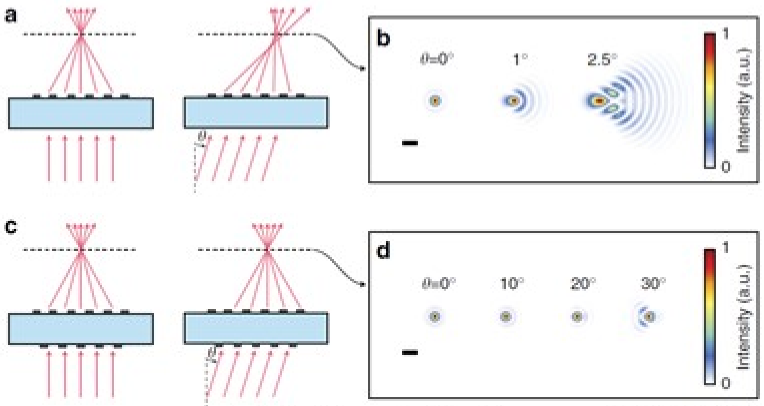
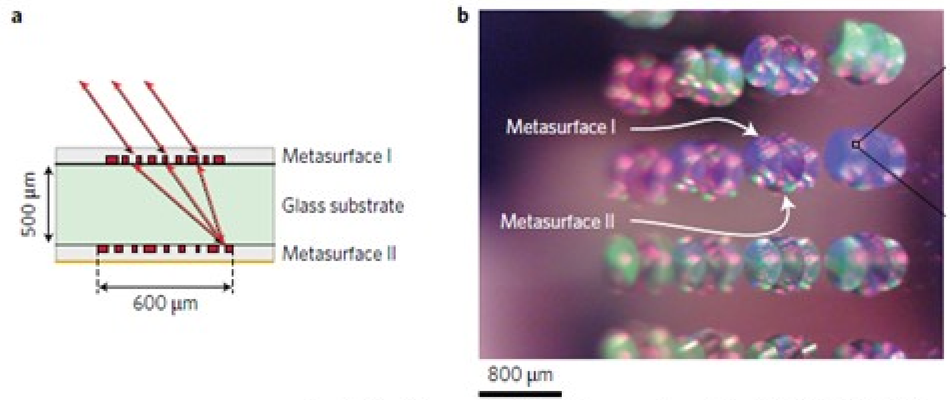
## Metalens applications

### ➢ Metalens free from off-axis aberration



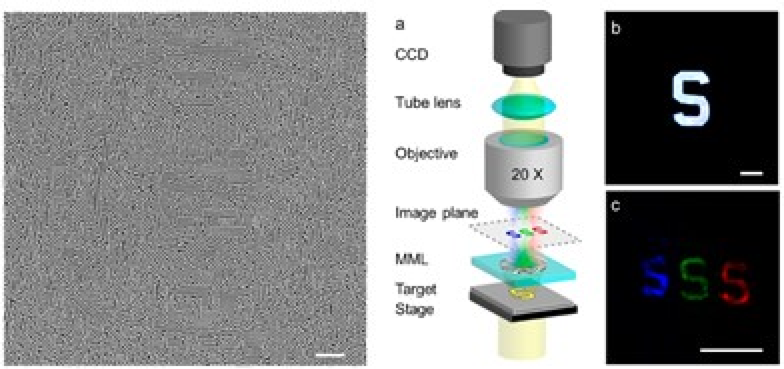

A. Arbabi et al., *Nat. Commun.* 7, 13682 (2016)

### ➢ Retroreflector



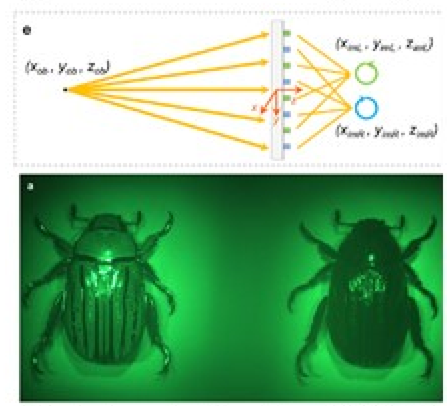

A. Arbabi et al., *Nat. Photonics.* 11, 415-420 (2017).

### ➢ Spectral imaging




D. Lin et al., *Nano Lett.* 16, 7671–7676 (2016)

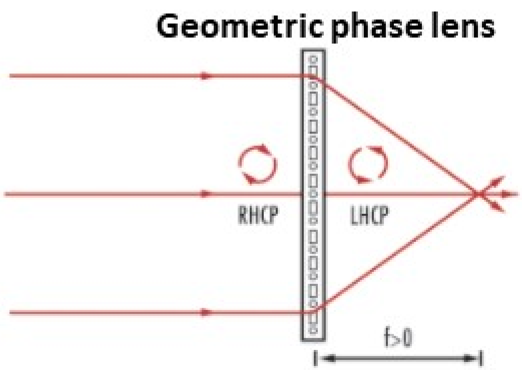
### ➢ Chirality-sensitive imaging

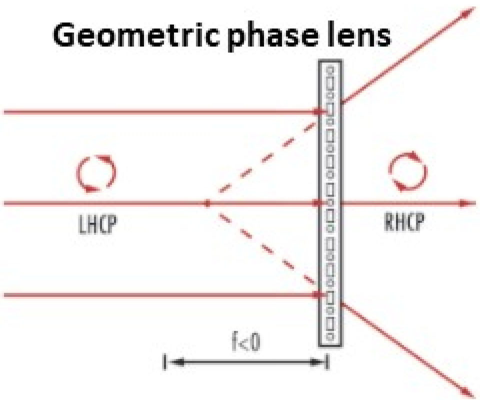


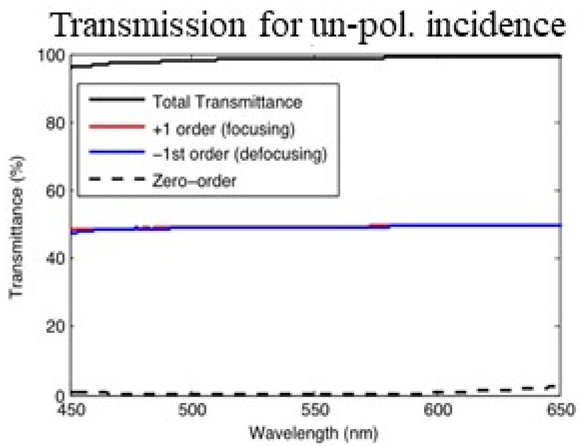

M. Khorasaninejad et al., *Nano Lett.* 16, 4595–4600 (2016).

# Metalens and prospect of metasurface

➢ **Geometric phase lens (PB phase lens) using liquid crystals (commercialized)**




http://www.imagineoptix.com/technology/geometric-phase-lens/

**Rotated half-wave plate**

$$E_t = \mathrm{T}\begin{pmatrix}1\\ i\sigma\end{pmatrix} = \exp(i2\sigma\theta)\begin{pmatrix}1\\ -i\sigma\end{pmatrix}$$

Geometric phase (PB phase)

**Generalized Snell's law**

$$\sin\theta_t = \frac{n_i}{n_t}\sin\theta_i + \sigma\frac{\lambda_0}{\pi}\frac{d\theta}{dx}$$

$$\sigma = \begin{cases}1 & \text{(RCP)}\\ -1 & \text{(LCP)}\end{cases}$$

- **Dual-polarity** focusing according to optical handedness
- Extremely high transmission
- Commercially available now

# Metalens and prospect of metasurface

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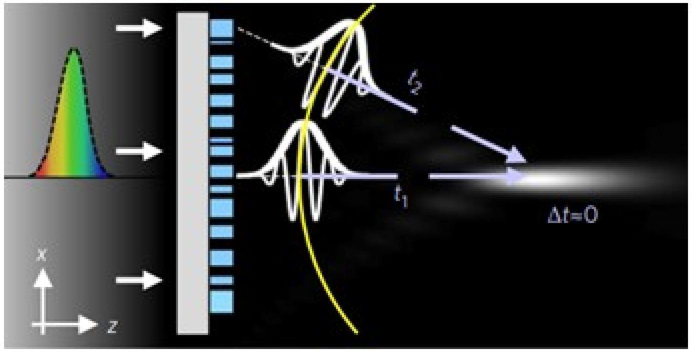
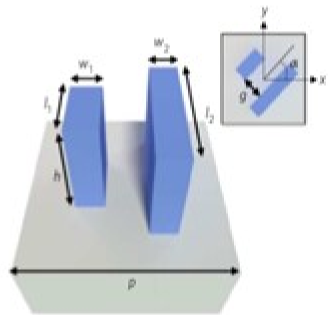
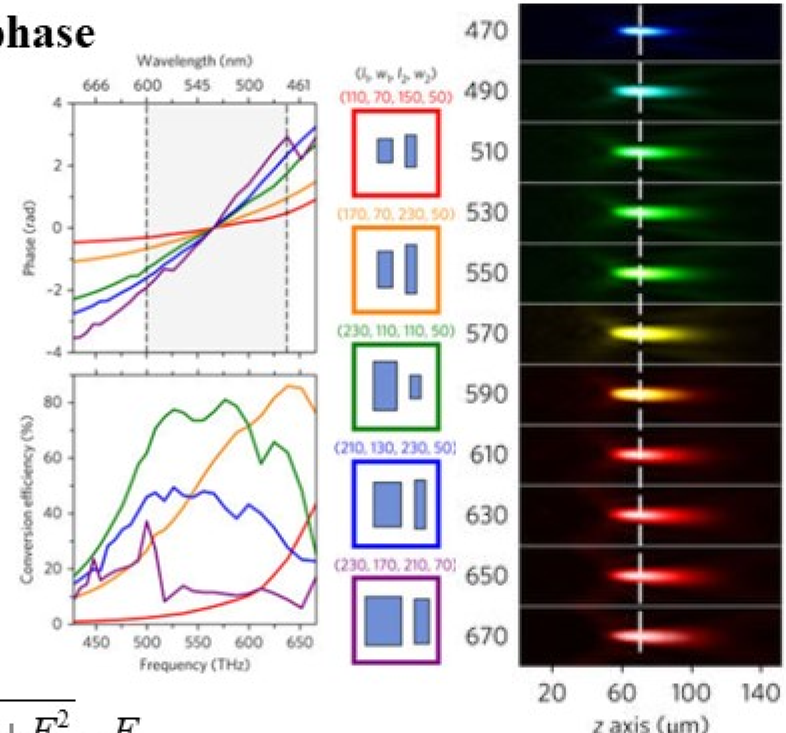
## Future of metalens: achromatic thin lens

- **Broadband achromatic metalens based on PB phase**




W. T. Chen, et al., Nat. nanotech. 1, 2018






$$\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2+F^2}-F\right) \approx \varphi(r,\omega_d) + \left.\frac{\partial\varphi(r,\omega)}{\partial\omega}\right|_{\omega=\omega_d}(\omega-\omega_d)$$

$$\Rightarrow \varphi(r,\omega) \approx \exp(in_{eff}(r,\omega)k_0 h)\exp(2i\theta(r)) \quad \& \quad \frac{\partial\varphi(r,\omega)}{\partial\omega} \approx -\frac{\sqrt{r^2+F^2}-F}{c}$$

- Coupled dielectric nanofins (→ truncated short $TiO_2$ waveguide)
- Investigation of $n_{eff}(r,\omega)$ and transmittance of nanofin for aberration compensation
- Group delay is designed to nearly non-dispersive for mitigating aberration.
- Visible wavelengths (470-670 nm)
- NA ~0.2 (@$f$ = 63 μm) and focusing efficiency up to 20%

# Metalens and prospect of metasurface

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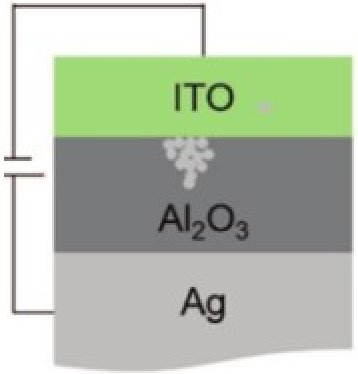
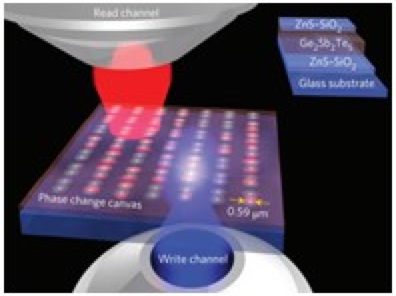
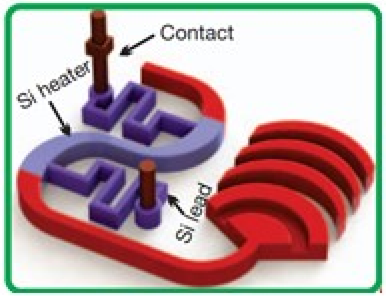
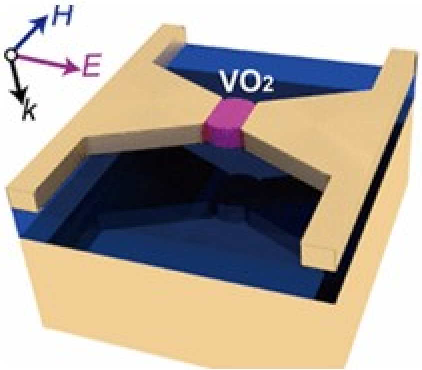
## Future of metasurfaces: active light modulation






| Tuning mechanism | **Field-effect ionic conductance** | **Optical pulse** | **Thermo-optic** | **Electro-thermal** |
|---|---|---|---|---|
| Materials | Indium tin oxide | $Ge_3Sb_2Te_6$ | Si | $VO_2$ |
| Wavelength | Visible | Visible / NIR | Telecom | NIR |
| Tunability | 78 % | - | - | 33 % |
| Speed | 0.02 s | 500 ms | - | 1.27 ms |
| Reference | K. Thyagarajan et al., *Adv. Mater.* 1701044 (2017). | Q. Wang et al., *Nat. Photon.* 10(1), 60 (2016). | J. Sun et al., *Nature* 493(7431), 195 (2013). | Z. Zhu et al., *Nano Lett.* 17(8), 4881 (2017). |

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# Conclusion



- **Metasurface hologram** shows a good potential to improve conventional holograms.
- Using X-shaped meta-atoms, we first demonstrated **broadband complex-amplitude holograms** with silicon base in the visible range.
- Metasurface lens (**metalens**) has attracted much interest to miniaturize optical applications including augmented reality (AR) and virtual reality (VR) devices.
- **Aberration-controlled** metalens and active modulation of light with **tunable metasurfaces** are important topics of study.

# THANK YOU

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