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LETTERS

Near-field focusing and magnification through self-assembled nanoscale spherical lenses

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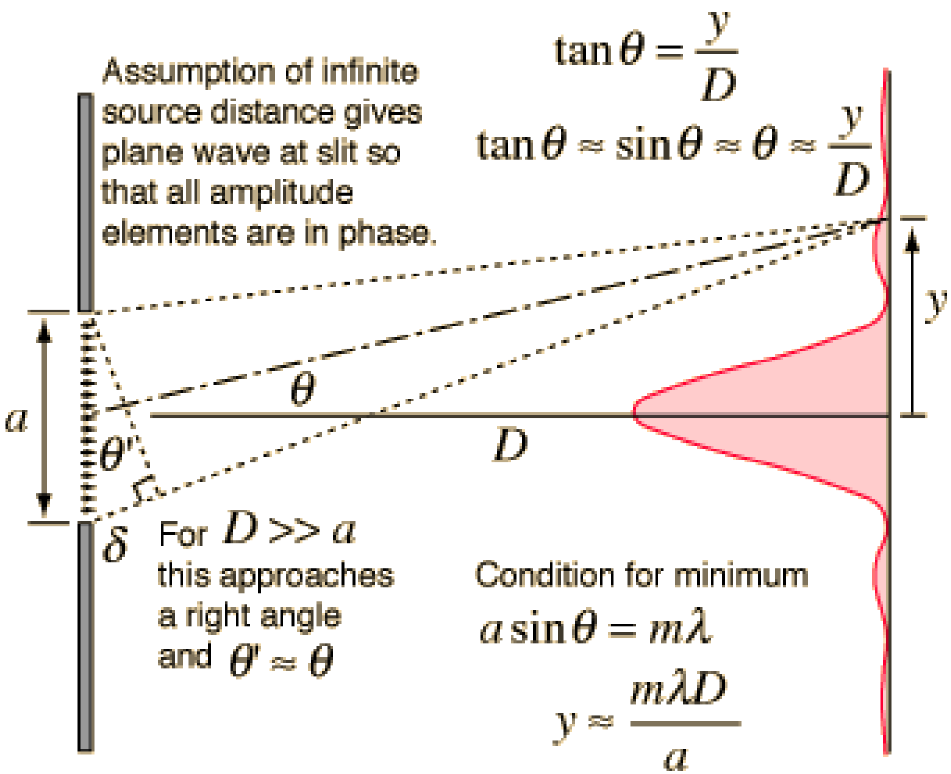
Nanolenses beat the barrier

The performance of a light microscope is intrinsically constrained by the Abbe diffraction limit. – 중 략 - Lee *et al*. are working on a new way of beating the limit, using nanoscale spherical lenses that self-assemble by bottom-up integration of cup-shaped organic molecules called calixarenes. Lenses produced in this way have very short focal lengths that can generate near-field magnification beyond the diffraction limit, enabling the resolution of features of the order of 200 nm. The lenses can be placed at will on a surface and, among other things, can be used to reduce the size of deep-ultraviolet lithography features.

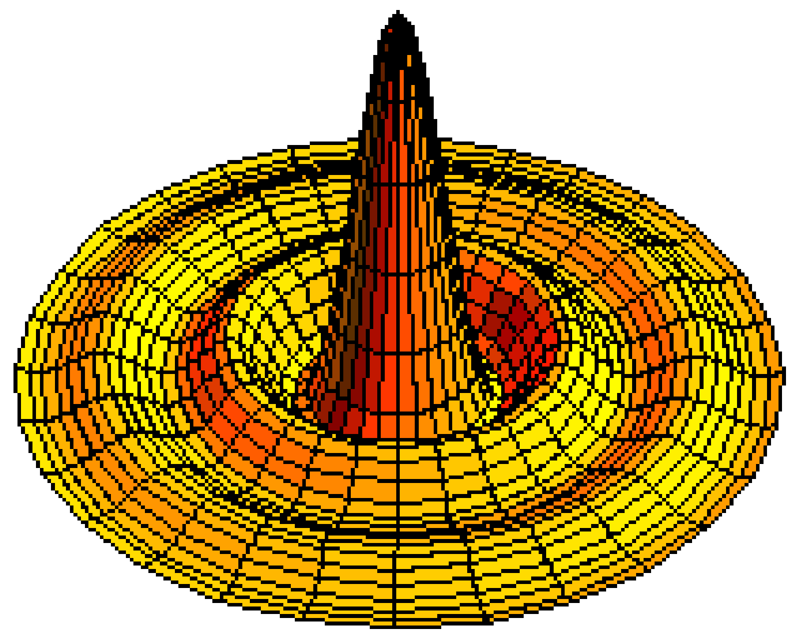
Diffraction Limit



Fraunhofer Diffraction

Single slit & circular aperture

Circular aperture -> Airy disk



Airy Disk

Diffraction Limit

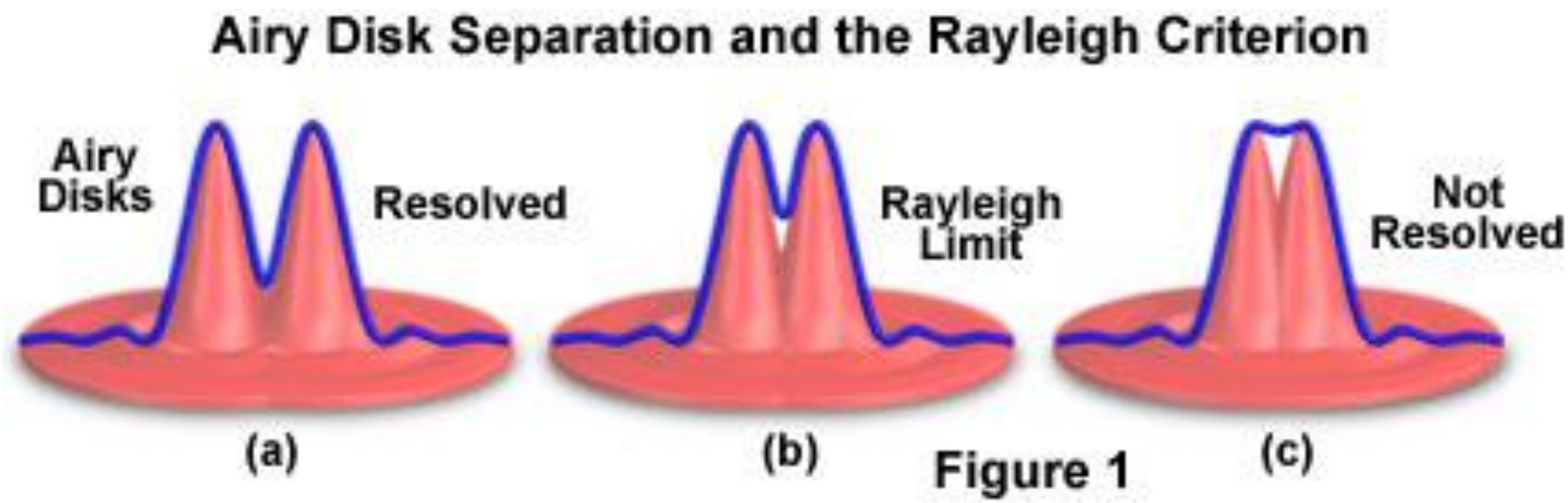


Figure 1

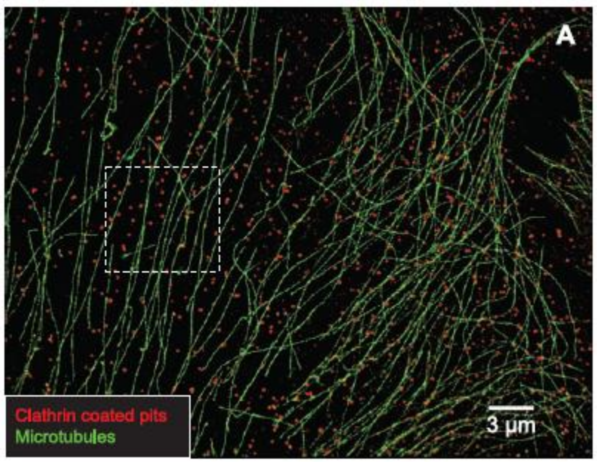
$$d = \frac{0.61\lambda}{NA}$$

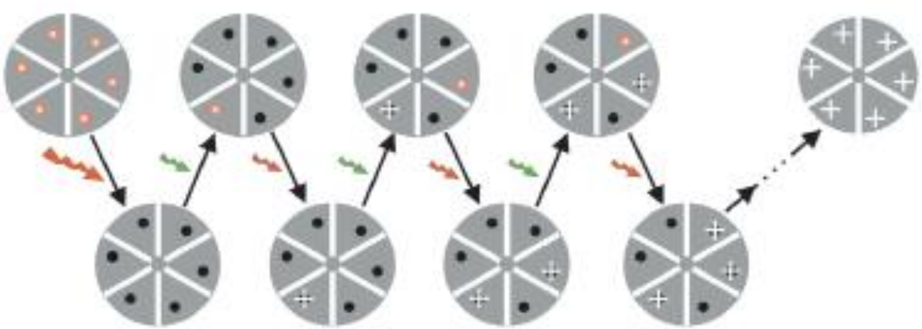
d = Rayleigh Criterion length
λ = wavelength
NA : Objectvie Numerical Aperture

Beyond the Diffraction Limit

Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM)

Michael J Rust[1,5], Mark Bates[2,5] & Xiaowei Zhuang[1,3,4]





NSOM ....

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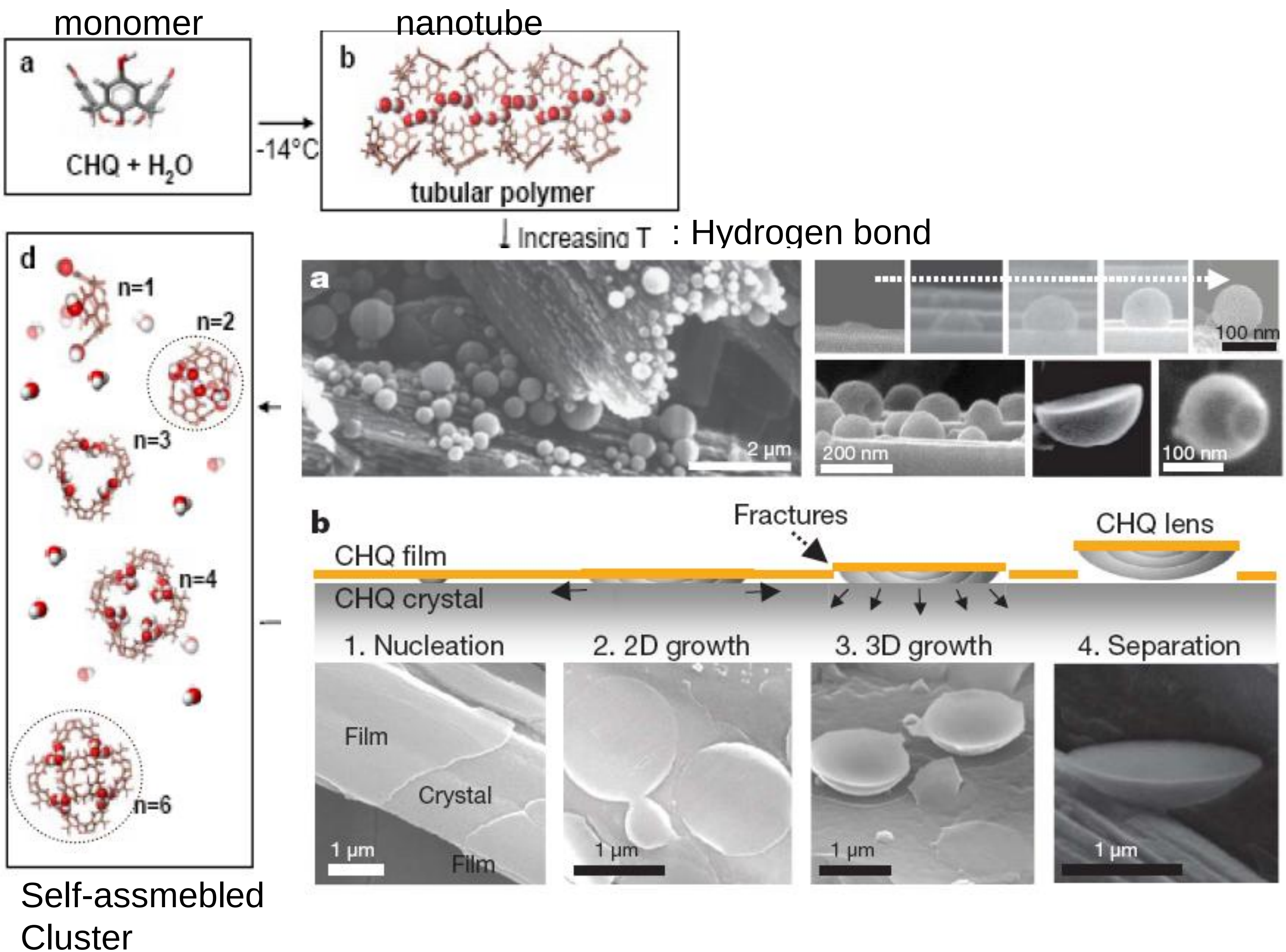
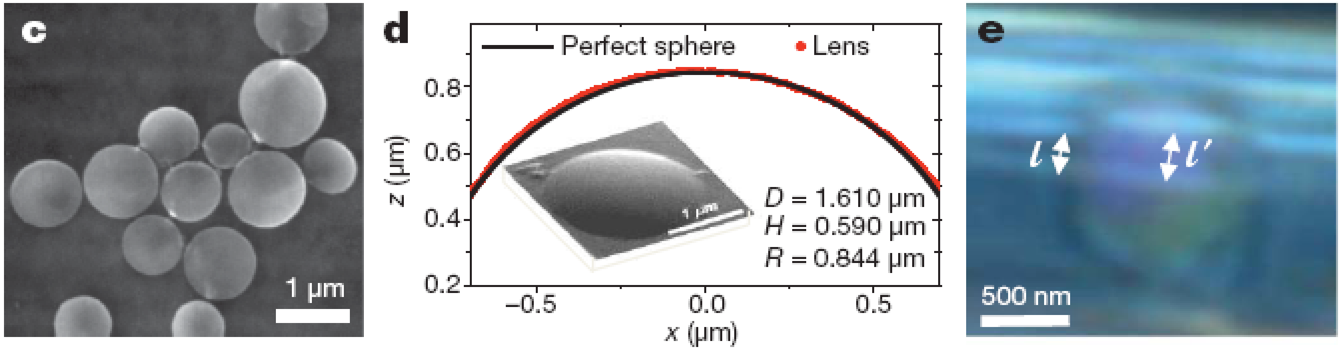
CHQ(calix-4-hydroquinone) molecules



Nanolens from the CHQ(calix-4-hydroquinone) molecules



D = 970nm
H = 220nm
Halogen Lamp excitation

Figure 1 | CHQ plano-spherical convex lenses. **a**, SEM images of growing CHQ nanospheres and their intermediate structures. **b**, Schematic diagrams and SEM images showing the self-assembly of CHQ lenses (see text for details). **c**, SEM image showing various sizes of CHQ lenses separated as an aqueous suspension and drop-dried on a substrate. **d**, AFM profile showing the near perfect spherical face of the lens. Inset, corresponding SEM image. **e**, Optical microscope image of CHQ lenses on a CHQ nanotube crystal, showing the magnification by the lens. The line spacing (l) behind the lens is considerably increased (l').

Thickness & Diameter can be controlled by Time and Temperature

Thickness H < 300 nm Diameter D = 0.05-3 μm

$$F = HM/(M-1) \sim 590nm$$

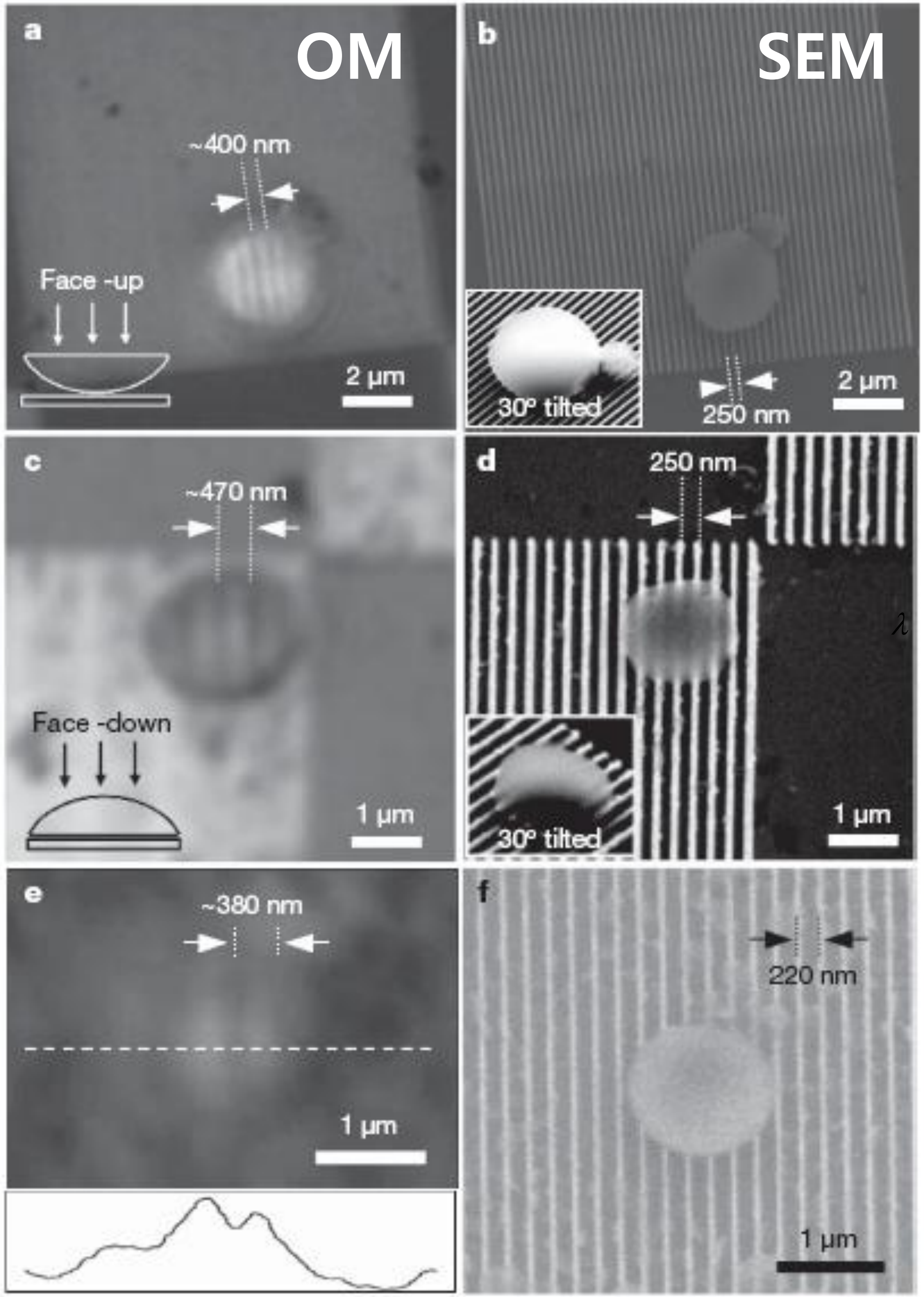
Measured Focal Length

M : Magnification Factor

$$F = (n-1)(1/R_1 - \cancel{1/R_2}) \sim 1.3\mu m$$

Focal Length by Geometrical Optics

Beyond the diffraction limit



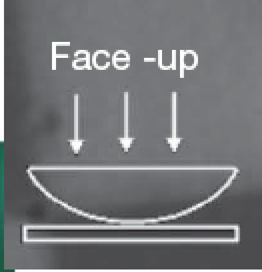
Measured by
NA = 0.9 Objective Lens

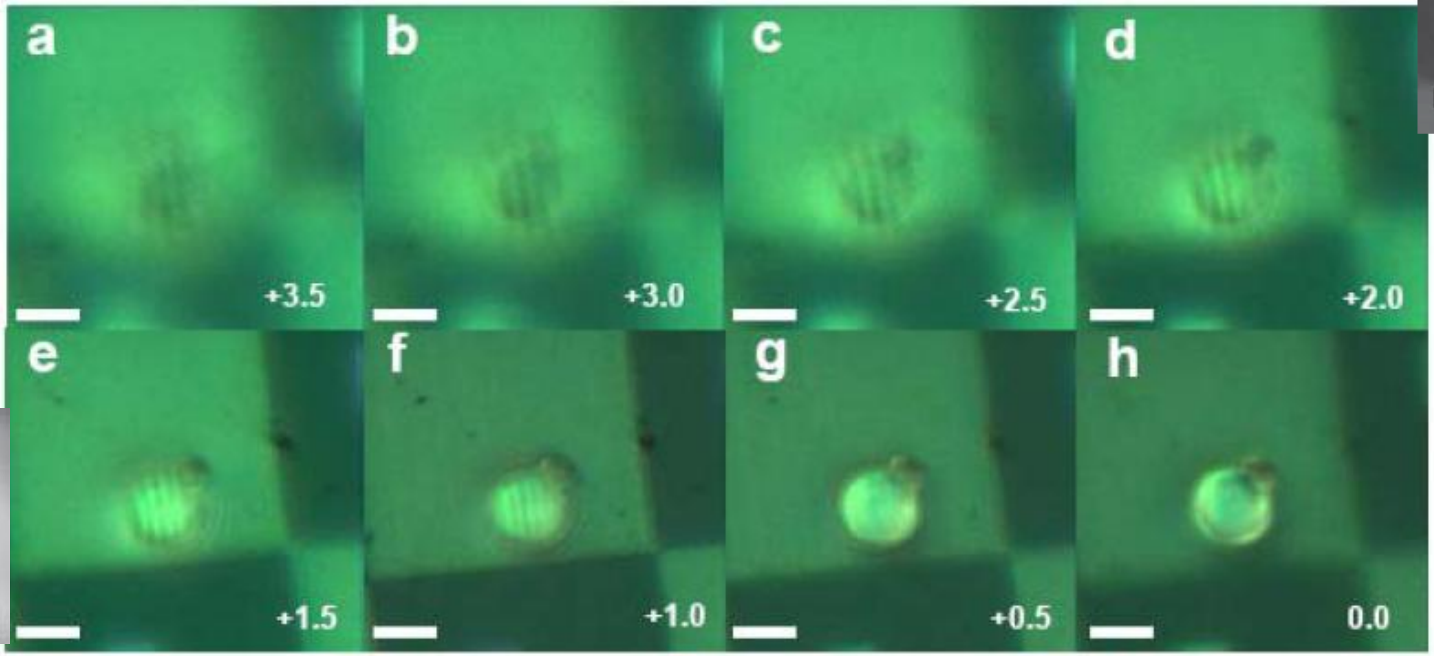
Diffraction Limit

For point object
R = 0.61 λ/NA = 320nm

For line object
R = 0.5 λ/NA = 250nm

Pin-cushion distortion





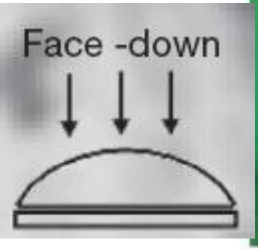
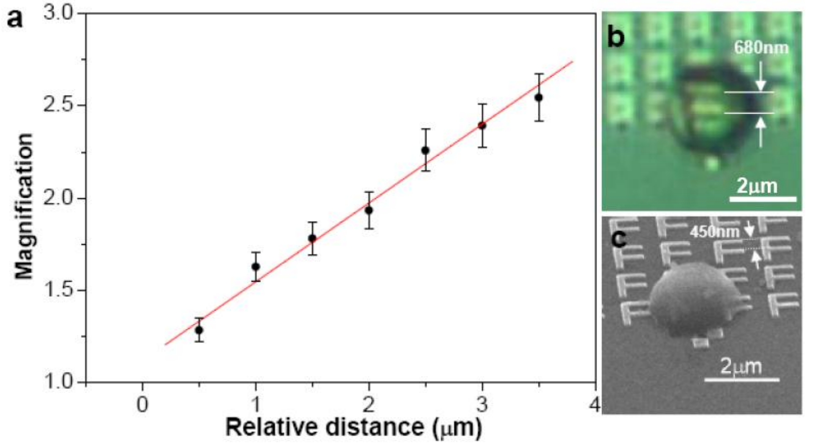


Figure S7 Reflection mode optical microscope images of a nanolens showing the magnified images of underlying objects (250 nm pitch stripe patterns), corresponding to the SEM image in Fig. 2b. The numbers indicate the relative distance (in μm) from the top of the lens. Lens dimension: D=~2.7 μm, H=~0.8μm (scale bars, 2μm).



Analysis

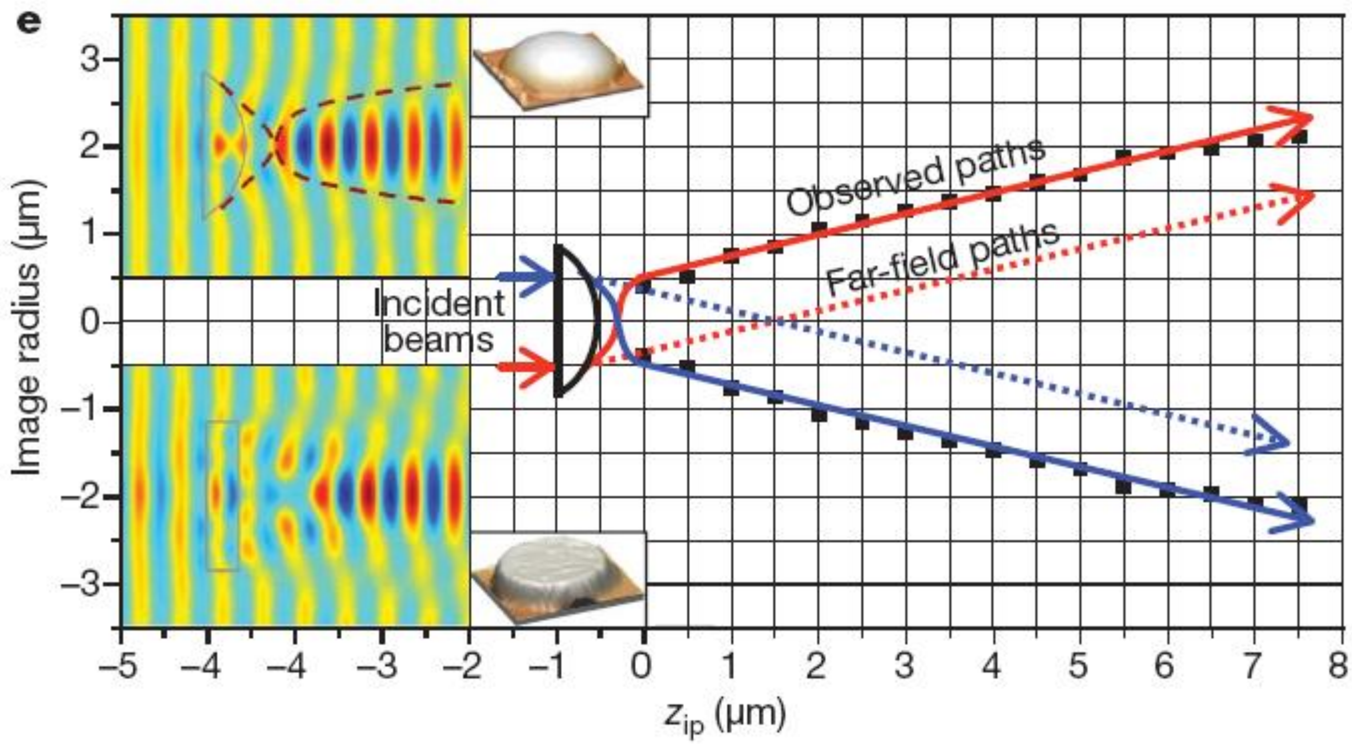
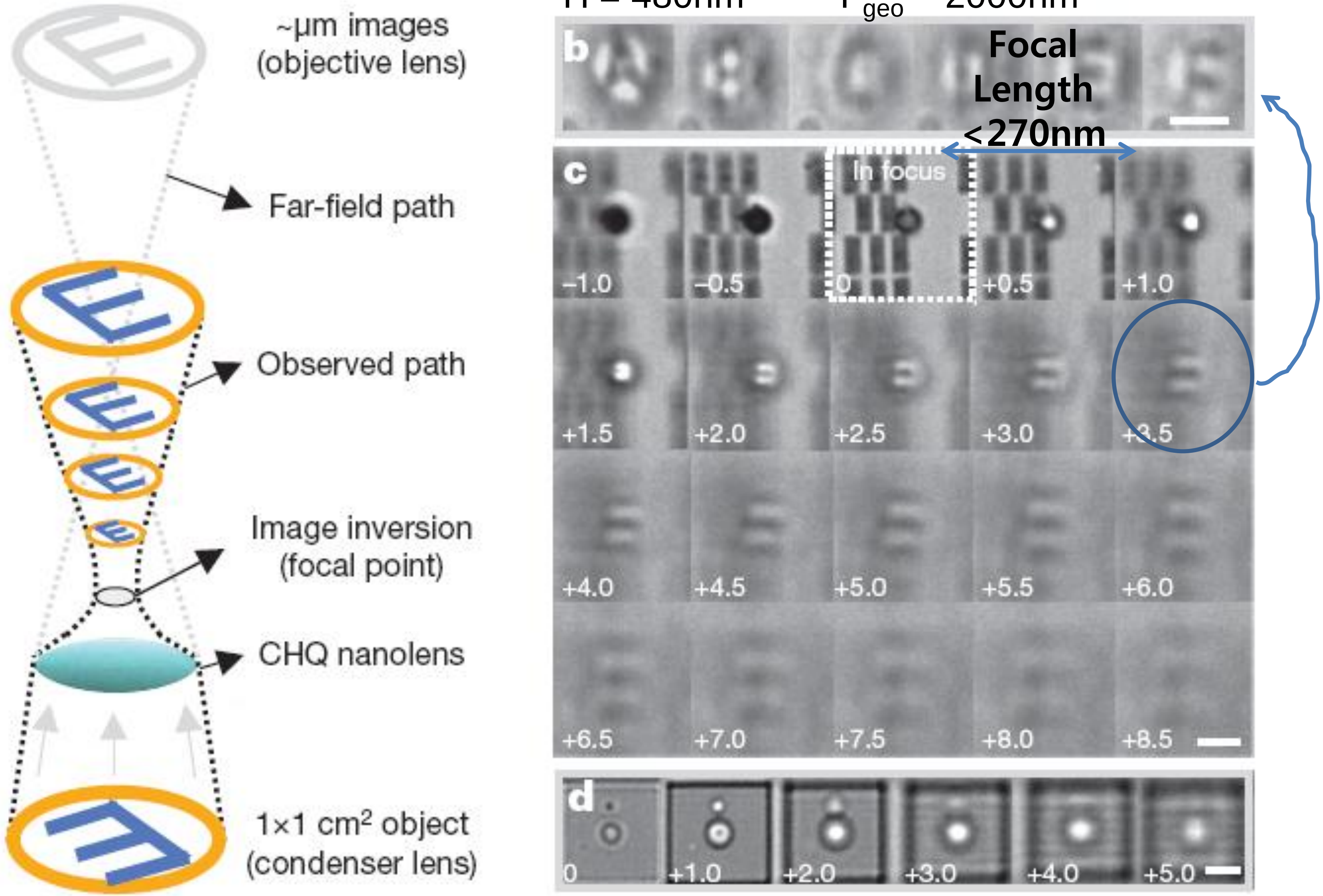


image formation. **e**, Beam trajectory with reduced focal length in the near-field PSC lens. Small insets on the left, AFM images of the CHQ lens (upper) and the PMMA disk (lower). Large insets on the left, FDTD simulation results of the radial component of the electric field (E_x) of the PSC lens (upper) and the PMMA disk (lower) ($\lambda = 472$nm). All scale bars, 2 μm.

Magnification Effect

D = 1700nm F_{ob} ~ 200nm
H = 480nm F_{geo} ~ 2000nm



WHY?

B1. Comparison between ray-tracing and FDTD simulation for a nanolens

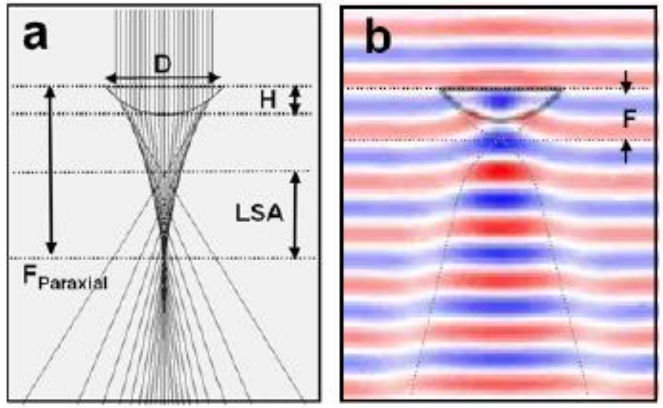


Figure S5 a, A Ray-tracing simulation result of the lens calculated by OSLO program packages (Sinclair Optics, Inc.). **b**, A finite-difference time-domain (FDTD) simulation result (E_x) obtained by FullWAVE 4.0 program (RSoft Design Group). D = 800nm, H = 280 nm and λ=365 nm.

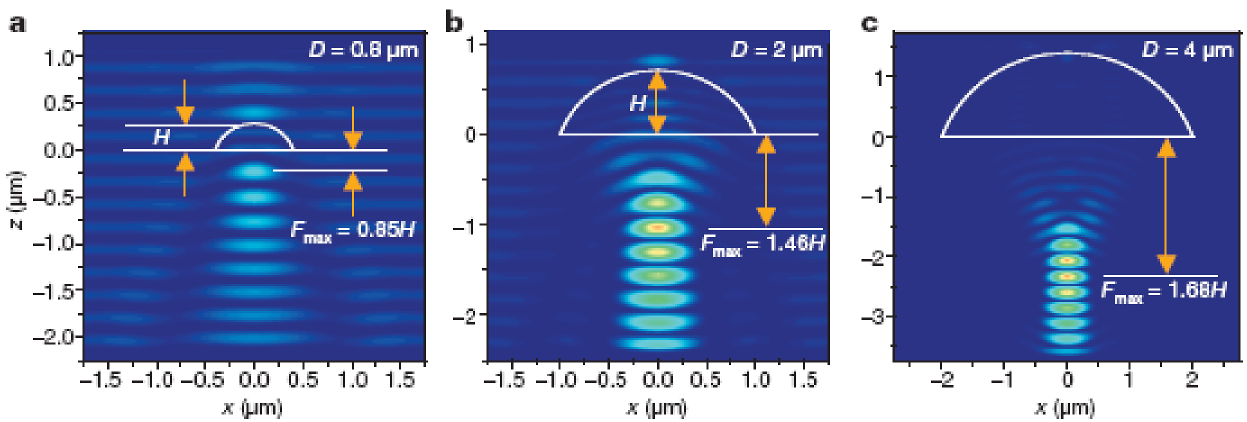
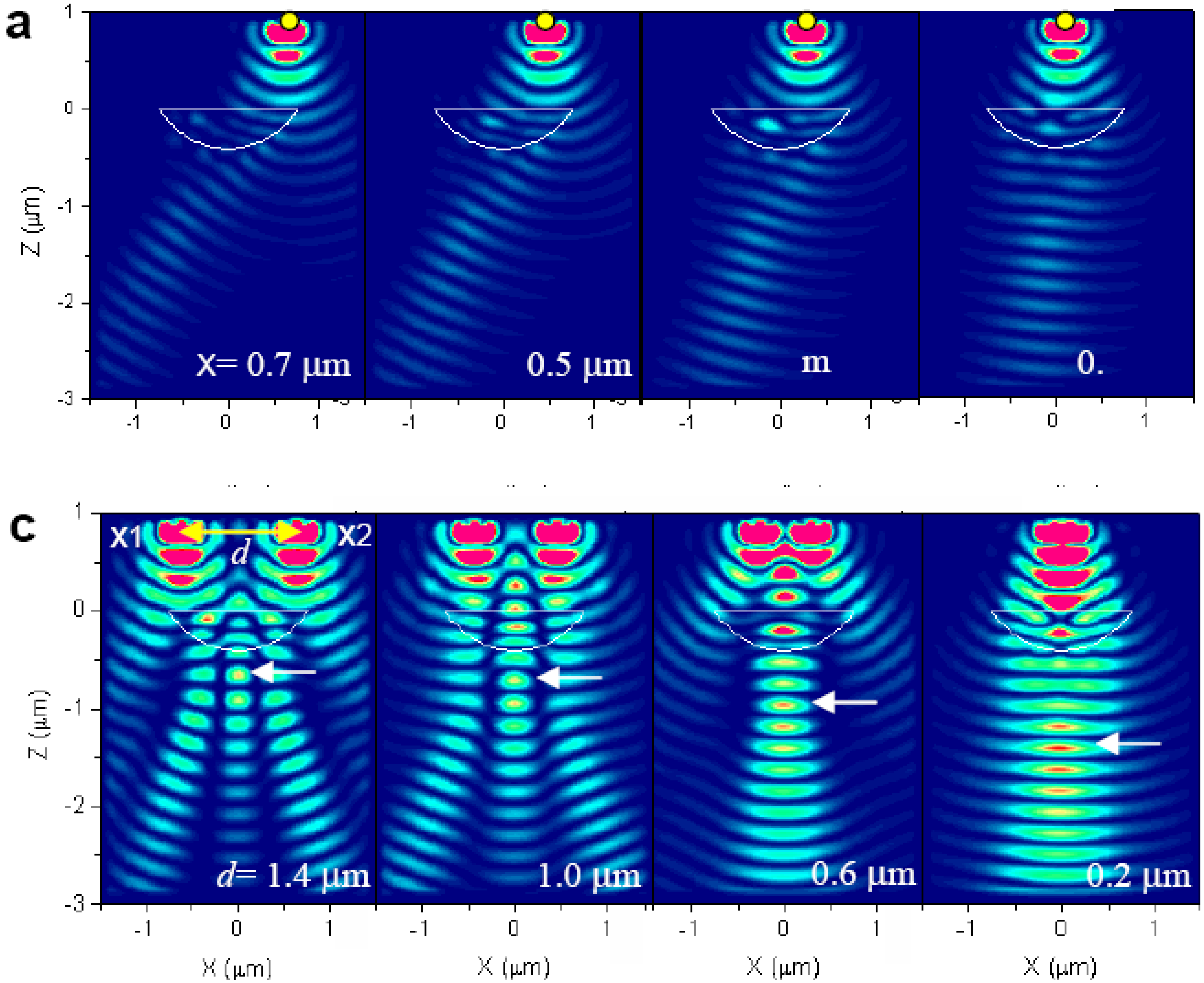
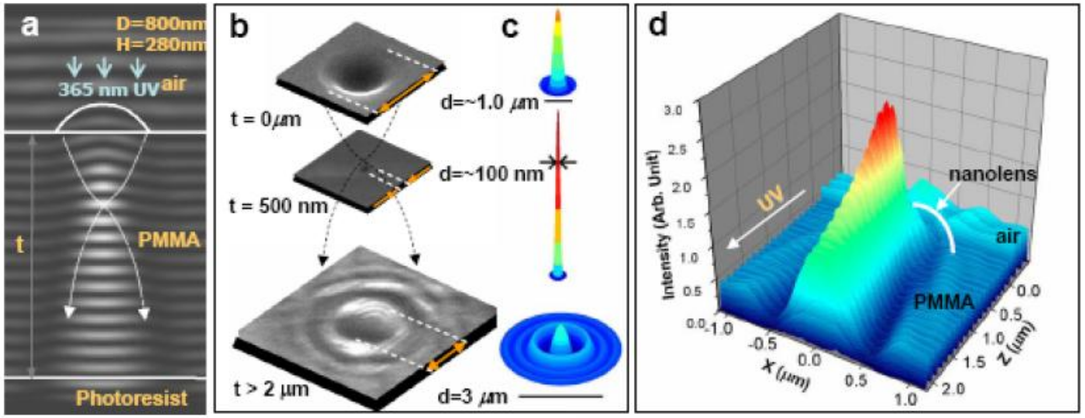


Figure 4 | Focal length changes for various sizes of CHQ lenses (fixed *H*/*D* = 0.35). a, $D = 0.8$ μm; **b**, $D = 2$ μm; **c**, $D = 4$ μm. Data were obtained from FDTD simulation results of $|E_x|^2$ ($\lambda = 472$ nm).

Focusing Behavior



Applications



UV-lithography