Structured light manipulation in strongly anisotropic metamaterials

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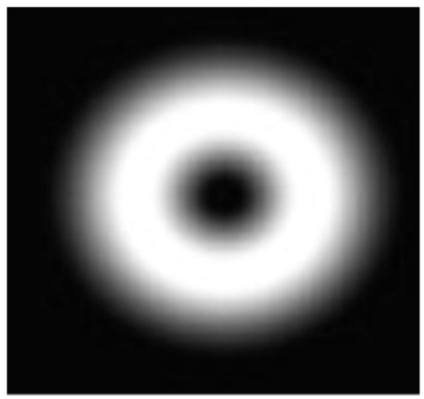
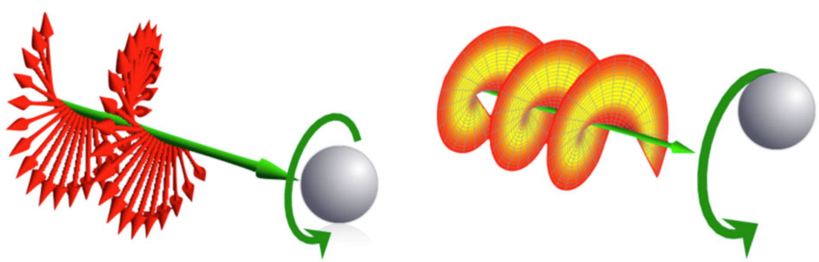
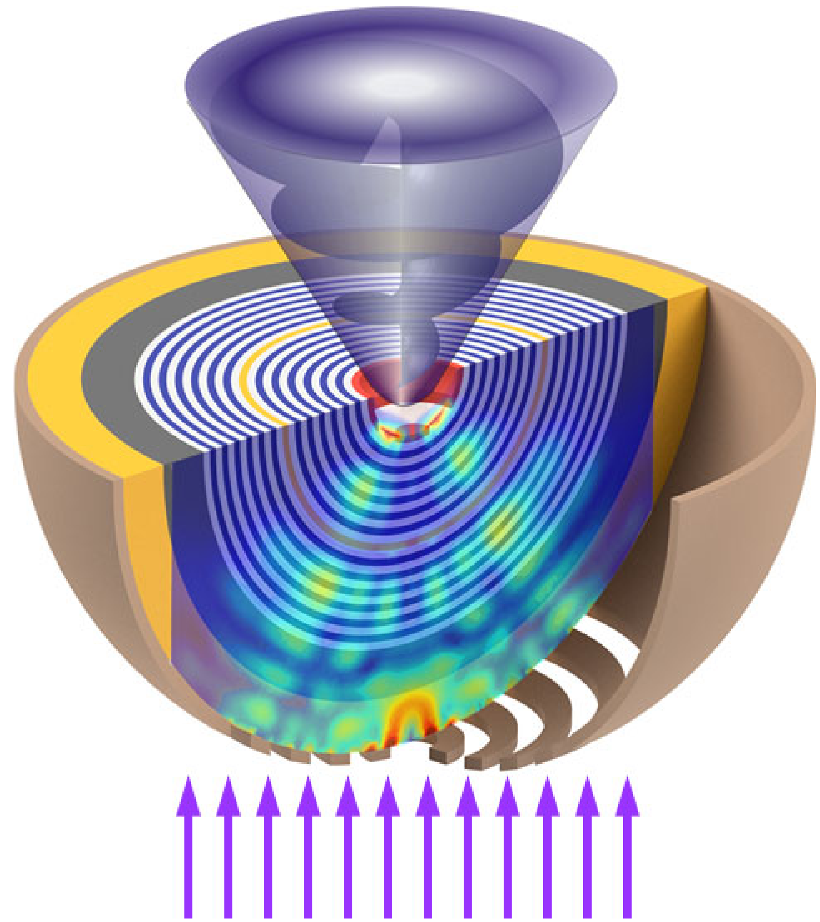
Duke University

Introduction





SAM OAM



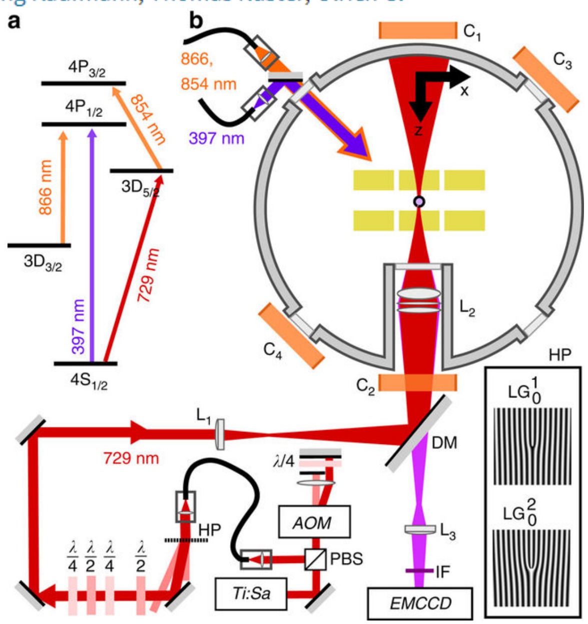
Hyperlens

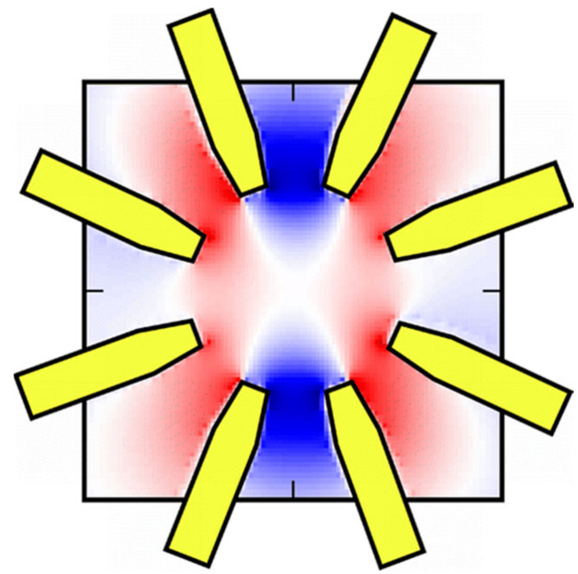
SAM – spin angular momentum
OAM – orbital angular momentum

Transfer of optical orbital angular momentum to a bound electron

Christian T. Schmiegelow, Jonas Schulz, Henning Kaufmann, Thomas Ruster, Ulrich G. Poschinger & Ferdinand Schmidt-Kaler

Nature Communications **7**,
Article number: 12998 (2016)
doi:10.1038/ncomms12998





Subwavelength Focusing of Light with Orbital Angular Momentum

Reinier W. Heeres* and Valery Zwiller
Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

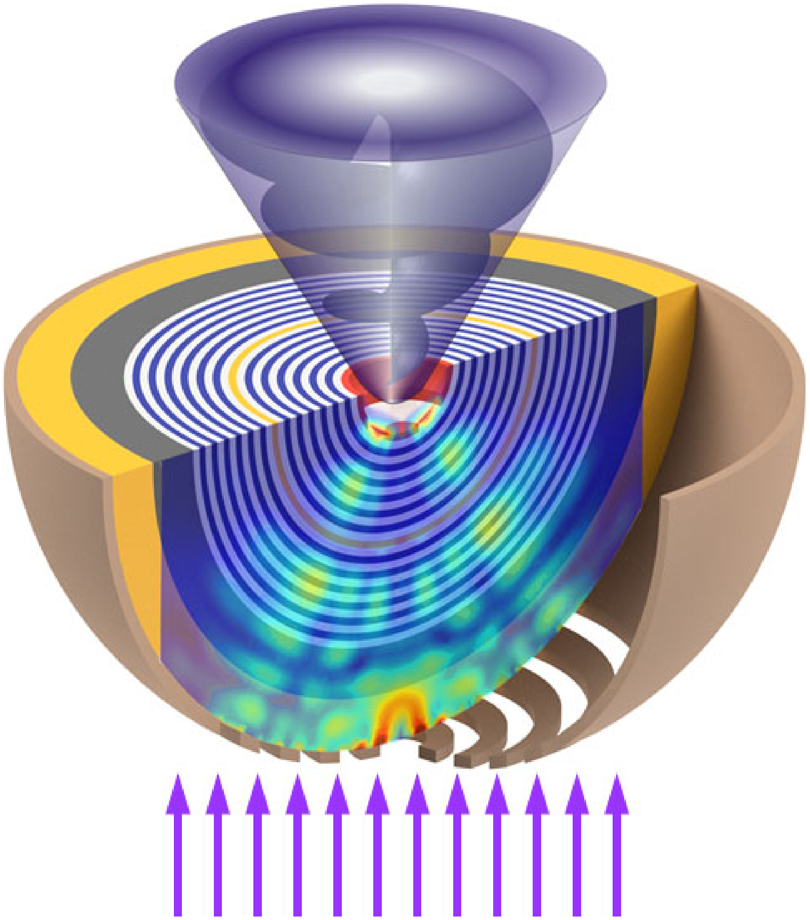
Nano Lett., **2014**, *14* (8), pp 4598–4601

Introduction

The spatial structure of light with OAM closely resembles the shape of atomic wave functions. It could therefore make symmetry-forbidden transitions possible in quantum dots, or “artificial atoms” [Eur. Phys. J. D 66, 157–165 (2012)]

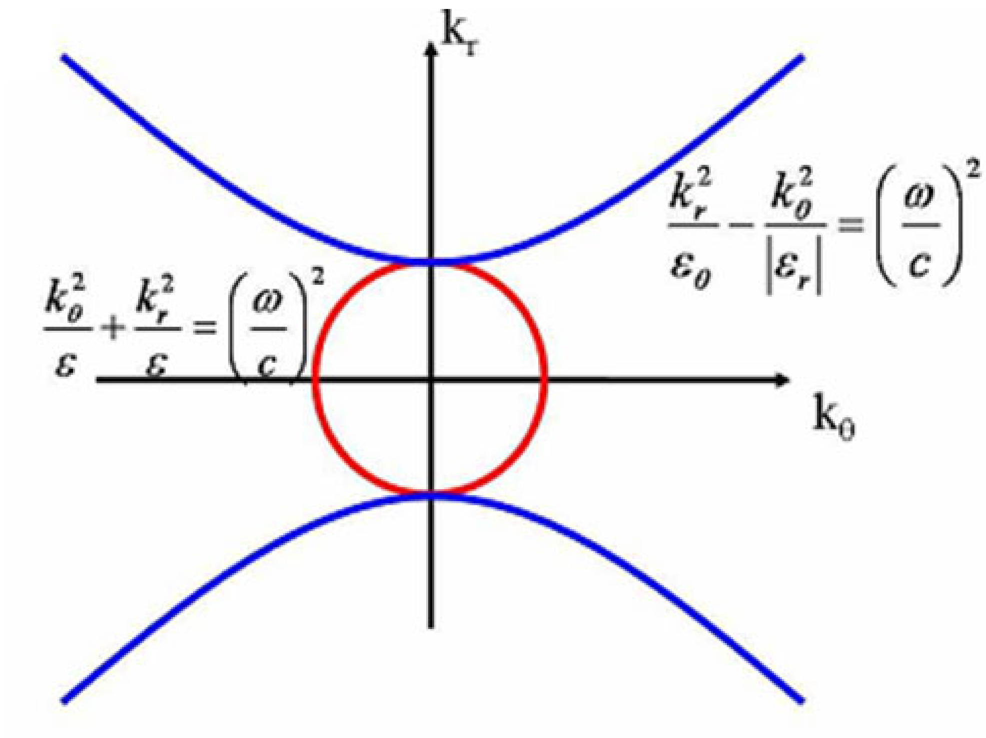
However, the symmetry of the transition probability integral can be modified by choosing the spatial properties of the driving field, making symmetry-forbidden transitions possible.

Yet, the vanishing intensity in the center of an OAM beam usually makes this effect weak.



In order to strengthen the interaction an OAM beam size has to be reduced to subwavelength dimensions.

Hyperbolic metamaterials (HMMs)

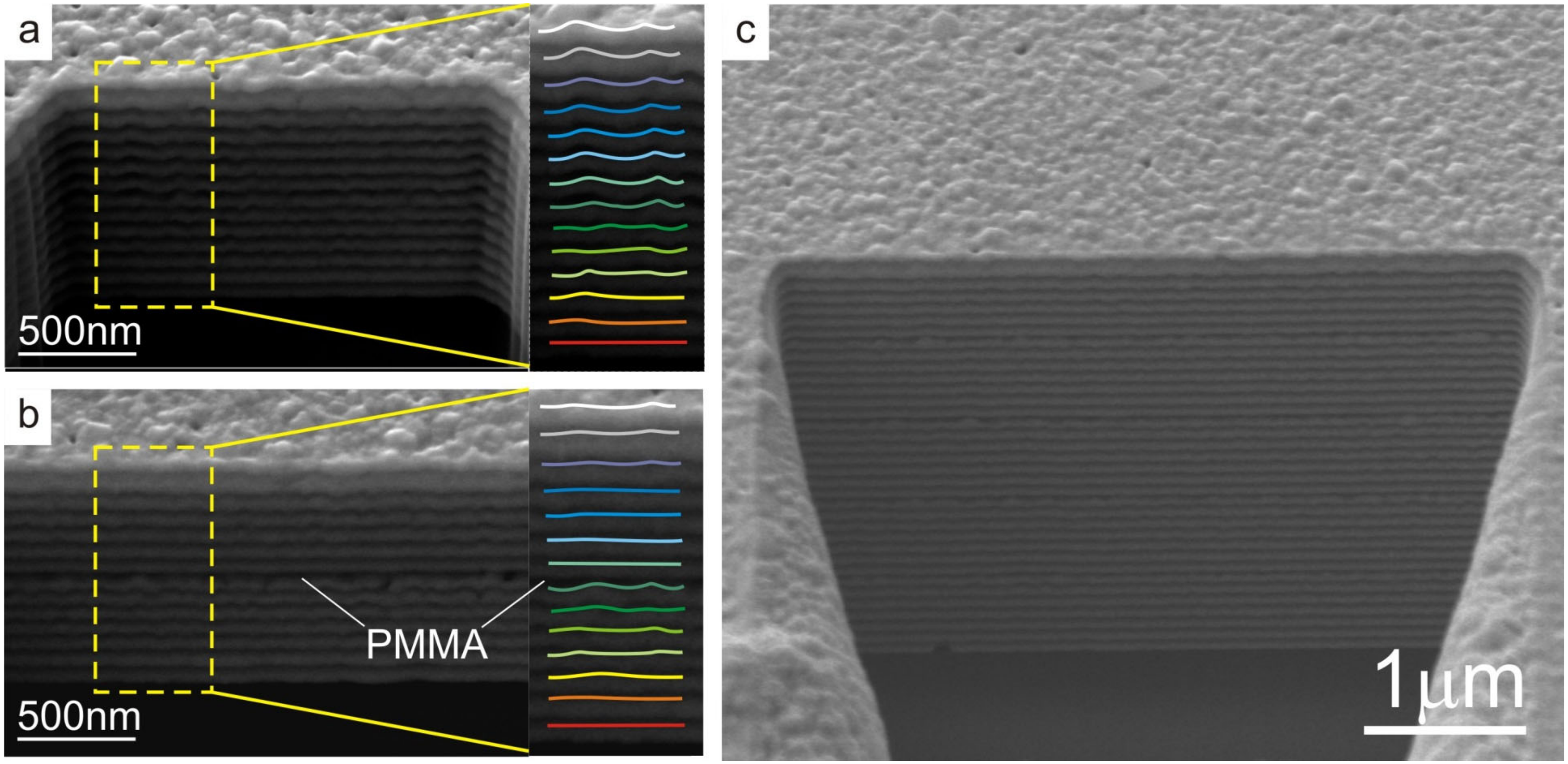


$$\tilde{\varepsilon} = \begin{bmatrix} \varepsilon_r & 0 \\ 0 & \varepsilon_\theta \end{bmatrix}$$

$$\varepsilon_r < 0, \quad \varepsilon_\theta > 0$$

- The most important property of HMMs is related to the behavior of waves with large magnitude wavevectors.
- In vacuum, such large wavevector waves are evanescent and decay exponentially.
- In HMMs waves with infinitely large wavevectors are allowed to propagate.

Deposition of thick hyperbolic MMs



(a) 27 layers Ag/Ti_3O_5 with no intermediate PMMA layer;
(b) Two-step deposition of 26 layers Ag/Ti_3O_5 with a PMMA layer separating two 13-layered structures;
(c) Five-step deposition of 65 layers of Ag/Ti_3O_5 with 4 intermediate PMMA layers separating every 13 layers.

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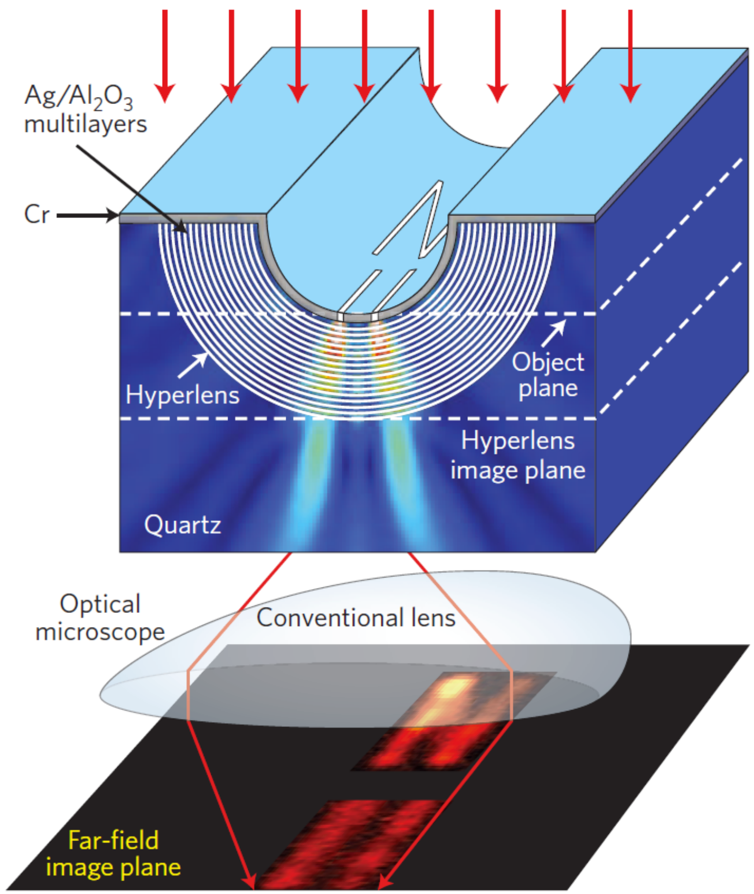
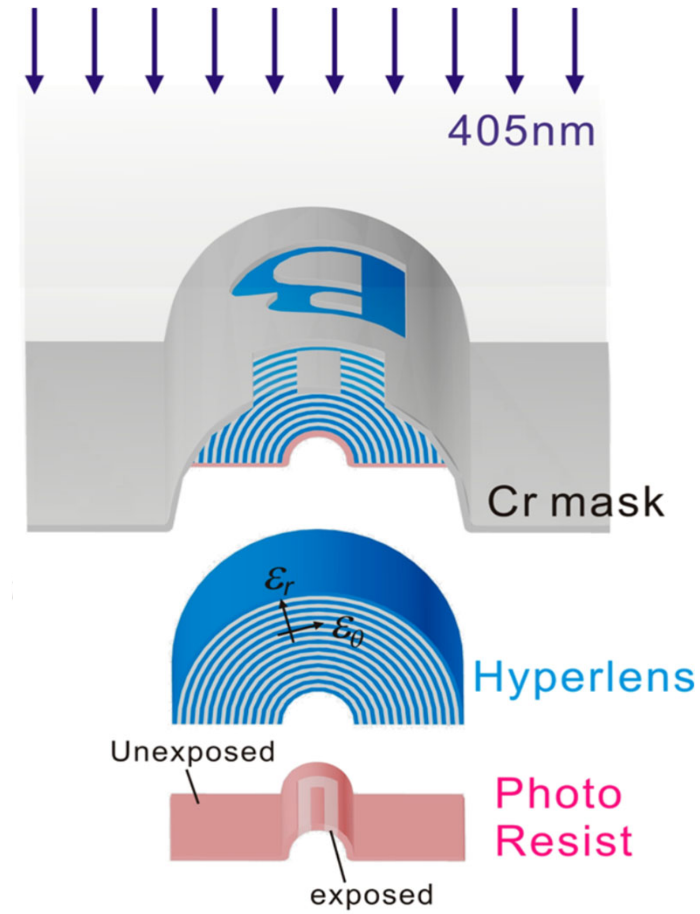
Magnifying and de-magnifying hyperlens

SPIE.

Magnifying hyperlens



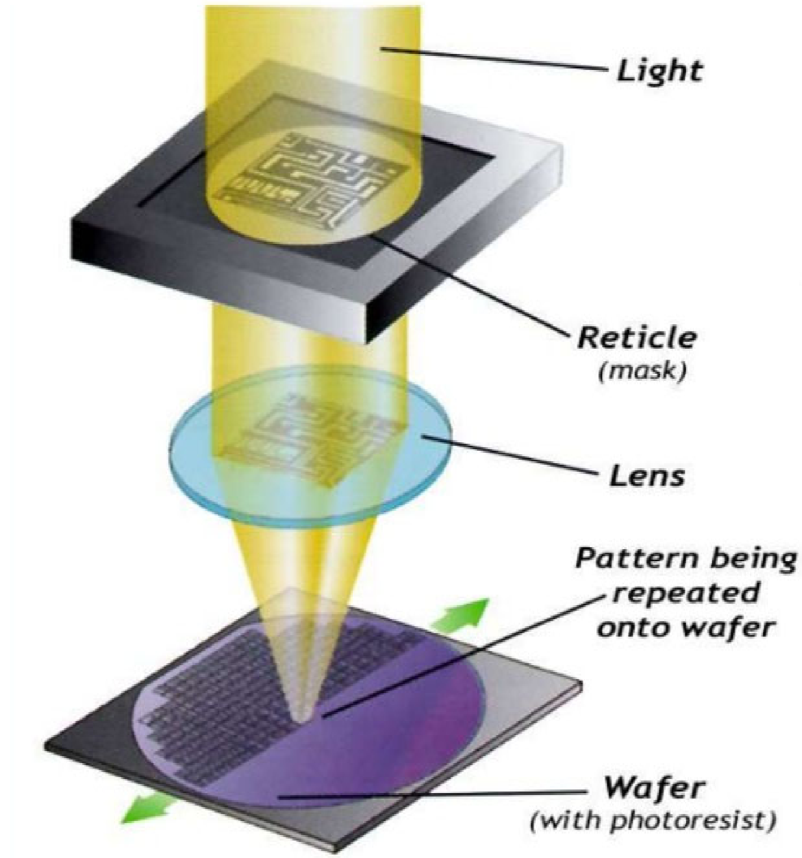
De-magnifying hyperlens



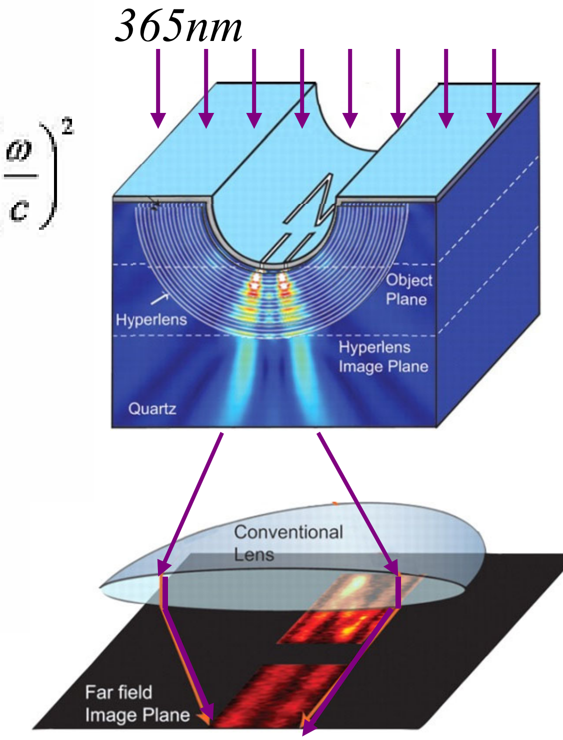
Hyperlens

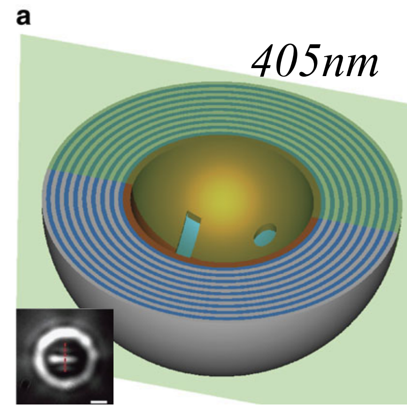
A promising way to sub-wavelength imaging

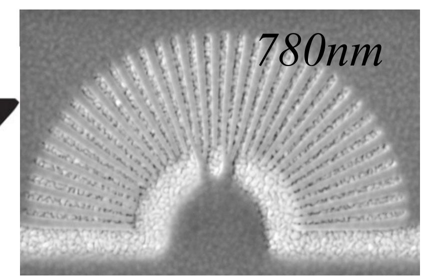
Hyperbolic metamaterial can support the transmission of the evanescent wave



$=\left(\frac{\omega}{c}\right)^2$

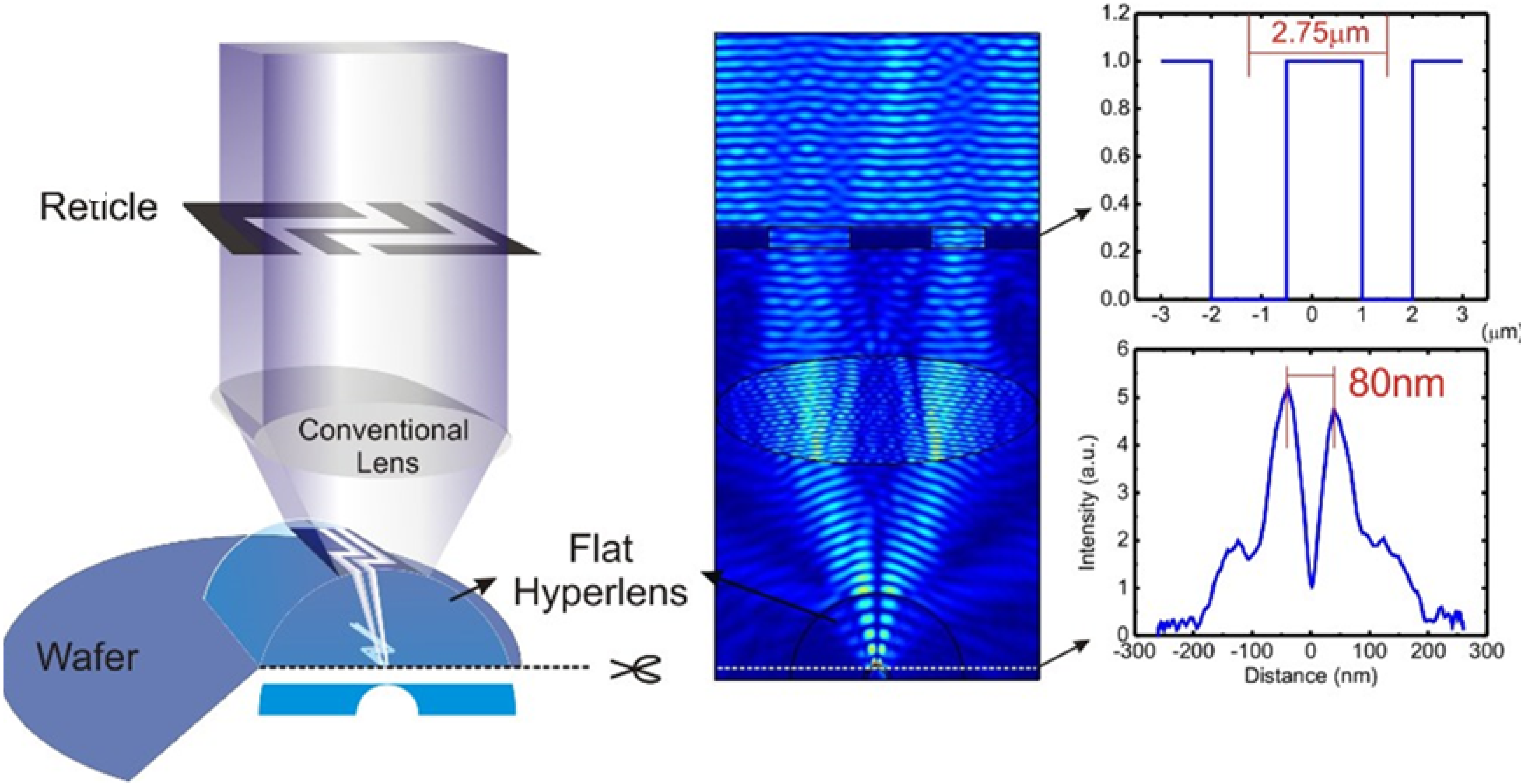






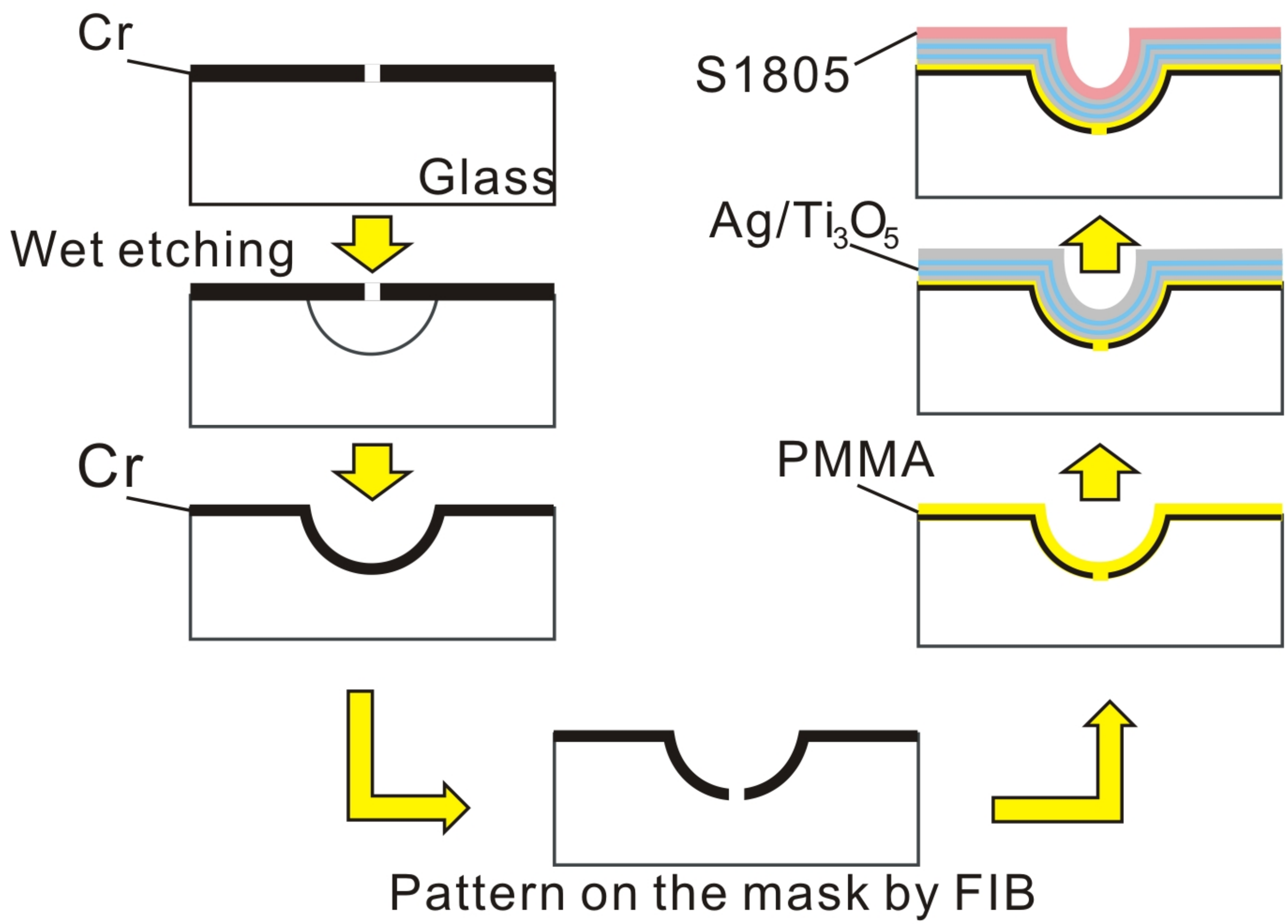
Jacob, Alekseyev,Narimanov, Opt. Exp. **14**, 8247–8256 (2006).
Salandrino, Engheta Phys. Rev. B **74**, 075103 (2006).
Liu, Z. et al. Science **315**, 1686 (2007).
Y. Xiong, et al., Appl. Phys. Lett. **94**, 203108 (2009).
Rho, J. et al. Nat. Commun. **1**, 143 (2010).
Y. Xiong, et al., Appl. Phys. Lett. **93**, 111116 (2008).
J. Sun, et al. Nat. Commun. **7**, 12018 (2015).
W. Wan, et al., Opt. Express **23**, 18501-18510 (2015).

Hyperlens photolithography



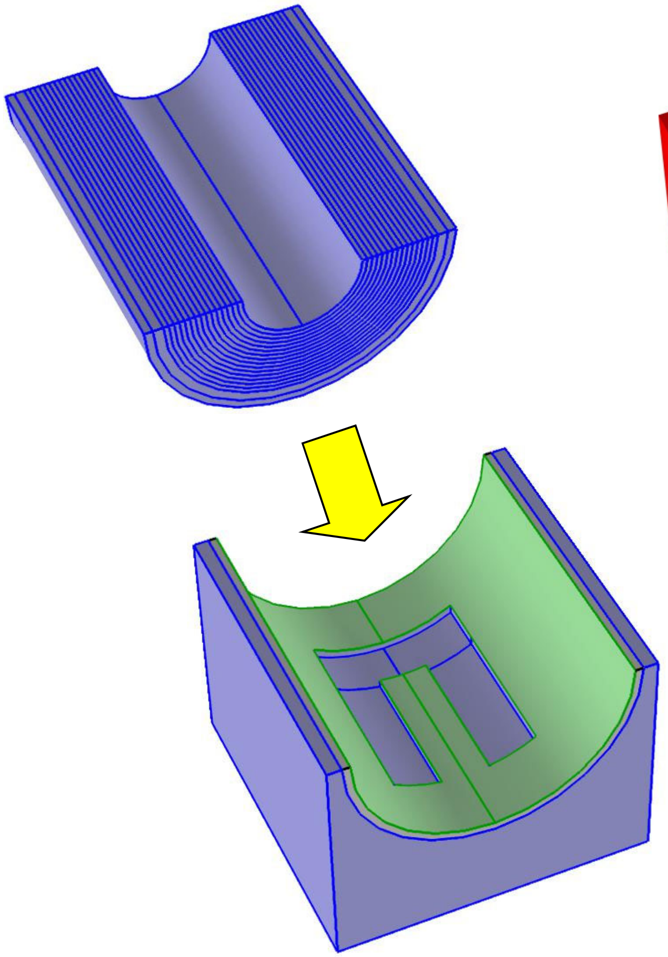
J. Sun, NML, Nano Lett. 2016
J. Sun, NML, ACS Nano. 2018
J. Sun, NML, J. Opt. 2018

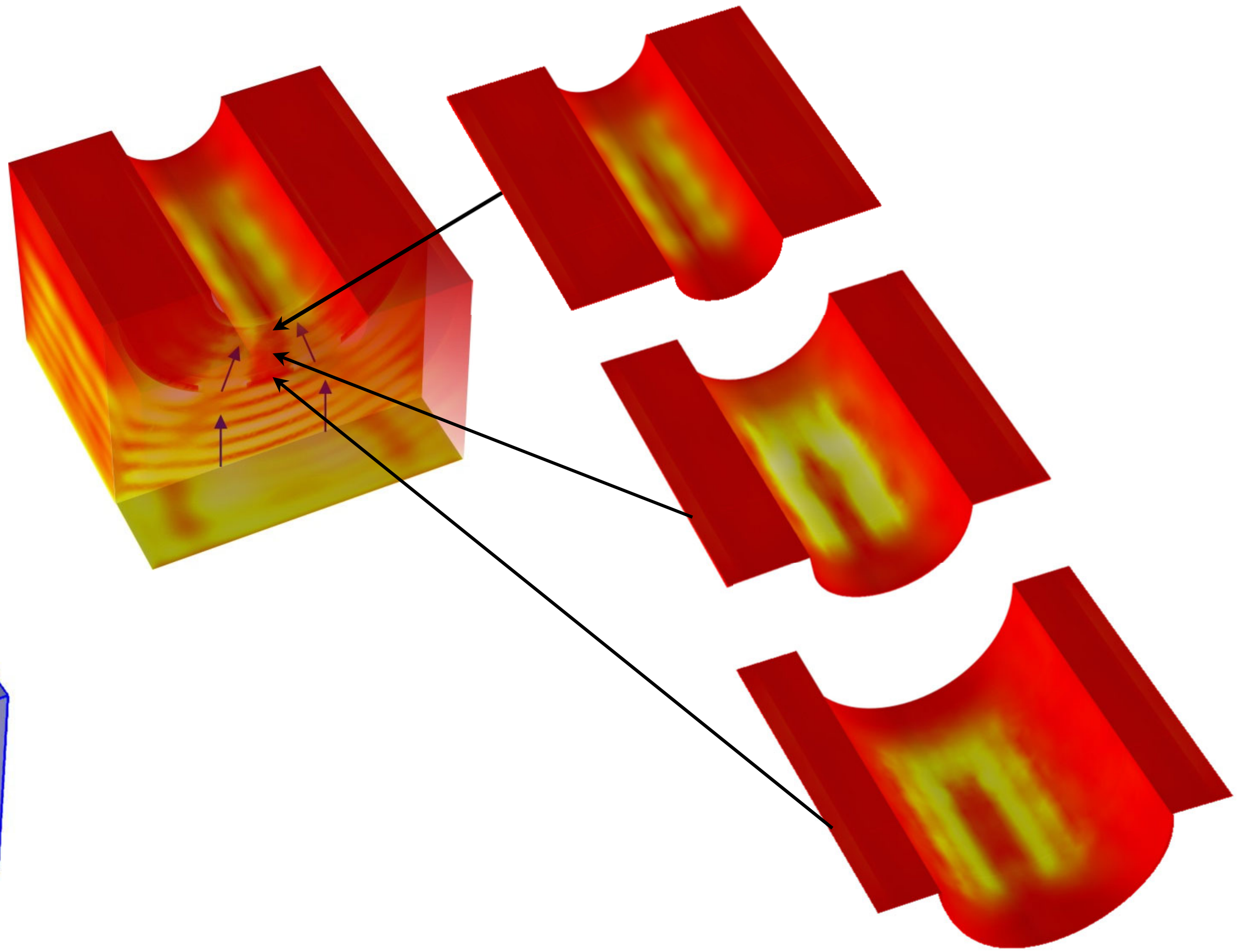
Fabrication



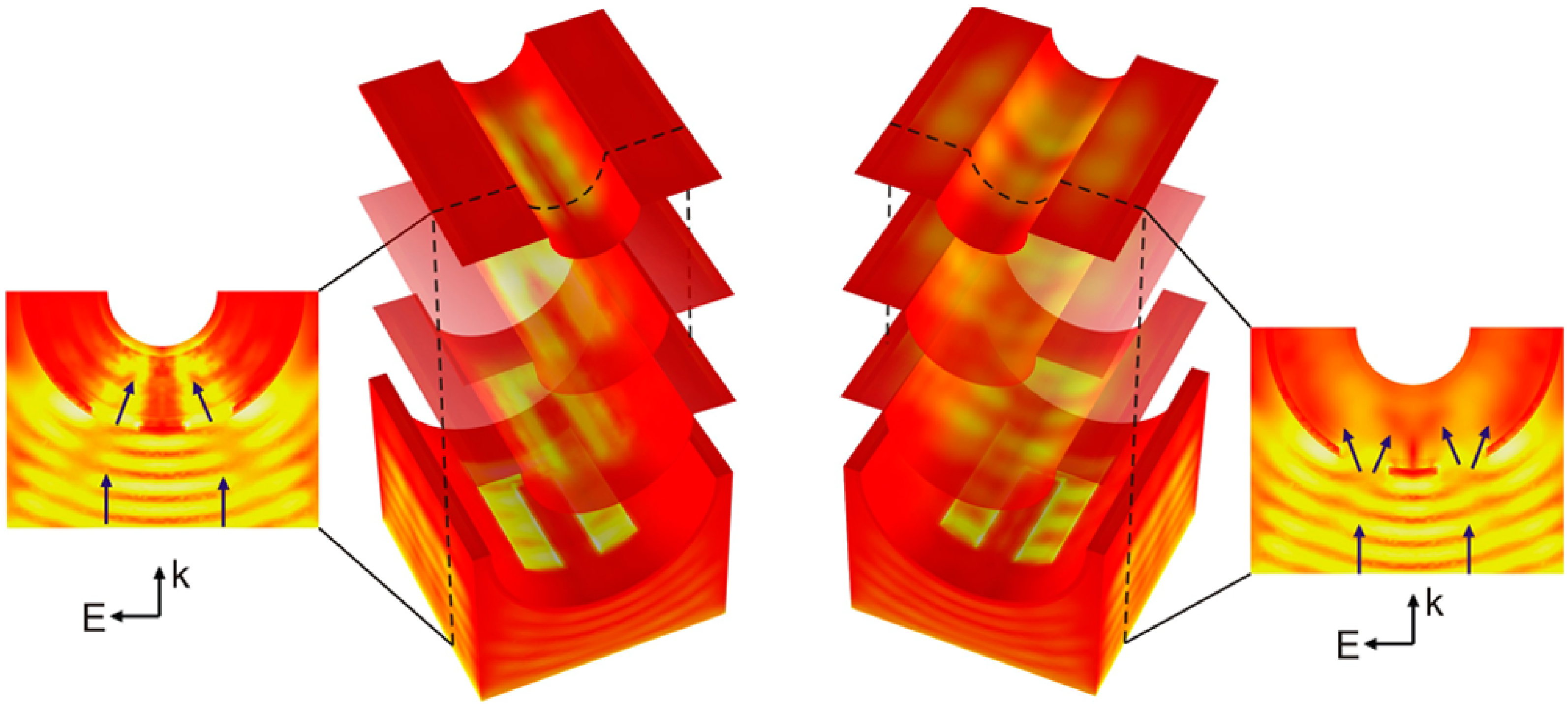
Design

Simulations of the wave propagation in a hyperlens - de-magnification

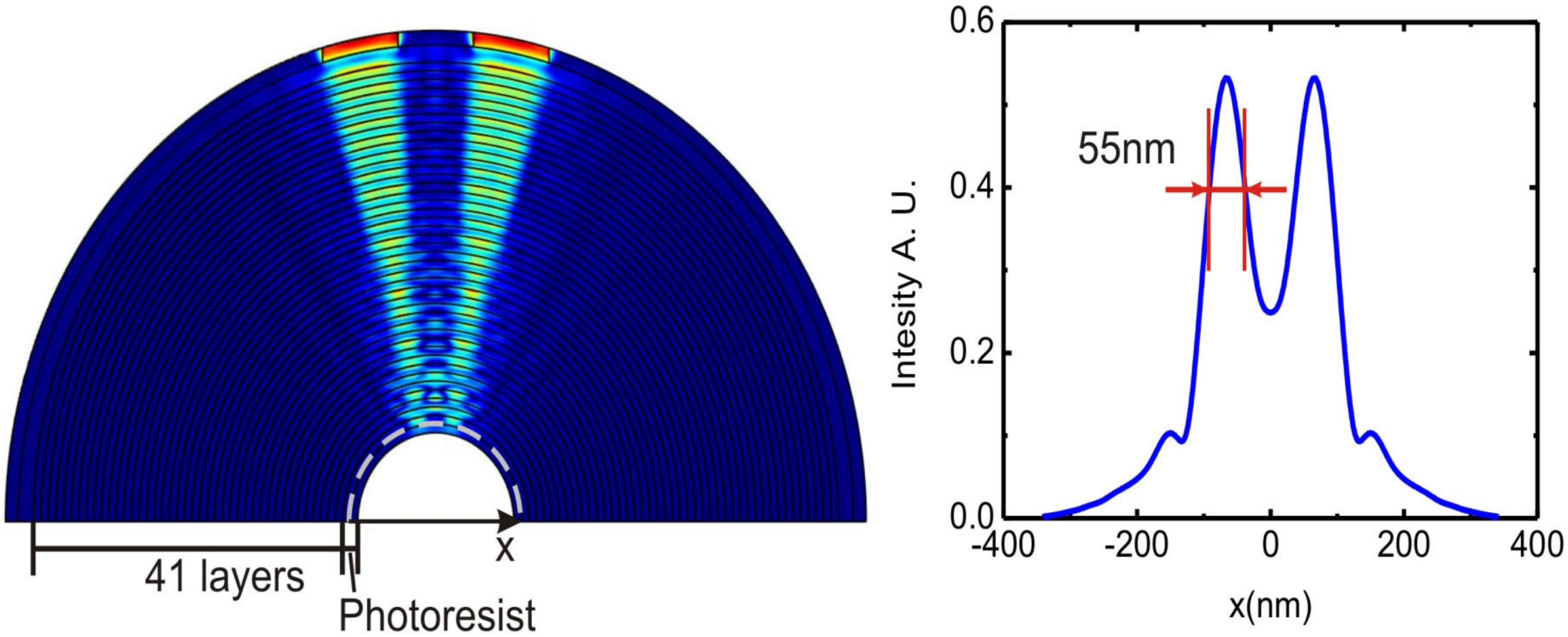




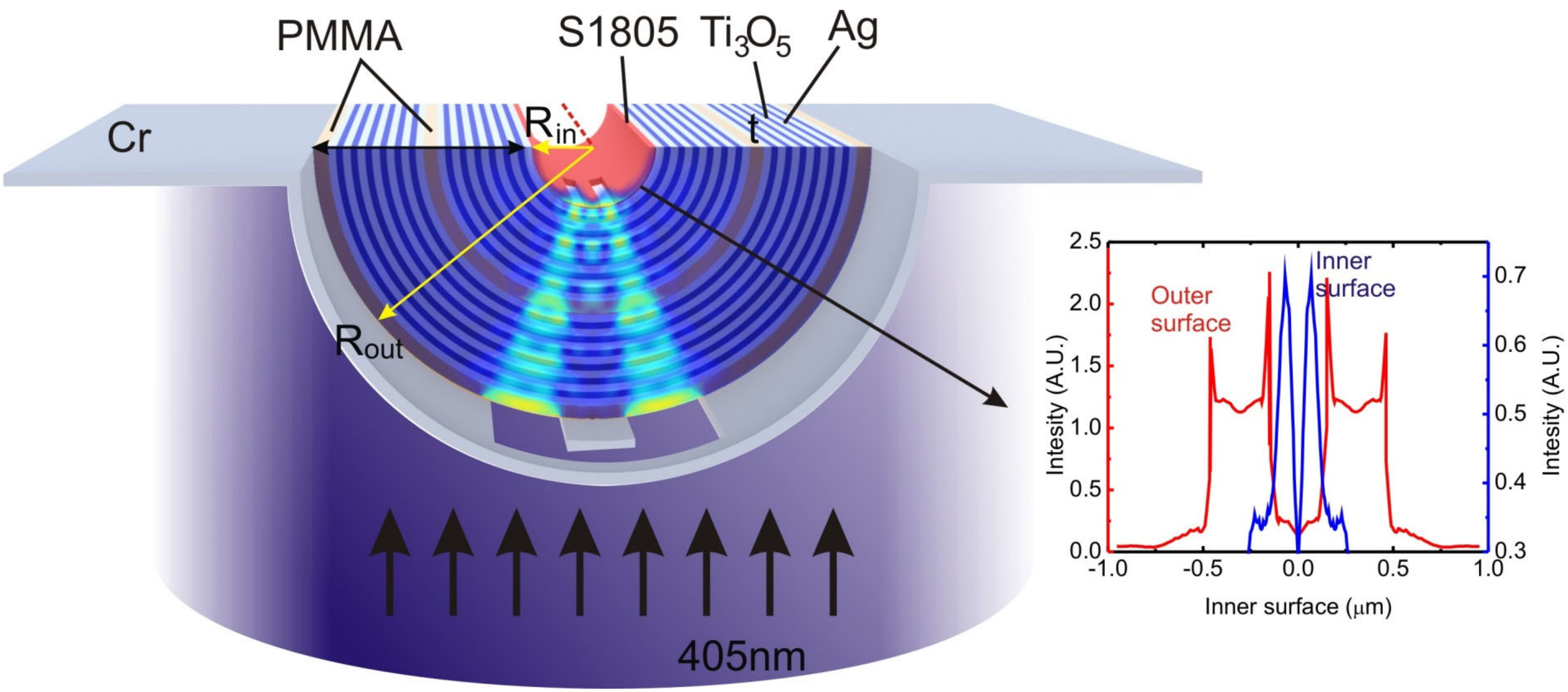
Hyperlens vs Reference Sample



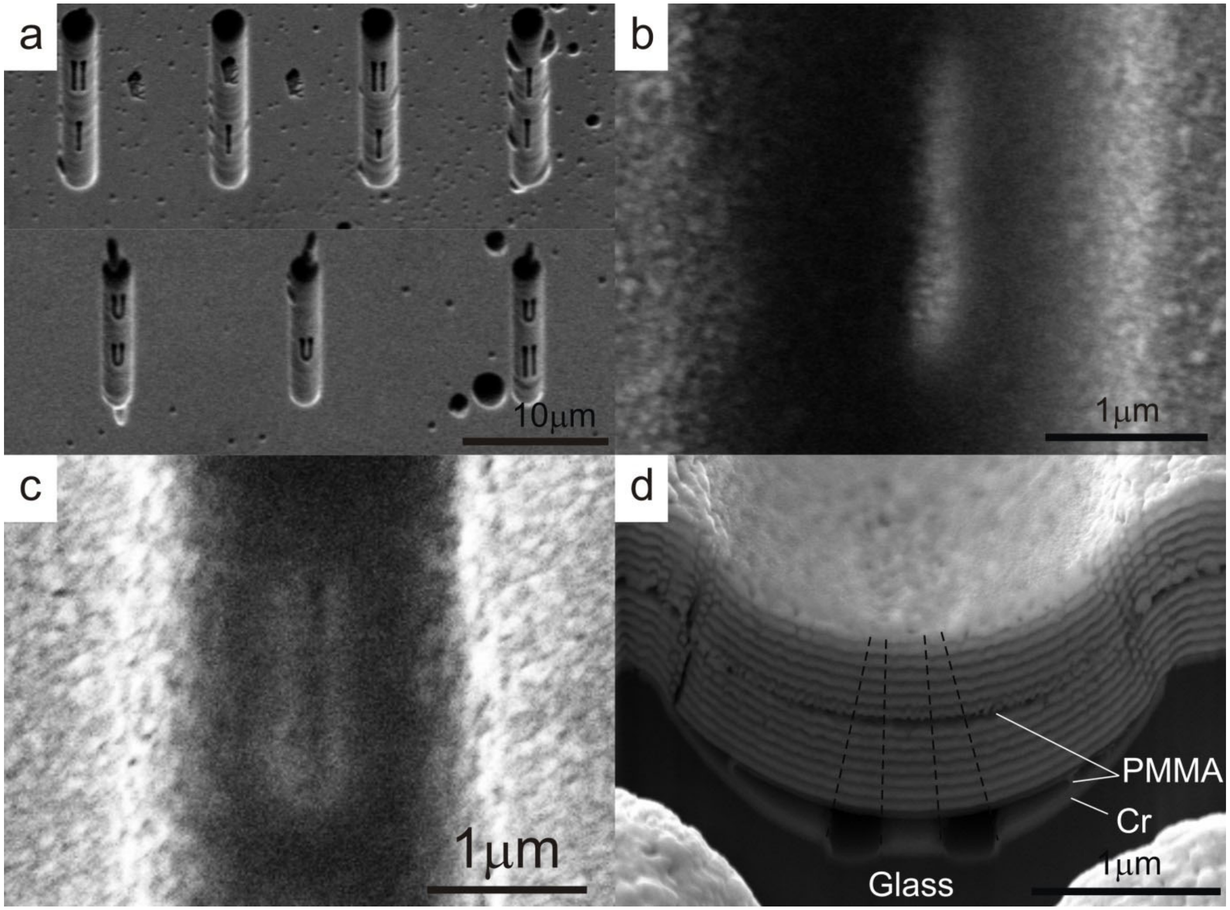
Numerical optimization: thicker hyperlens



“Cascaded” hyperbolic metamaterials



De-magnification using “cascaded” HL



Smallest feature size is 80 nm, corresponding to 3.75 de-magnification

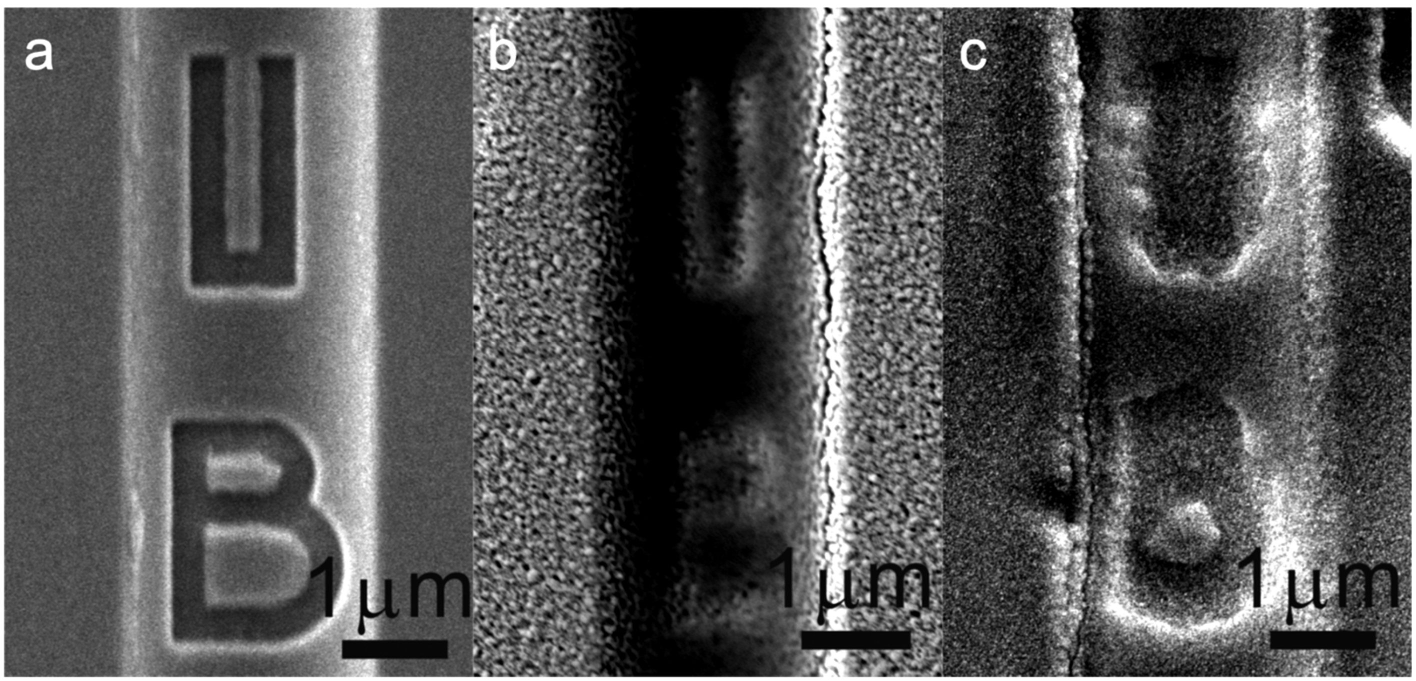
Hyperlens vs Reference Sample

An experimentally realized de-magnifying hyperlens consisted of 13 layers of alternating layers of Ag and Ti_3O_5. The permittivities of the Ti_3O_5 and Ag at 405nm are 5.85 and $-4.84+0.22i$, respectively.

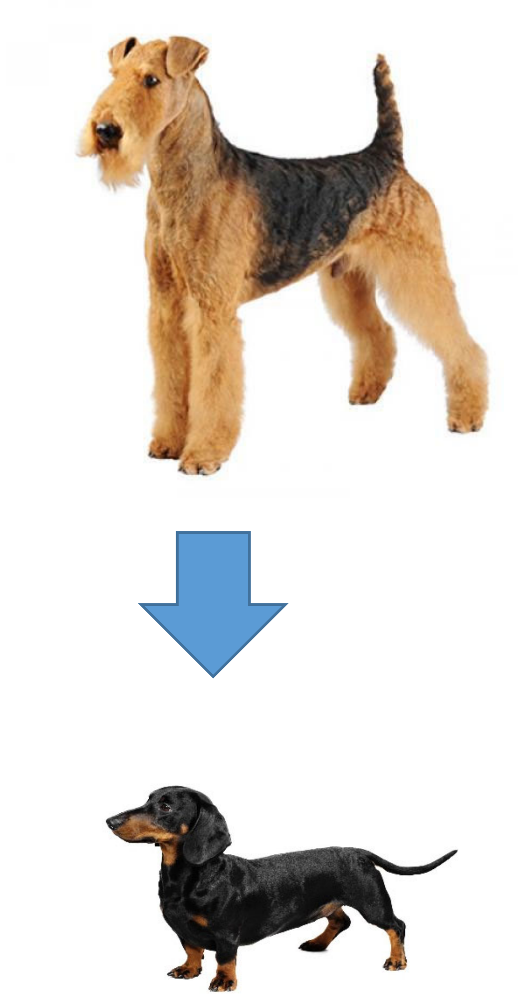
$$\varepsilon_\theta = \varepsilon_d f + \varepsilon_m (1-f) = 0.51+0.11i$$

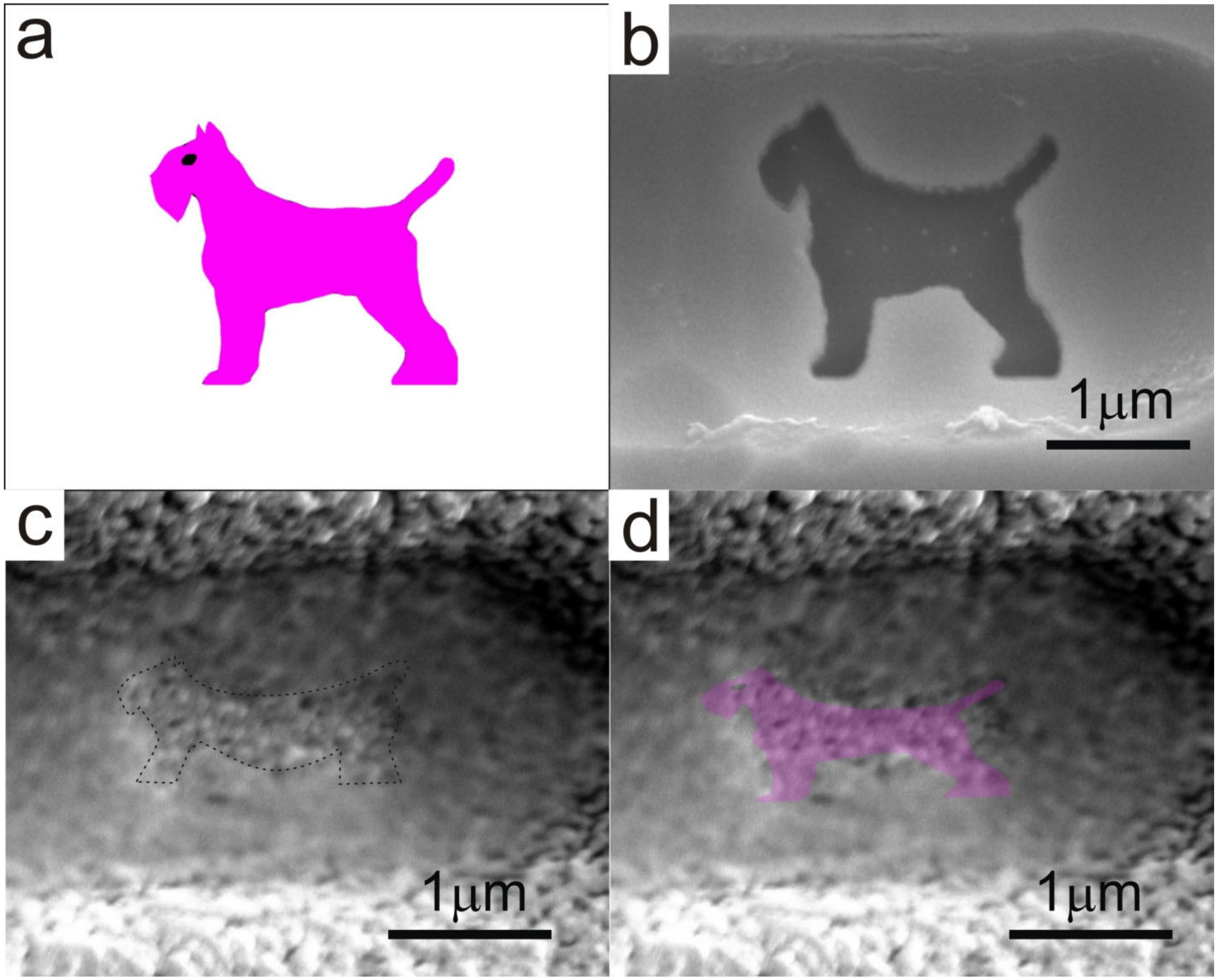
$$\varepsilon_r = \frac{\varepsilon_d \varepsilon_m}{\varepsilon_m f + \varepsilon_d (1-f)} = -53+14.1i$$

Original Pattern With hyperlens Reference (MgF_2) sample



Complex patterns





SAM → OAM → SAM conversion

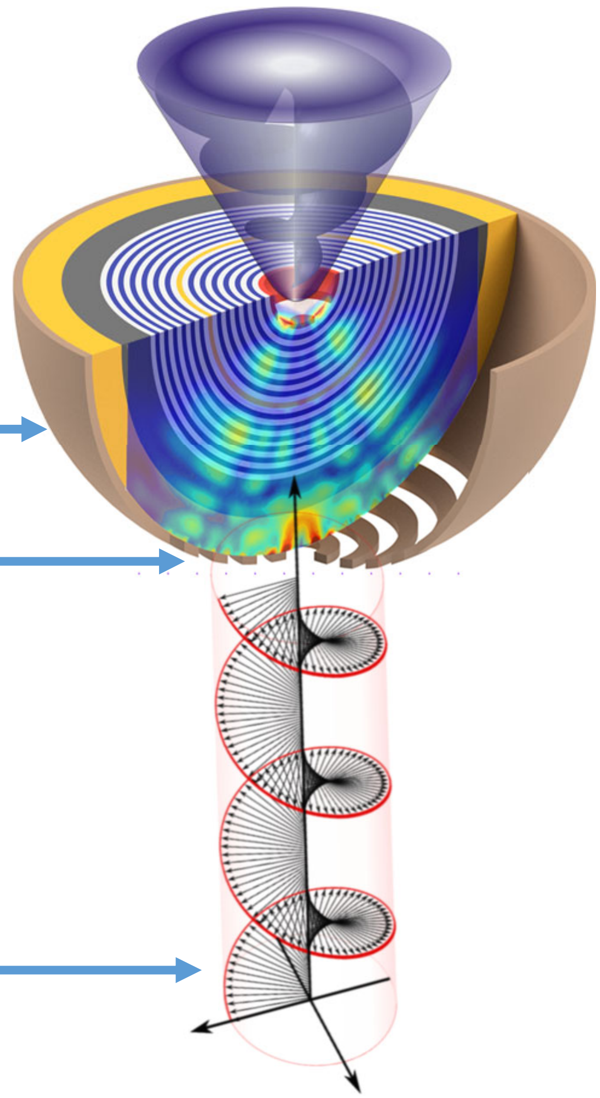
Demagnifying hyperlens

→ Focusing below diffraction limit
OAM-to-SAM conversion

SAM-to-OAM converter

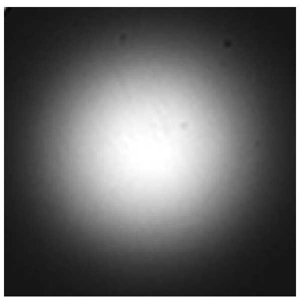
→ Radially polarized OAM beam
with topological charge 1

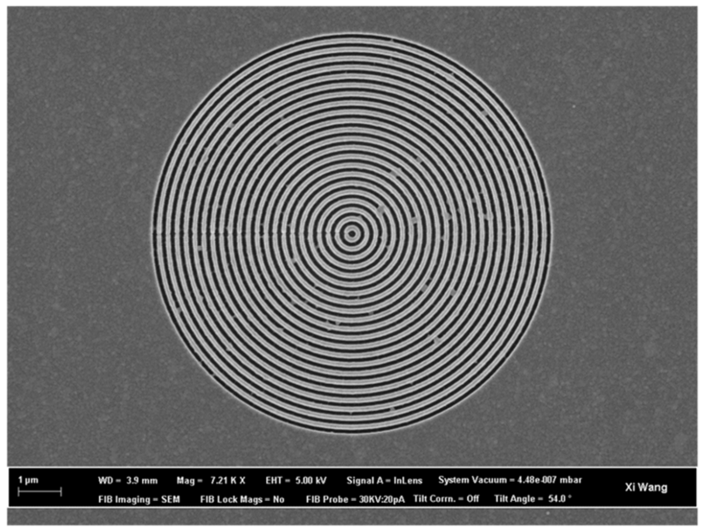
Circularly polarized Gaussian beam

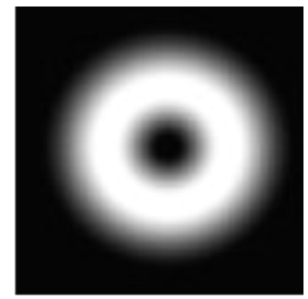


Concentric ring SAM-OAM converter

The circular polarization can be decomposed into the combination of radial polarization and azimuthal polarization components with a spiral phase wavefront. Concentric subwavelength metal grating reflects most of azimuthal polarization components while allow radial polarization vortex to pass through.

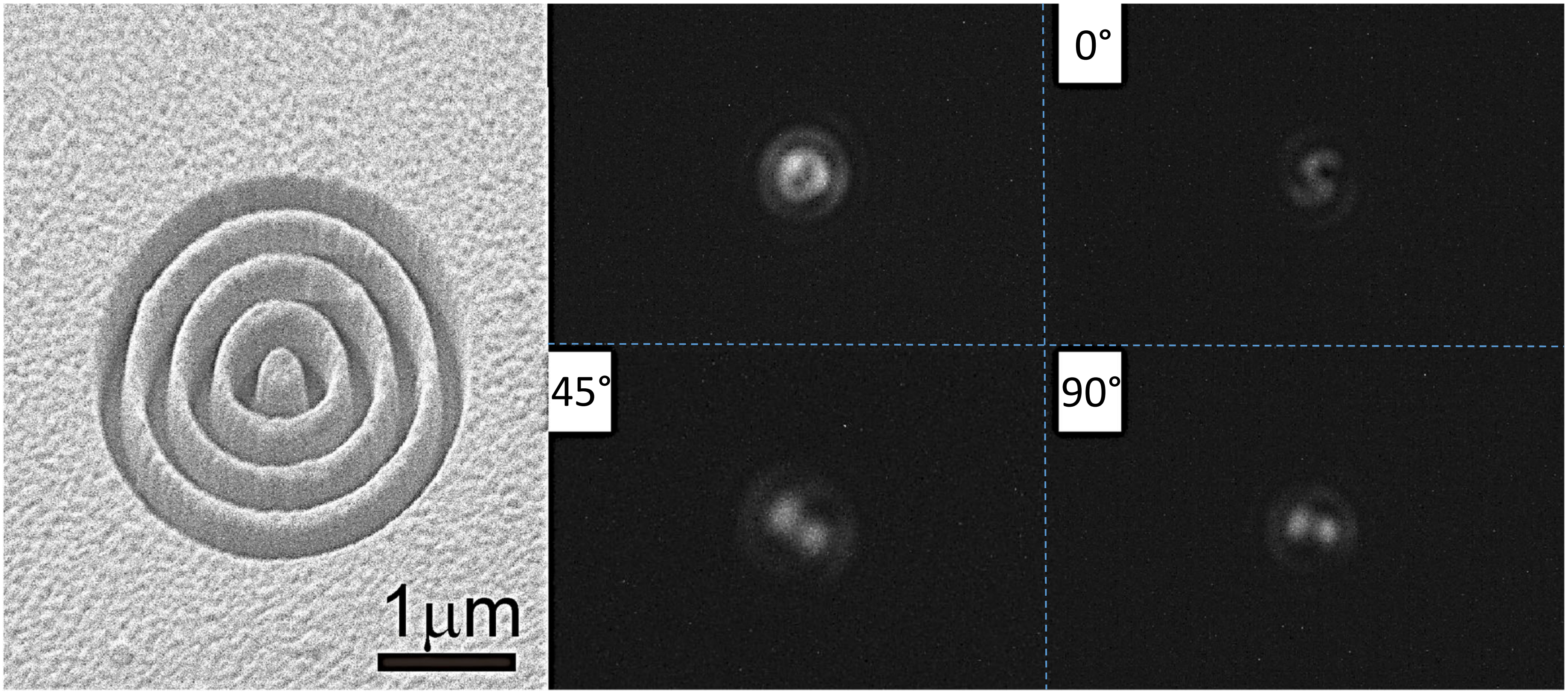




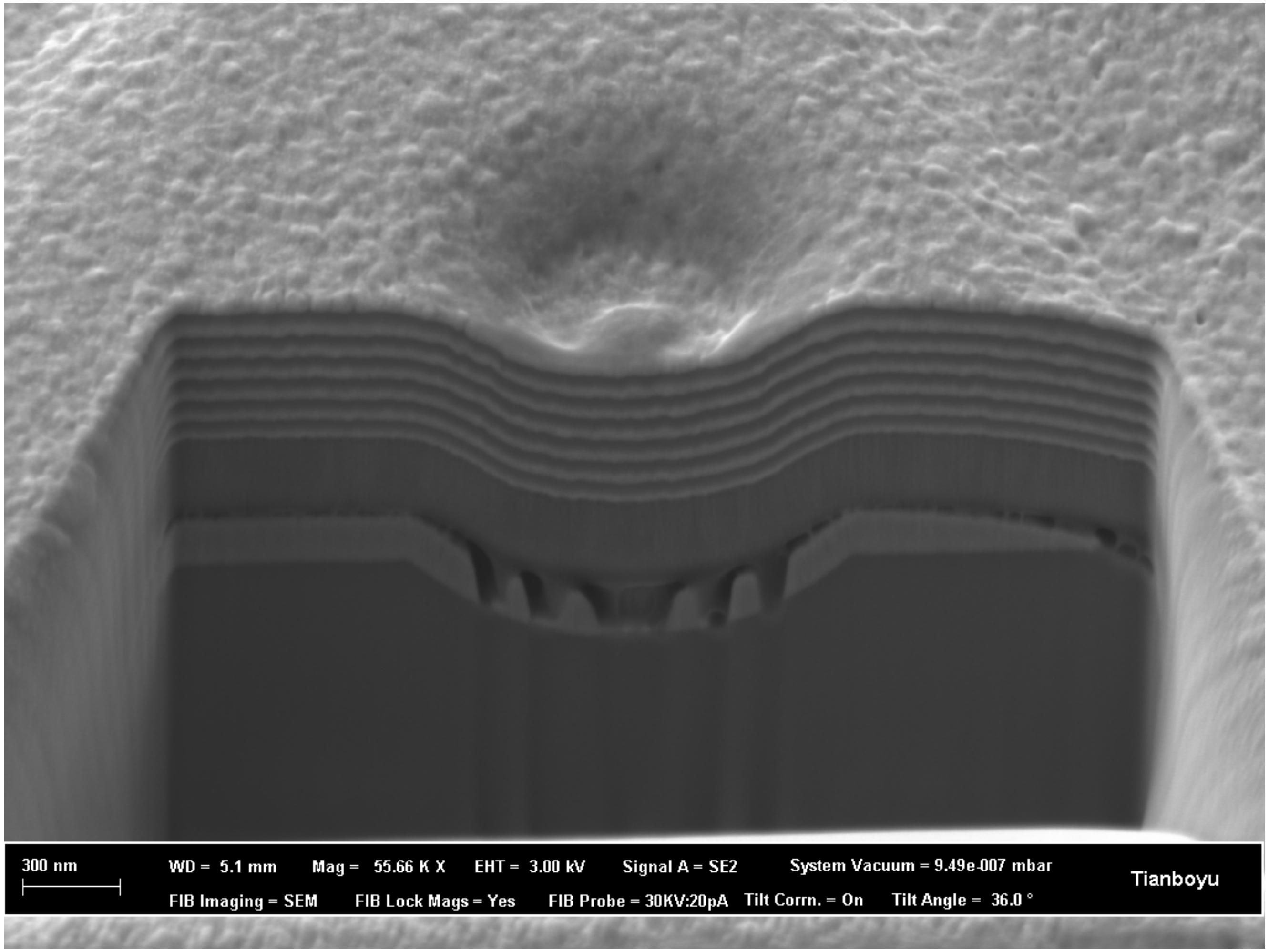


$$
\begin{aligned}
\overline{E}_{in} &= \overline{e}_x + j\overline{e}_y \\
&= (\cos\phi\,\overline{e}_r - \sin\phi\,\overline{e}_\phi) + j(\sin\phi\,\overline{e}_r + \cos\phi\,\overline{e}_\phi) \\
&= \overline{e}_r(\cos\phi + j\sin\phi) + j\overline{e}_\phi(\cos\phi + j\sin\phi) \\
&= e^{i\phi}(\overline{e}_r + j\overline{e}_\phi)
\end{aligned}
$$

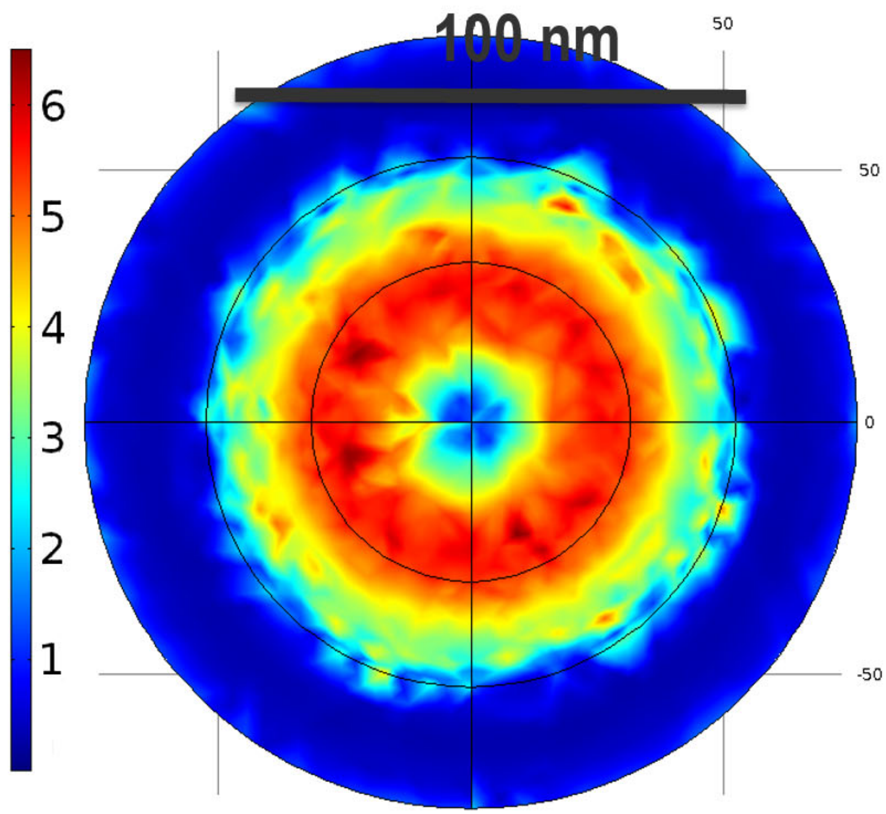
Concentric ring SAM-OAM converter

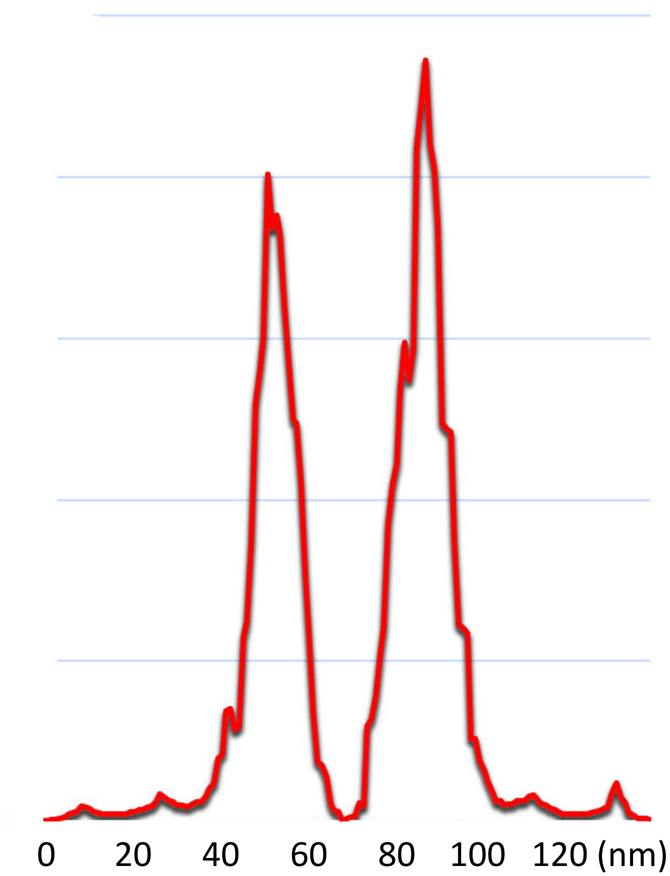


Hyperlens with SAM-OAM converter

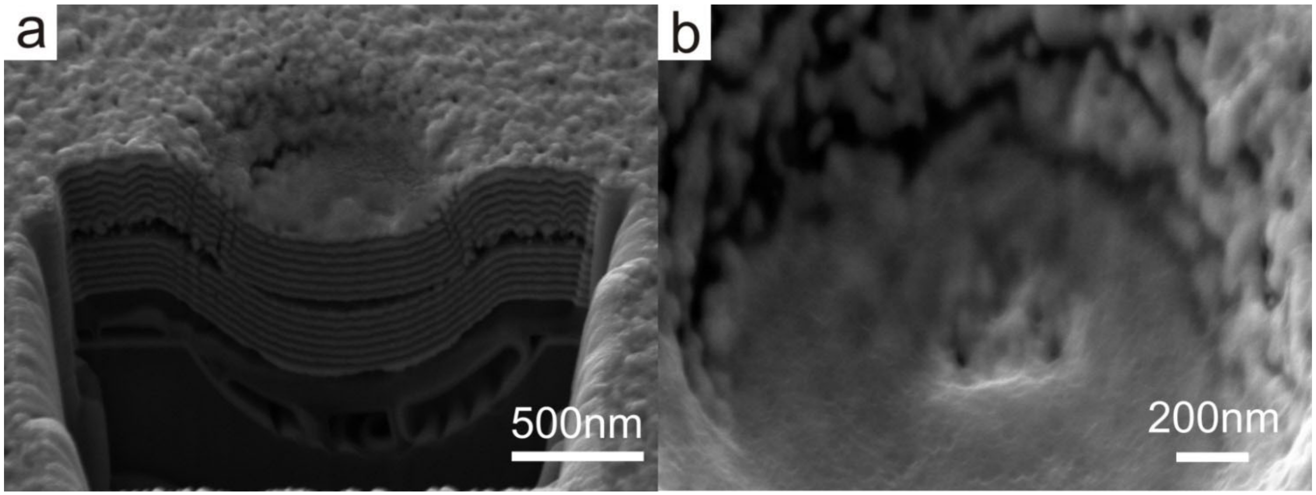


Numerical simulations

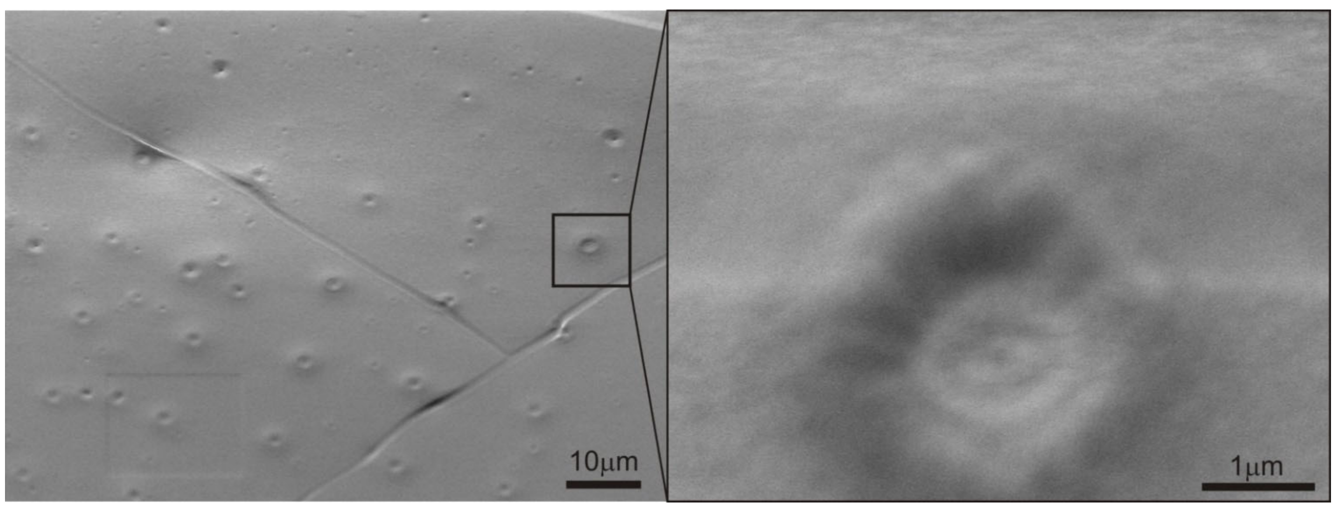




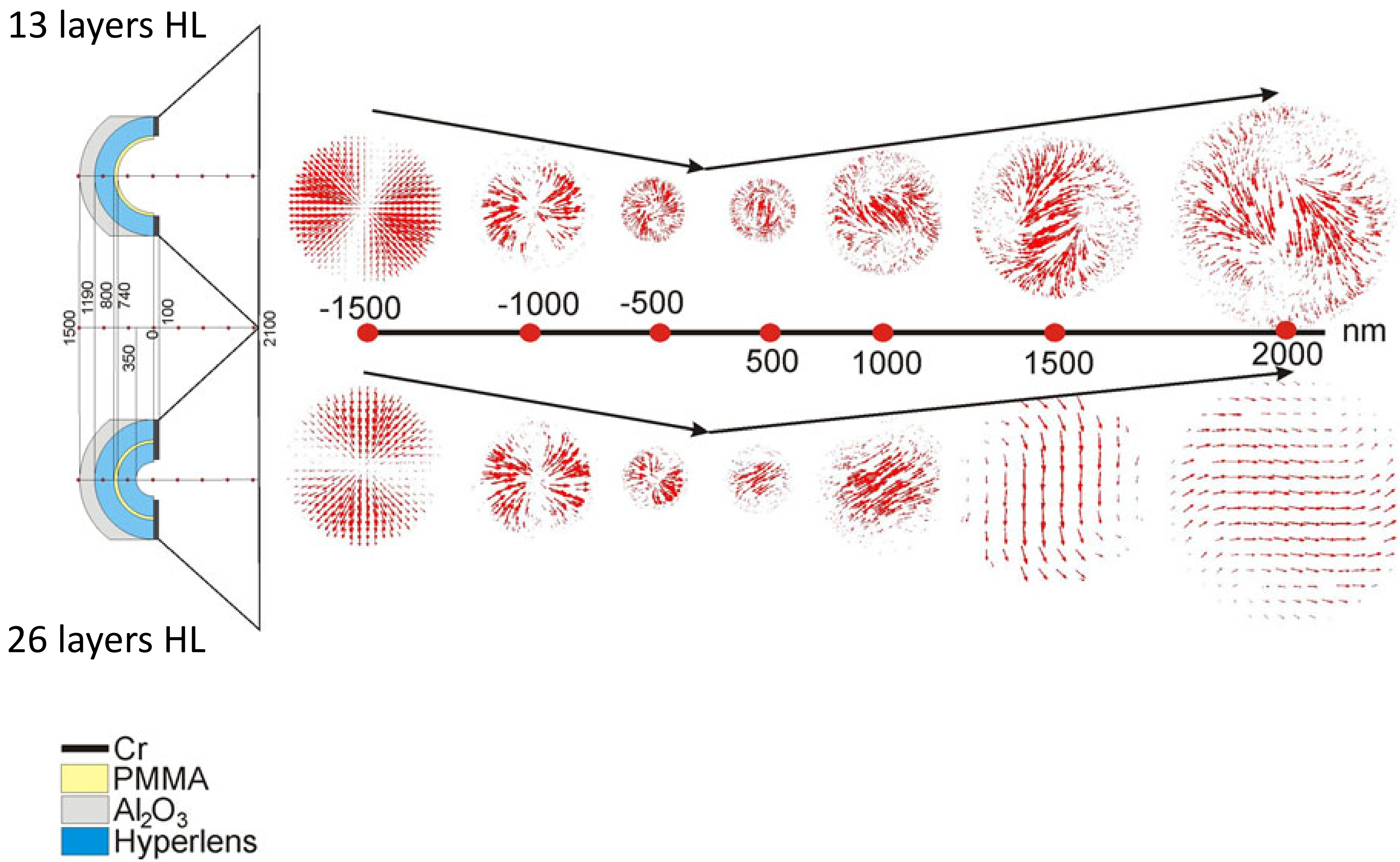
OAM beam de-magnification



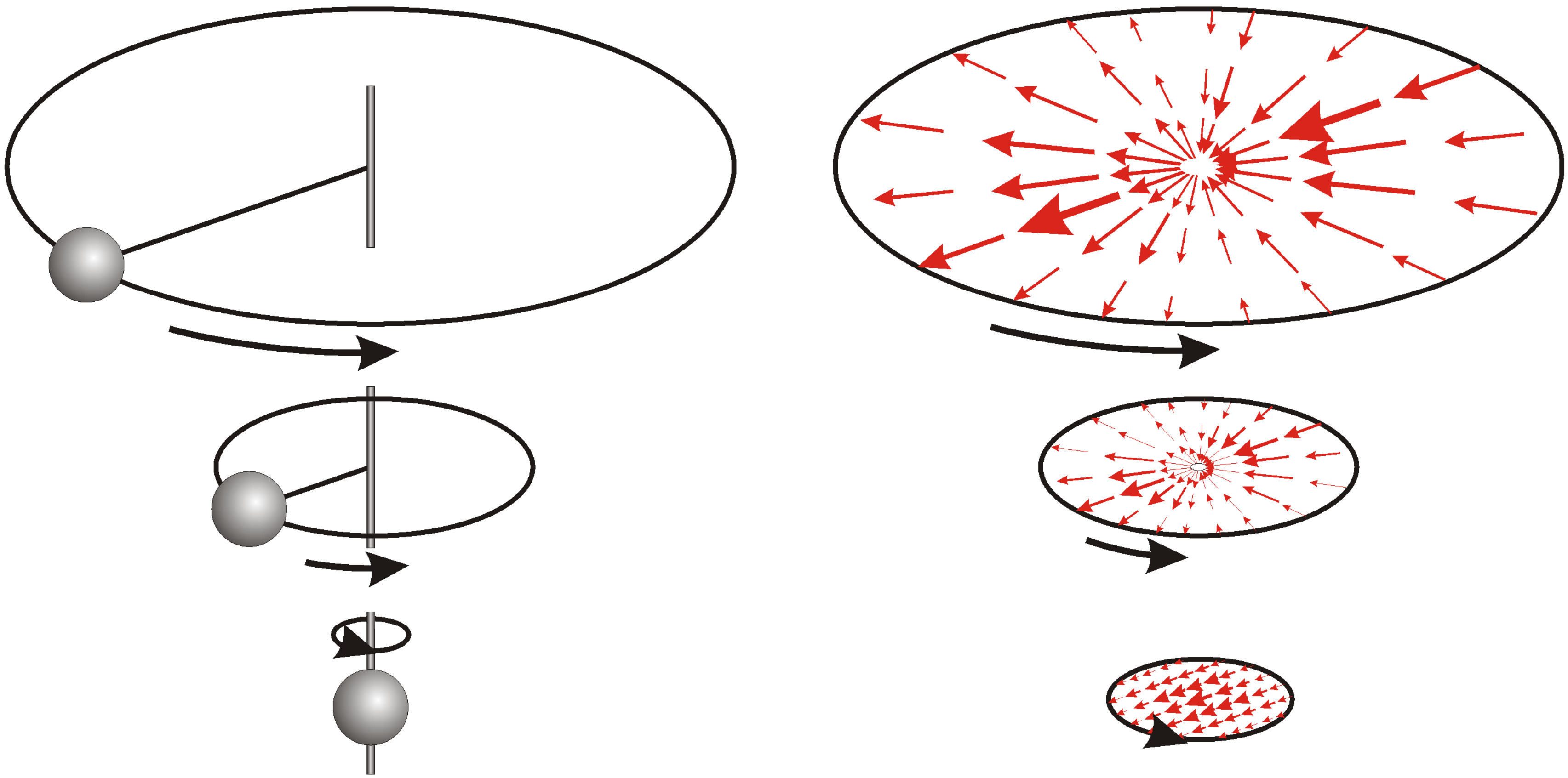
300 nm doughnut–shaped developed pattern on the photoresist



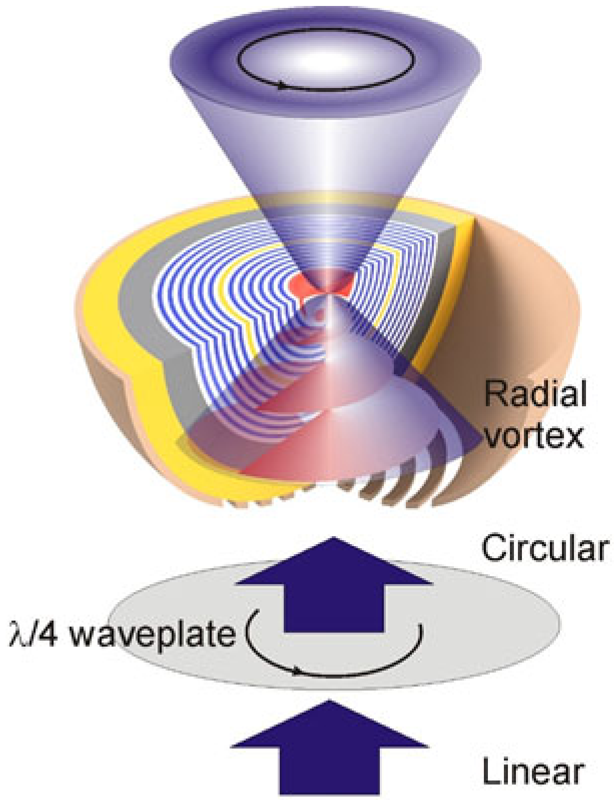
Focusing with a hyperlens

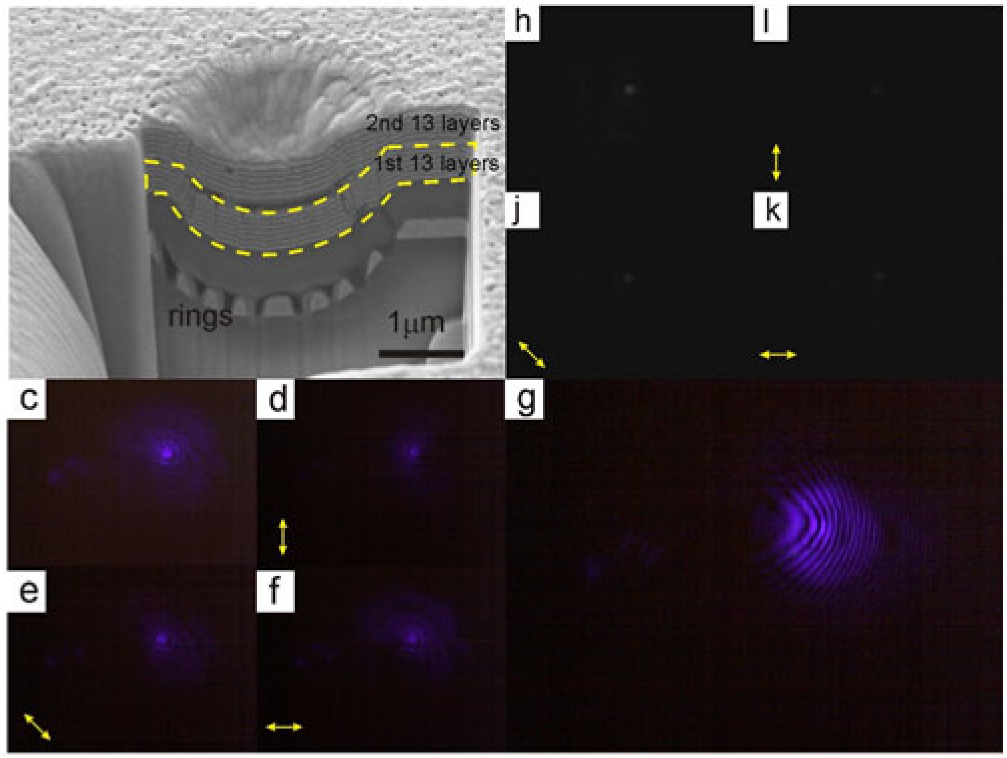


Mechanical analogy



Focusing with a hyperlens



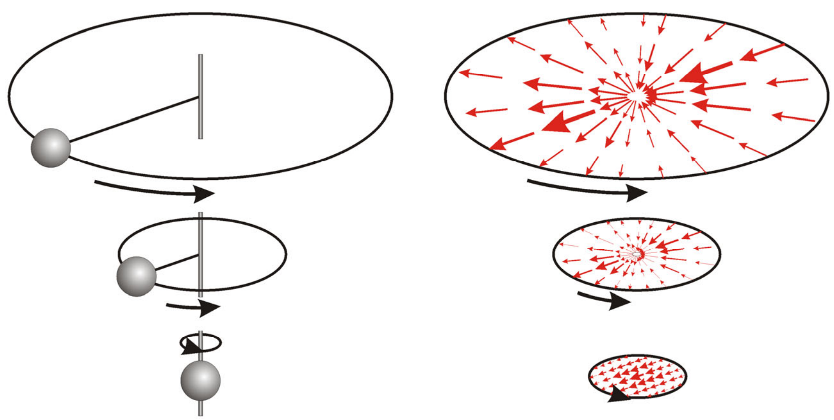


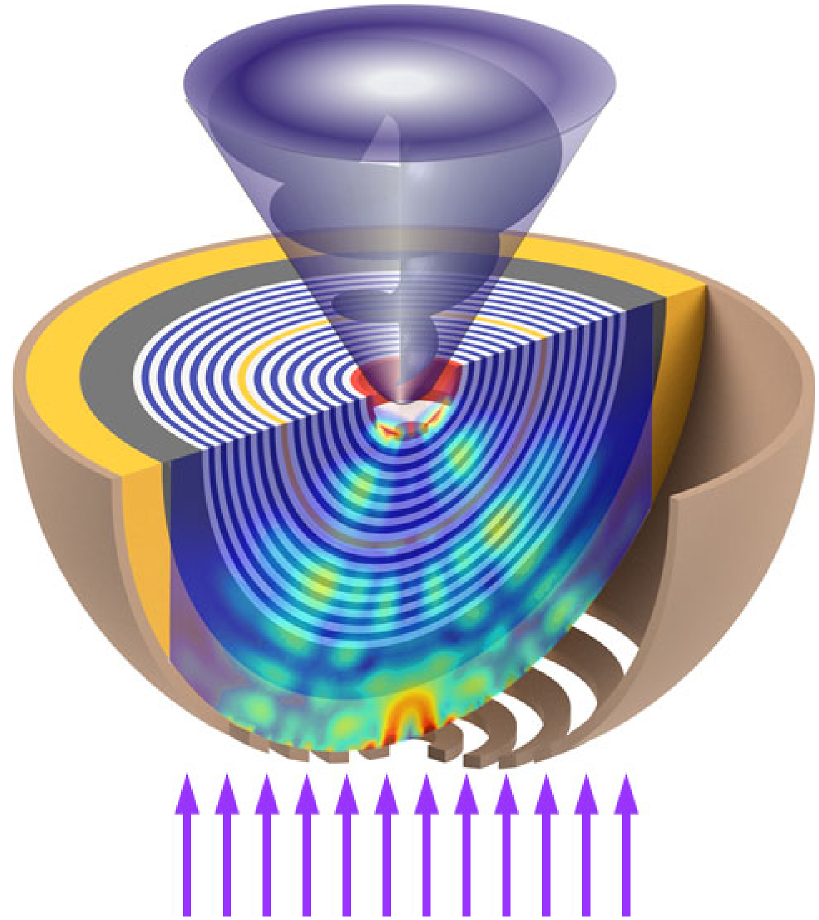
- Incident beam of circular polarization is transformed into a radially polarized vortex beam at the input and then focused by the hyperlens
- The output beam is circularly polarized with no OAM

Summary

We predicted and demonstrated the OAM-to-SAM conversion that can be

- achieved by focusing a radially polarized OAM beam down to the subwavelengh scale using a hyperlens
- understood using a simple mechanical "throwing hammer" analogy





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