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Accelerating beam generation by dielectric metasurfaces fabricated through low-temperature ALD

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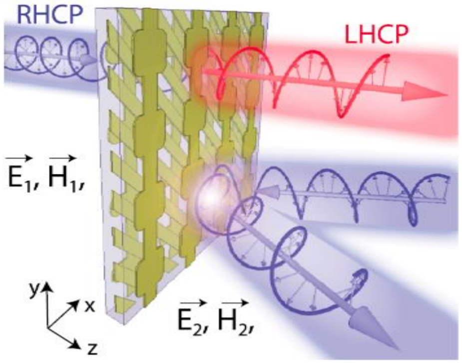
Outline

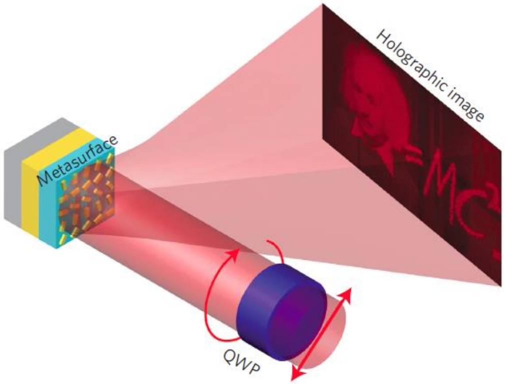
- Background & Motivation for Optical Metasurface
- All Dielectric Metasurface Device design
- All Dielectric Metasurface Device fabrication
- Optical Characterization
- Conclusion

Applications of Optical Metasurfaces



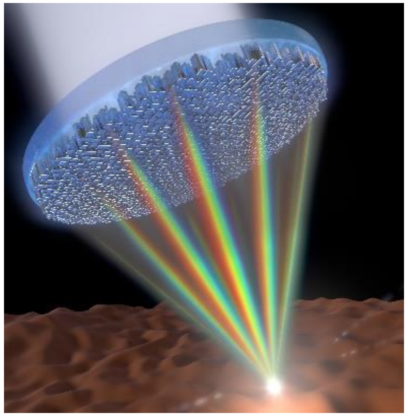
Metallic structure for Light Asymmetric Transmission

Pfeiffer, *et al.*, **Phys. Rev. Lett.**, *2014*



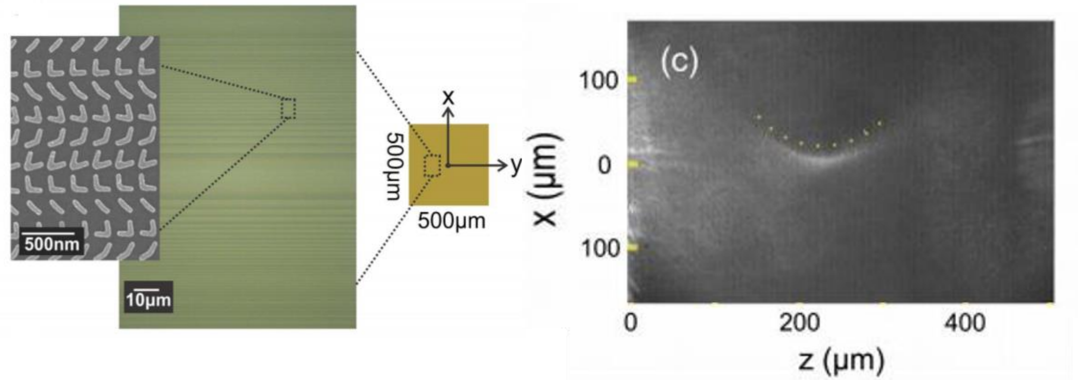
Metallic structure on metal mirror for Holographic display

Zheng, *et al.*, **Nat Nanotechnol.**, *2015*



Dielectric on GaN for Optical Imaging

Chen, *et al.*, **Nat Nanotechnol.**, *2018*



Self-accelerating Beams **in the near infrared with plasmonic metasurfaces**

Henstridge, *et al.*, **Optica,** 2018

Self-accelerating beams

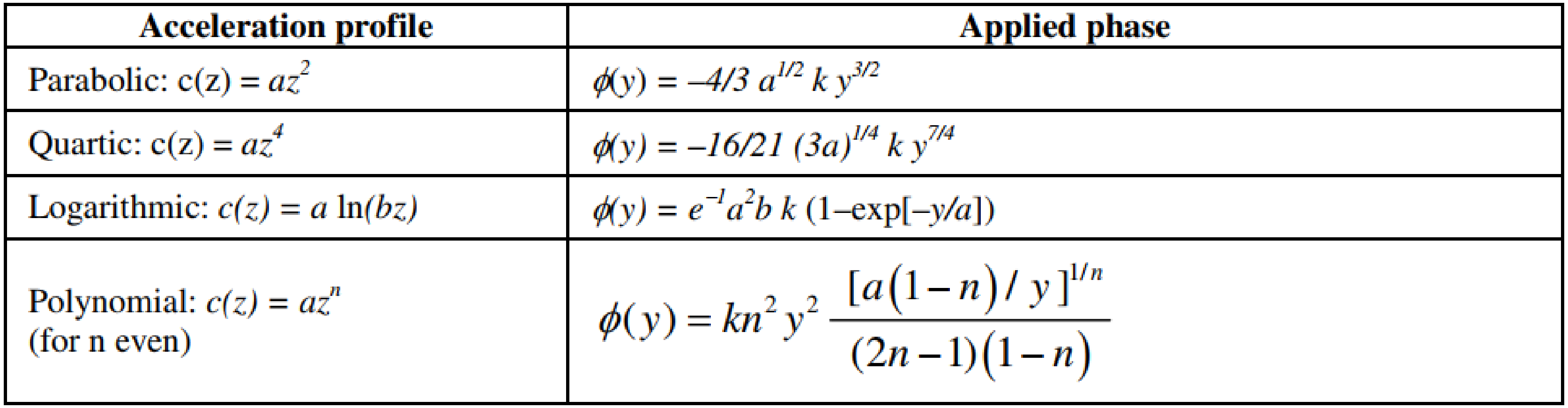
- An exotic diffraction-free solution to Maxwell’s equations
- A wave packet propagating along a curved trajectory
- **This work: Spin-controlled generation of self-accelerating beams in the visible with all dielectric metasurfaces**

All-dielectric Metasurface for Self-accelerating Beam

- **Motivation**
  - It is a novel idea to apply all-dielectric metasurface for self-accelerating beam at visible light range
  - Compact wafer level generation of self-accelerating beam compared to traditional methods; semiconductor process flow can be applied in device fabrication
- **Benefits of all-dielectric metasurface**
  - Reduced optical loss compared to plasmonic structure
  - Be operated under transmission mode

Self-accelerating beam generation with a phase mask

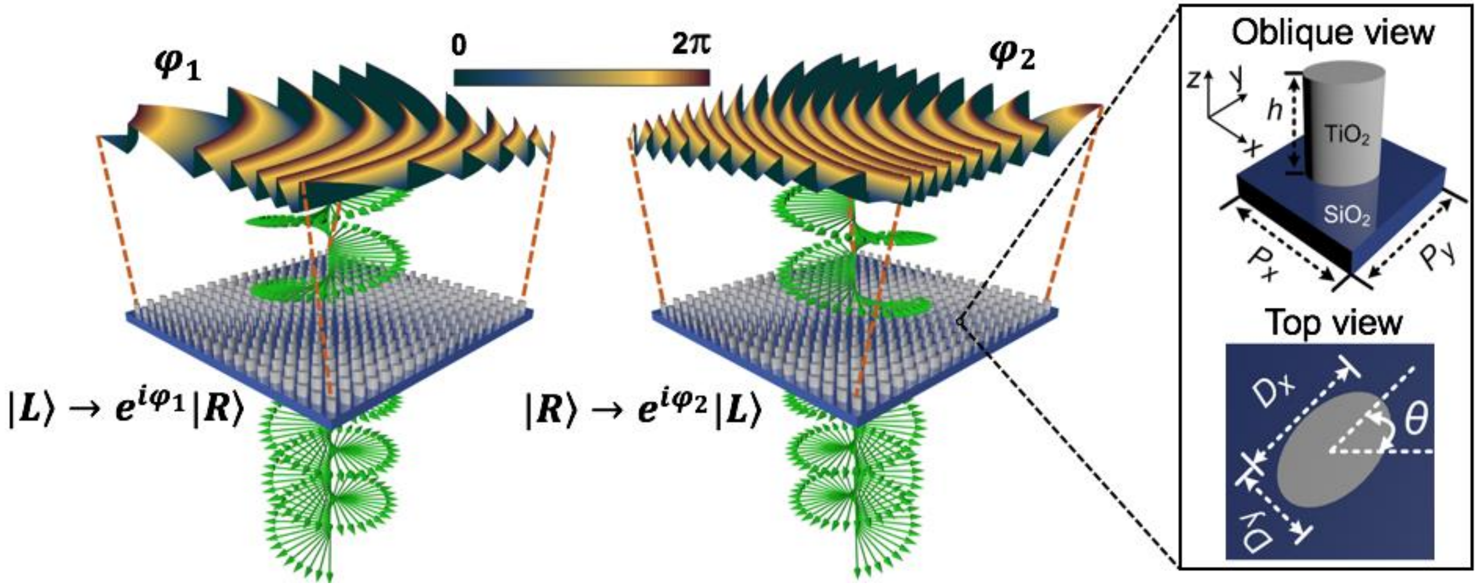
Accelerating beams propagating along a certain trajectory can be generated with associated phase masks



Acceleration profile	Applied phase
Parabolic: $c(z) = az^2$	$\phi(y) = -4/3\, a^{1/2}\, k\, y^{3/2}$
Quartic: $c(z) = az^4$	$\phi(y) = -16/21\, (3a)^{1/4}\, k\, y^{7/4}$
Logarithmic: $c(z) = a \ln(bz)$	$\phi(y) = e^{-1} a^2 b\, k\, (1 - \exp[-y/a])$
Polynomial: $c(z) = az^n$ (for n even)	$\phi(y) = kn^2 y^2 \dfrac{[a(1-n)/y]^{1/n}}{(2n-1)(1-n)}$

L. Froehly, *et al.*, *Arbitrary accelerating micron-scale caustic beams in two and three dimensions*, **Optics Express**, 2011

Spin-controlled self-accelerating beam generation

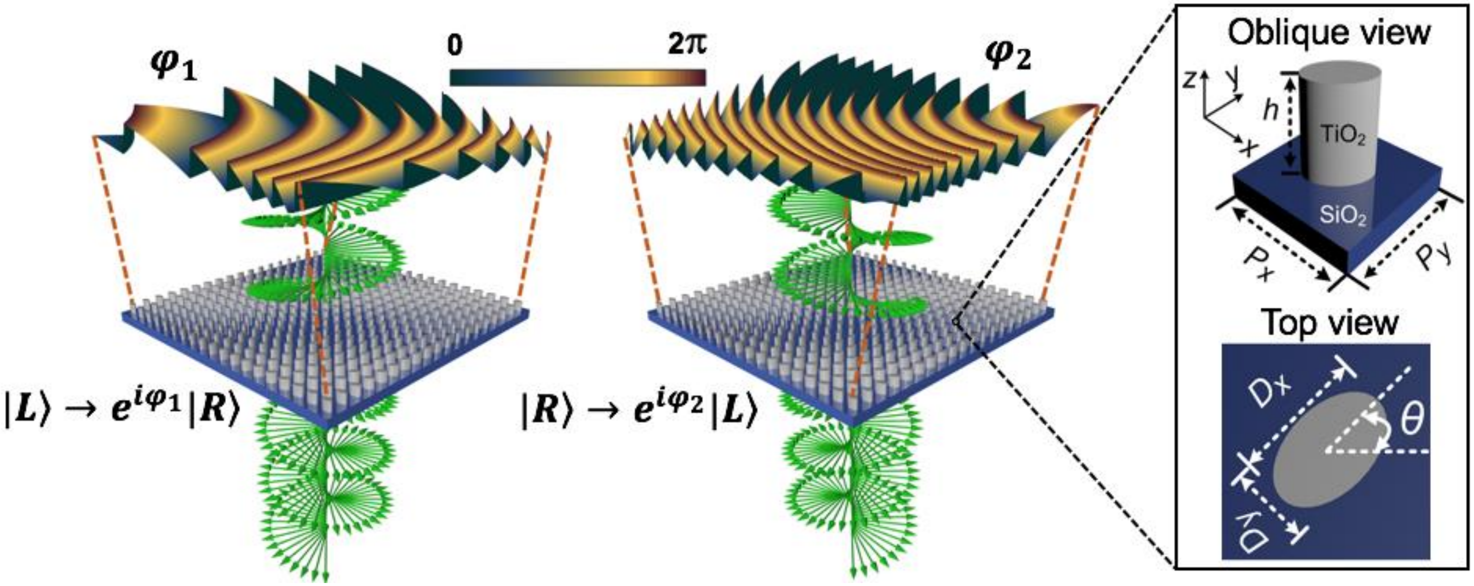


Target: design an all dielectric plate to independently output phase profiles $\varphi_1(x,y)$ and $\varphi_2(x,y)$ for the input LCP and RCP light

The light transformation characteristics of such a metasurface can be described by a Jones Matrix $J(x,y)$

$$e^{i\varphi_1(x,y)}|R\rangle = J(x,y)|L\rangle$$
$$e^{i\varphi_2(x,y)}|L\rangle = J(x,y)|R\rangle$$

Spin-controlled self-accelerating beam generation



The Jones Matrix can be further expressed as:

$$J(x,y) = \frac{1}{2}\begin{bmatrix} e^{i\varphi_1(x,y)} + e^{i\varphi_2(x,y)} & ie^{i\varphi_2(x,y)} - ie^{i\varphi_1(x,y)} \\ ie^{i\varphi_2(x,y)} - ie^{i\varphi_1(x,y)} & -e^{i\varphi_1(x,y)} - e^{i\varphi_2(x,y)} \end{bmatrix}$$

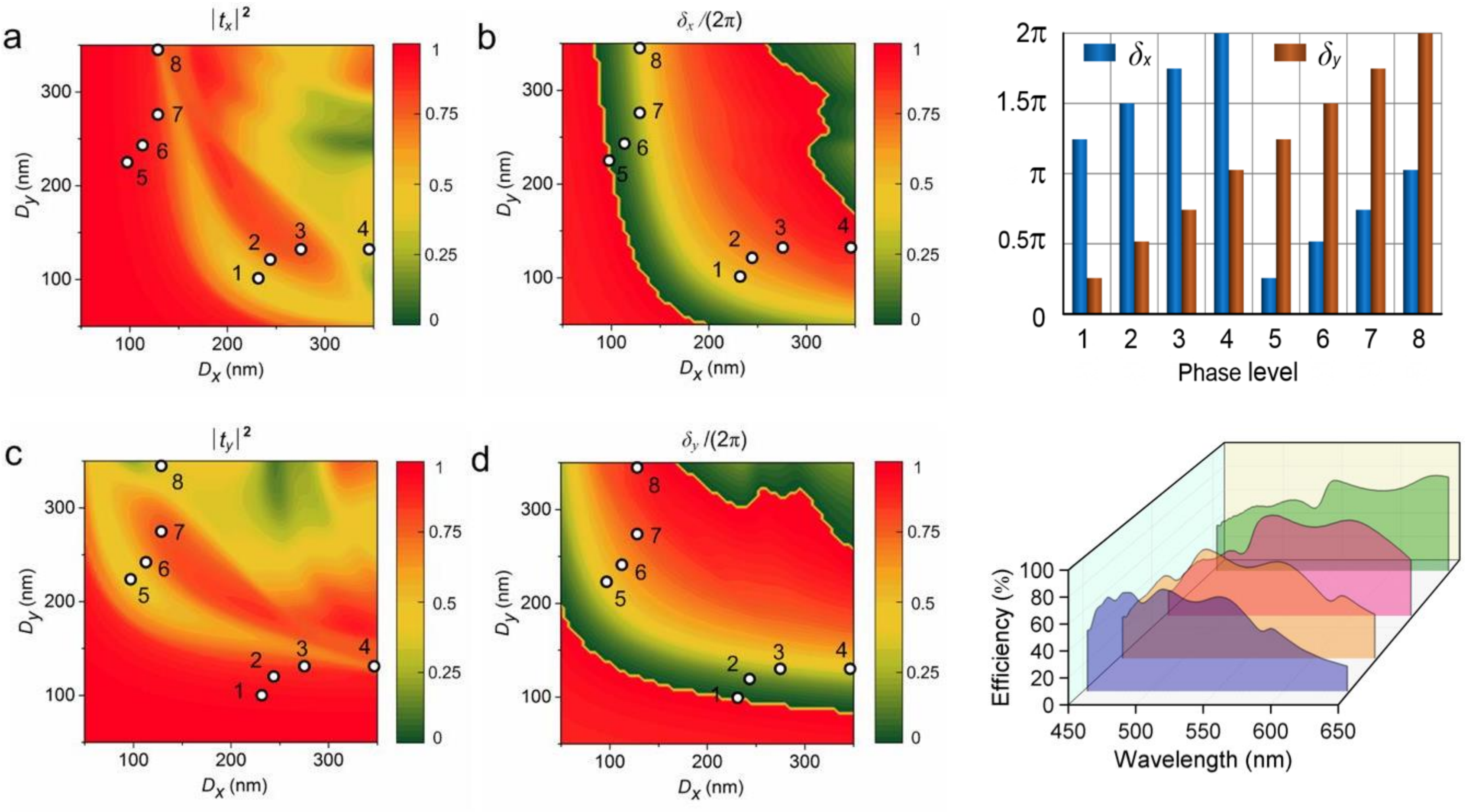
Requiring the nanostructures to have:

$$\begin{cases} \delta_x(x,y) = [\varphi_1(x,y) + \varphi_2(x,y)]/2 \\ \delta_y(x,y) = [\varphi_1(x,y) + \varphi_2(x,y)]/2 - \pi \\ \theta(x,y) = [\varphi_1(x,y) - \varphi_2(x,y)]/4 \end{cases}$$

Design of elliptical pillars

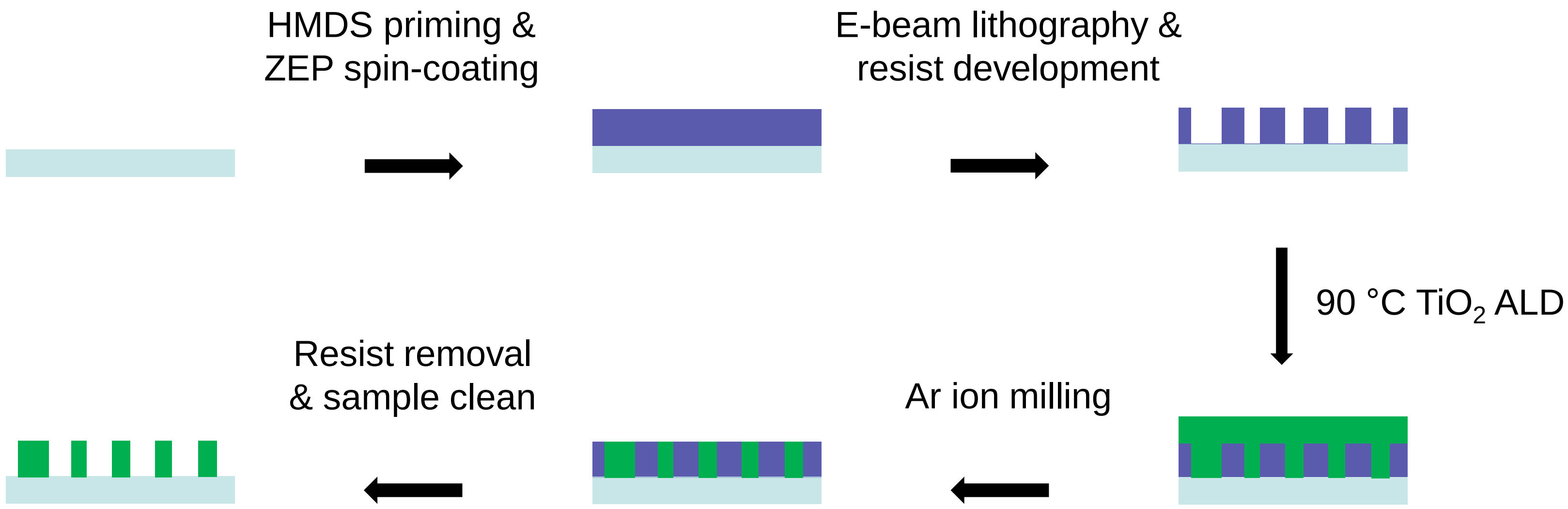
- **Choice of Material**
  - High refractive index in visible light range (TiO2: 2.61)
  - Low adsorption in the visible light range (TiO2: 0)
  - Amorphous material is preferred
- **Choice of Nano Structure**
  - Nano pillars with defined Dx, Dy and orientation angle which can be easily created by E-beam litho.
  - Z 600nm with choice of high refractive index material so it is not high AR structure

Design of elliptical pillars



- Four fundamental TiO2 pillars & their rotated structures along the y-axis
- All pillars acts closely as a half-wave plates with the required phase shift along the two principle axes

Device Fabrication


HMDS priming & ZEP spin-coating

E-beam lithography & resist development

90 °C TiO_2 ALD

Ar ion milling

Resist removal & sample clean

☐ **Requirement of the TiO_2 ALD**

- Low-temperature operation (no resist reflow)
- Plasma-free operation (no resist deterioration)
- AR: no more than 6:1 by design (z 600nm while Dx or Dy in between 100nm and 350nm)

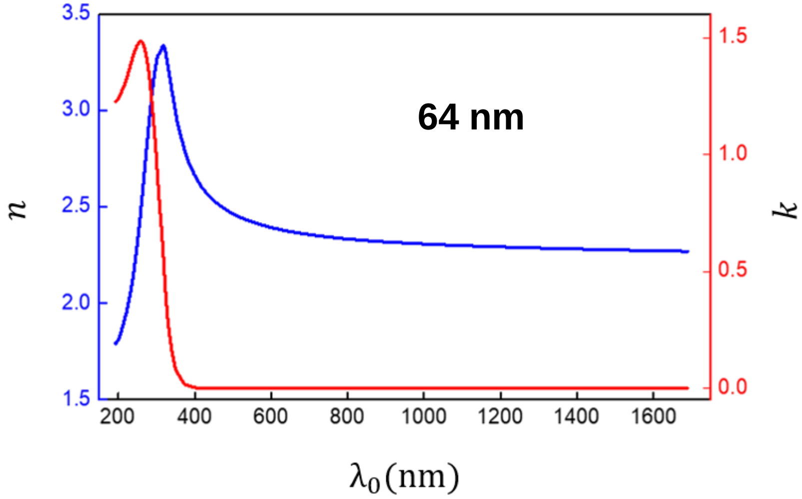
Low-temperature TiO_2 ALD

☐ Deposition:

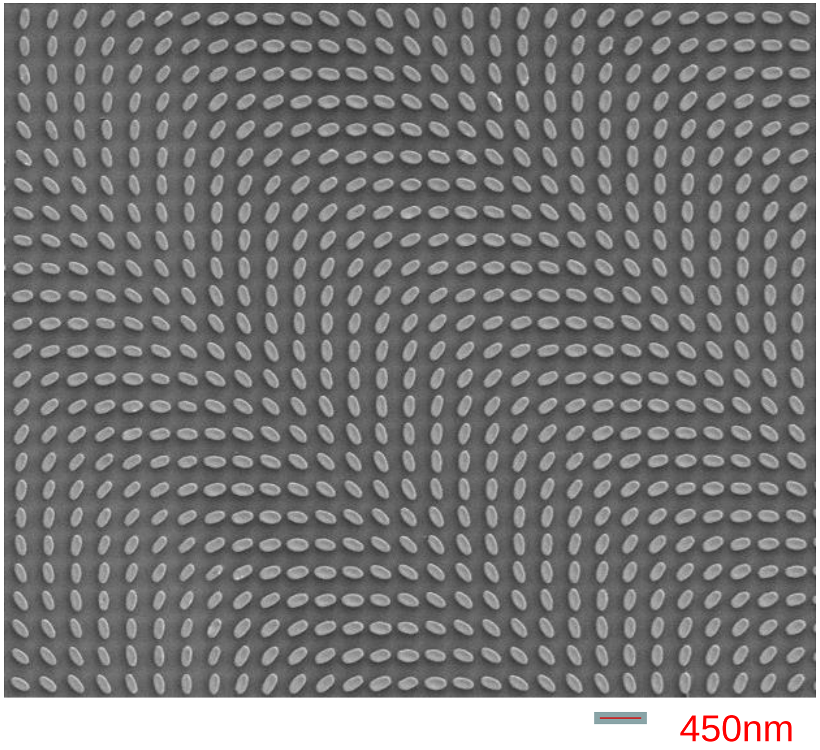
- Arradiance GEMStar™
- Fused silica wafers and Si witnesses
- 200nm of TiO2 by TDMATi with water (90C)

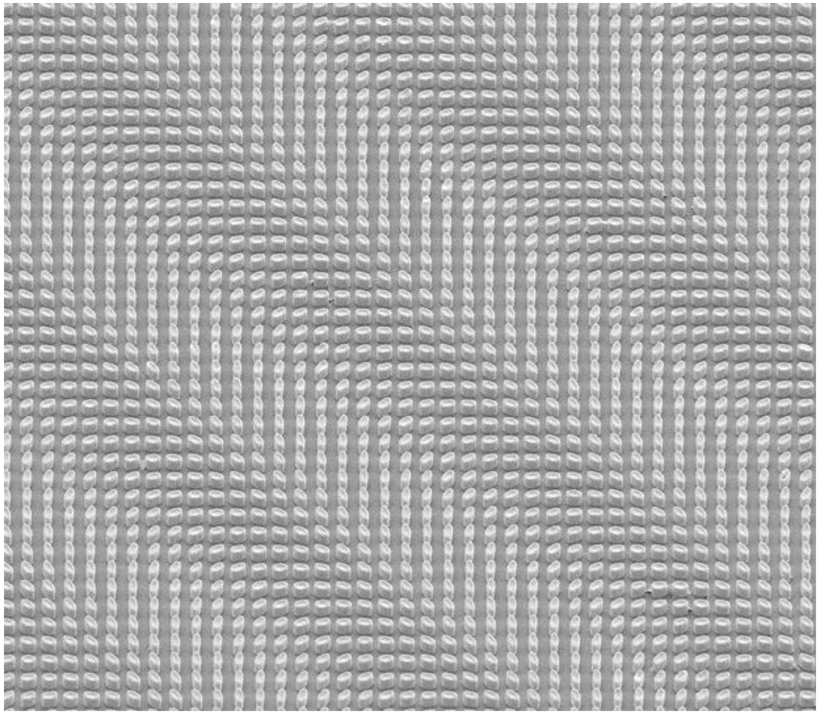
☐ Measurement:

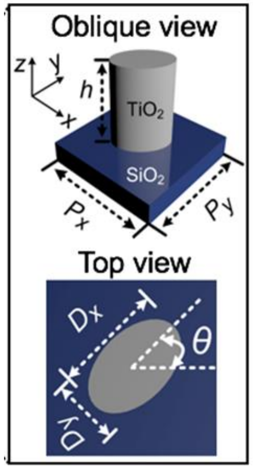
- Thickness by ellipsometer
- Optical constants by ellipsometer
- Imaging by SEM



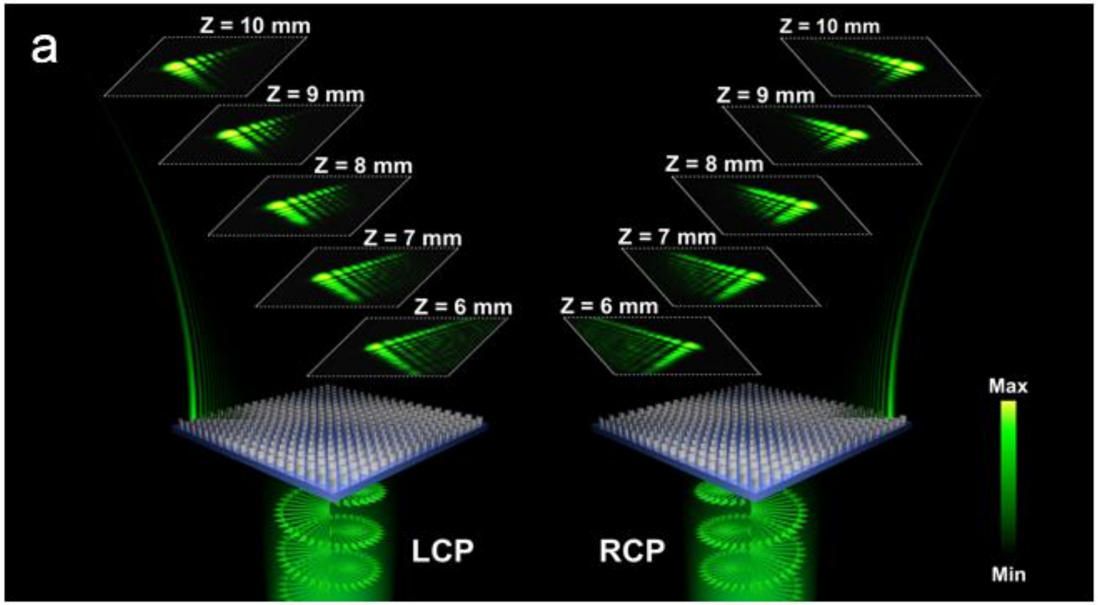
Fabricated TiO2 Metasurfaces



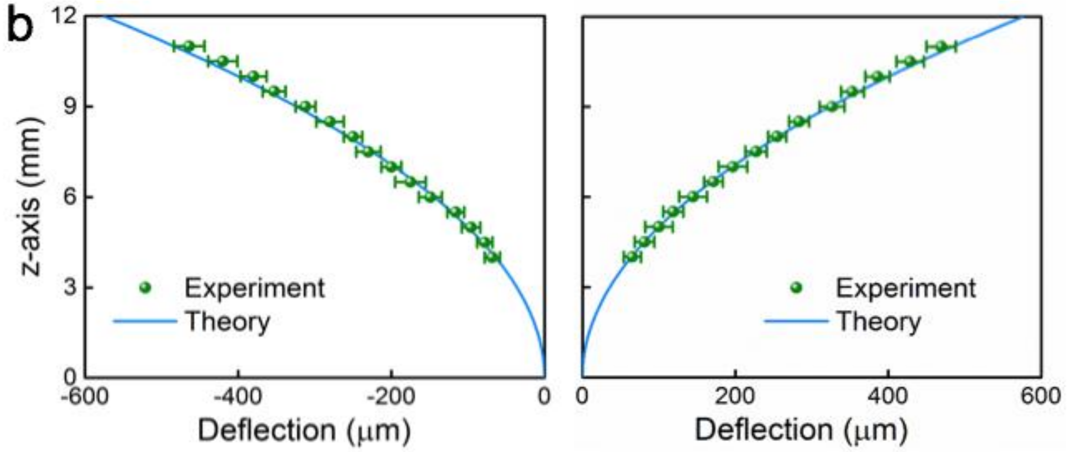




Example 1: spin-controlled propagation



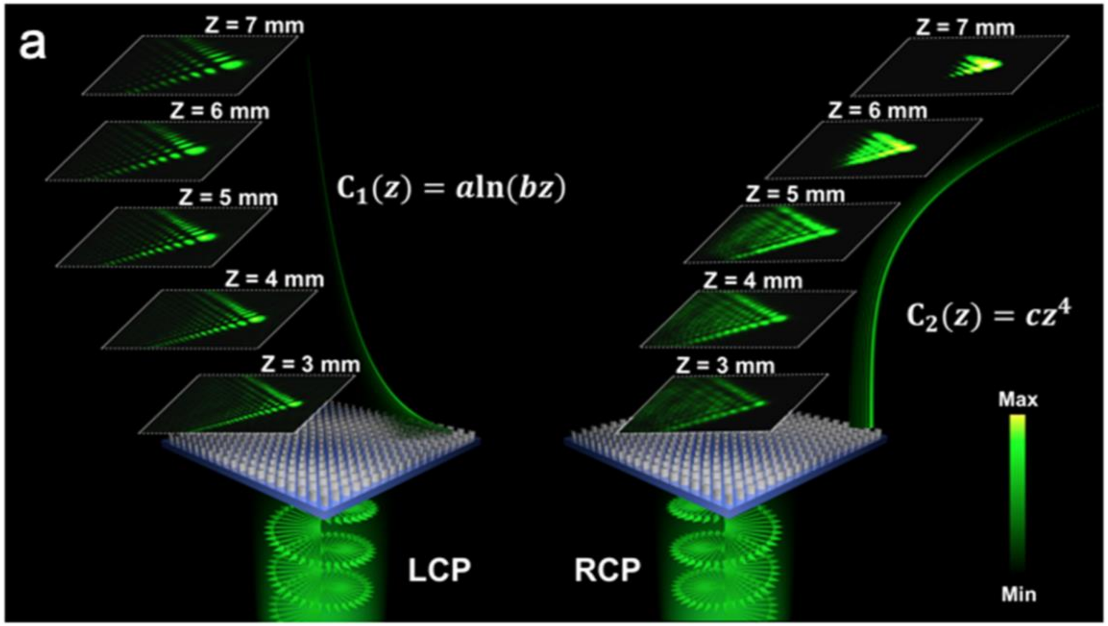
$$\begin{cases} x = nz^2 \\ y = nz^2 \end{cases} \qquad n = 4\ \mathrm{m}^{-1}$$



$$\varphi_1(x,y) = -\frac{4}{3} n^{\frac{1}{2}} k\left(x^{\frac{3}{2}} + y^{\frac{3}{2}}\right)$$

$$\varphi_2(x,y) = \varphi_1(w - x, w - y)$$

Example 2: spin-controlled beam switching



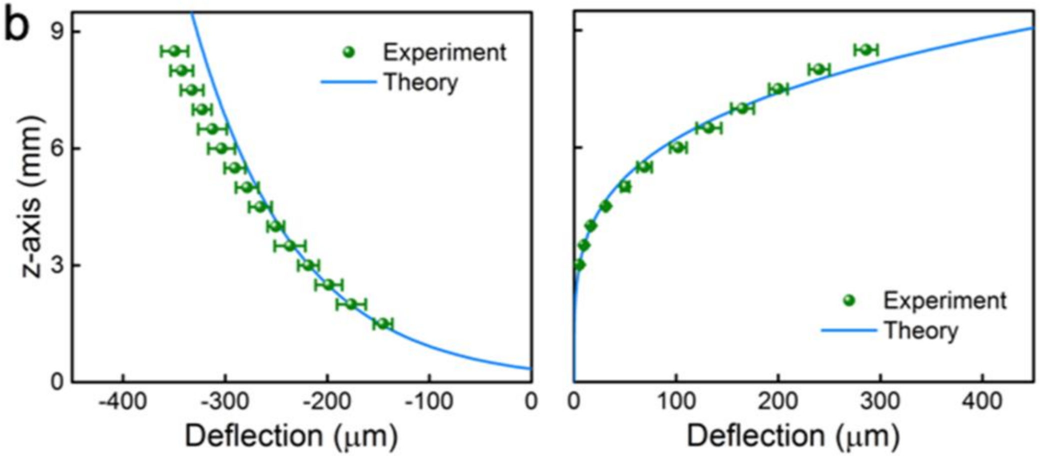
$$C_1: \begin{cases} x = a\ln(bz) \\ y = a\ln(bz) \end{cases}$$

$$C_2: \begin{cases} x = cz^4 \\ y = cz^4 \end{cases}$$

a = -10^{-4} m

b = 8×10^{3} m^{-1}

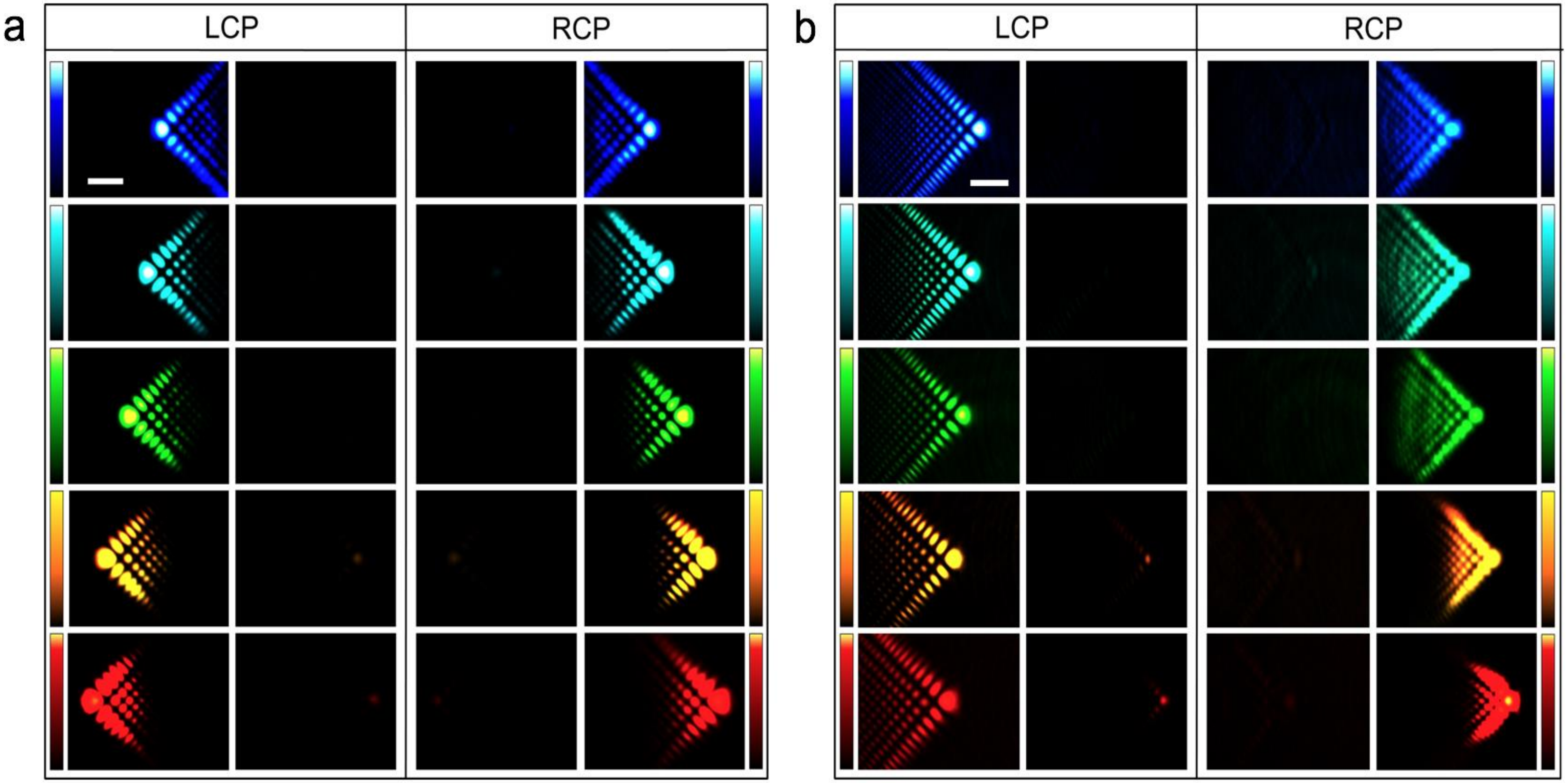
c = 6.7×10^{4} m^{-3}



$$\varphi_1(x,y) = e^{-1}a^2bk\left[2 - exp^{\left(-\frac{x}{a}\right)} - exp^{\left(-\frac{y}{a}\right)}\right]$$

$$\varphi_2(x,y) = -\frac{16}{21}(3c)^{\frac{1}{4}}k\left(x^{\frac{7}{4}}+y^{\frac{7}{4}}\right)$$

Example 3: broadband operation in the visible



Summary

- High efficiency and versatile generation of self-accelerating beams with a TiO_2-based all-dielectric metasurface.
- By changing the design of metasurface, broadband and spin controlled self-accelerating beams can be achieved.
- Successful device fabrication through a semiconductor process incorporating low-temperature ALD.

Further reading: Fan, et al., Broadband generation of photonic spin-controlled arbitrary accelerating light beams in the visible, *Nano Letters*, 2019