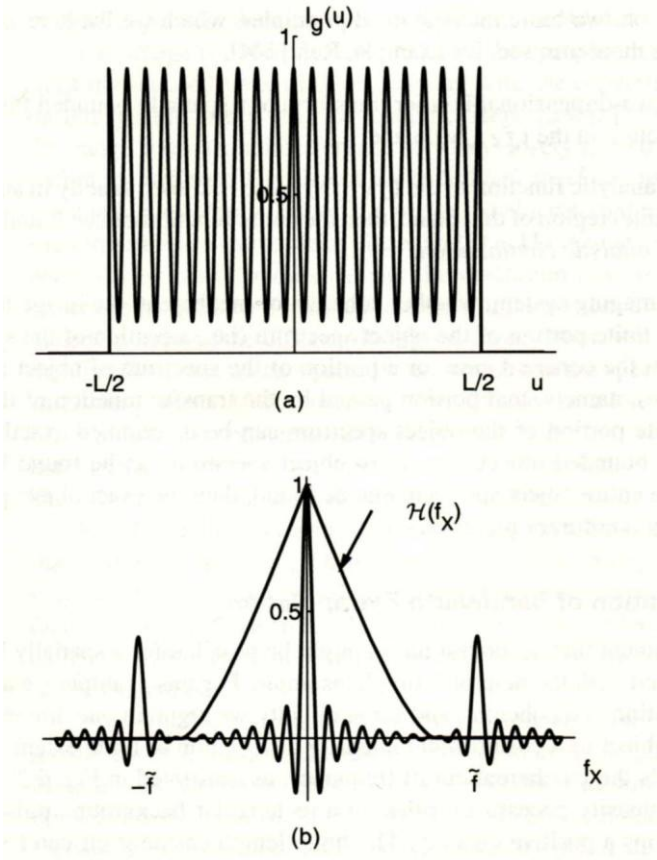
Resolution beyond Classical Diffraction Limit (Super-resolution)

Some mathematical fundamentals

Theorem 1. The 2D Fourier transform of a spatially bounded function is an analytic function in the (f_X, f_Y) plane.

Theorem 2. If an analytic function in the (f_X, f_Y) plane is known exactly in an arbitrary small (but finite) region of that plane, then the entire function can be found (uniquely) by means of analytic continuation.

Bandwidth Extrapolation



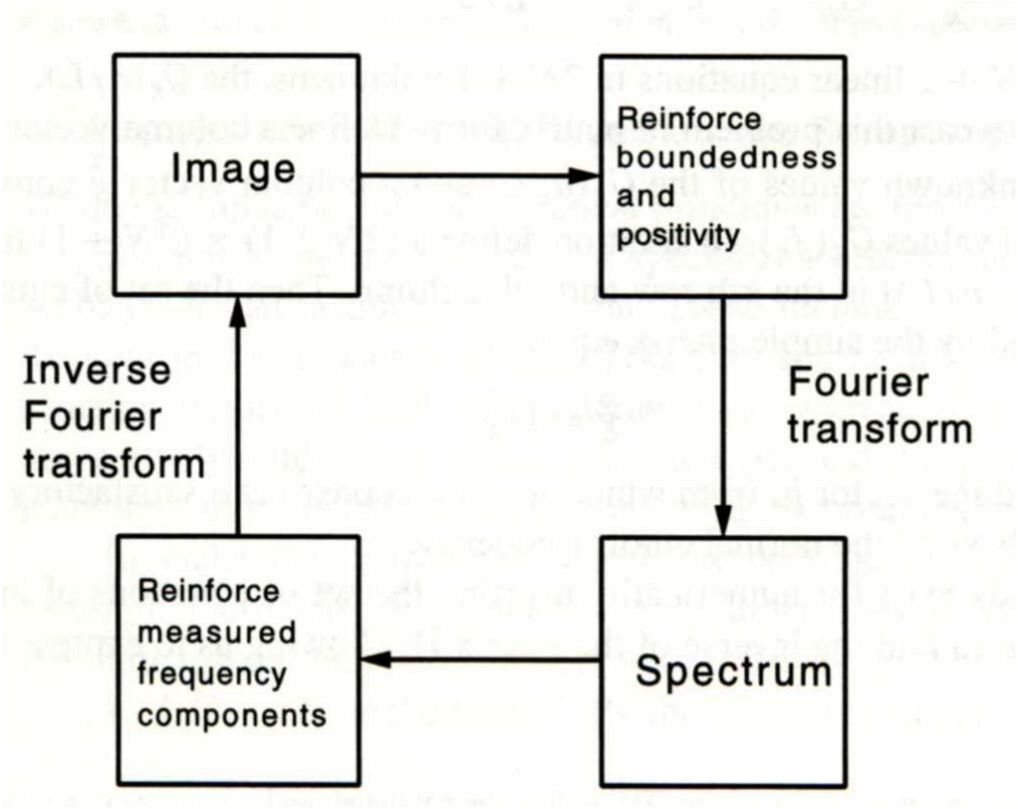
Extrapolation based on Sampling Theorem

$$\mathcal{G}_g(f) = \sum_{n=-\infty}^{\infty} \mathcal{G}_g\left(\frac{n}{L}\right) \operatorname{sinc}\left[L\left(f - \frac{n}{L}\right)\right]$$

$$\mathcal{G}_g(f) \approx \sum_{n=-N}^{N} \mathcal{G}_g\left(\frac{n}{L}\right) \operatorname{sinc}\left[L\left(f - \frac{n}{L}\right)\right]$$

$$\hat{\mathcal{G}}_g(f_k) = \sum_{n=-N}^{N} \mathcal{G}_g\left(\frac{n}{L}\right) \operatorname{sinc}\left[L\left(f_k - \frac{n}{L}\right)\right] \qquad k = 1, 2, \ldots, 2N+1$$

Iterative Extrapolation Method



Increasing Resolution in Digital Holographic Microscopy

Grating placed in the signal arm increases resolving power

$1+t_0\cos(2\pi/\Lambda)$

t_0 : *diffraction efficiency*, Λ : *period of grating*

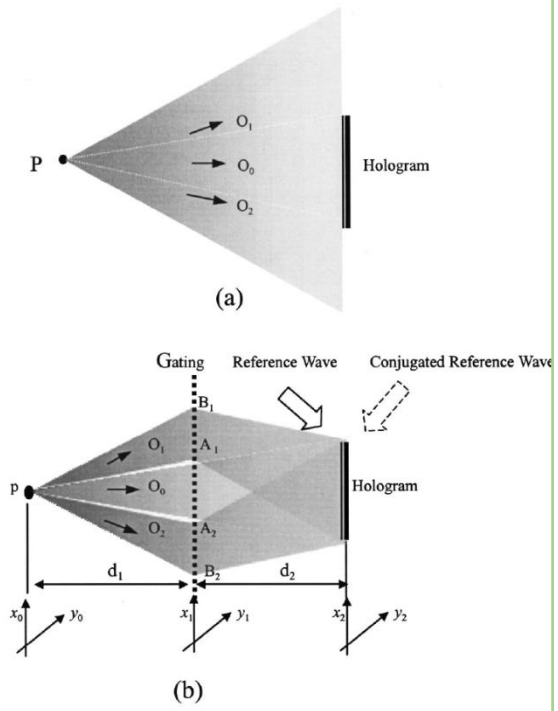


FIG. 2. Ray diagrams of the object wave: (a) without grating in setup an (b) with a grating in setup.

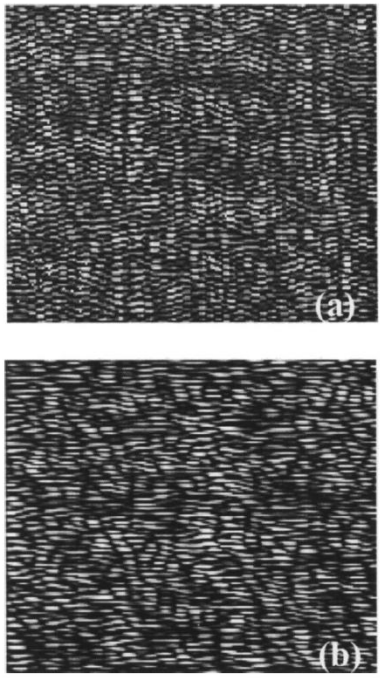


FIG. 3. Holograms recorded with the setup in Fig. 1: (a) with a gr setup and (b) without a grating in setup.

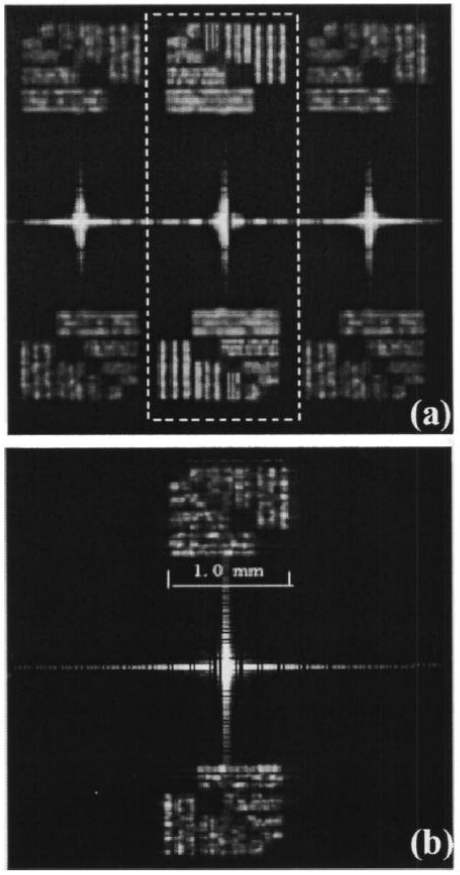
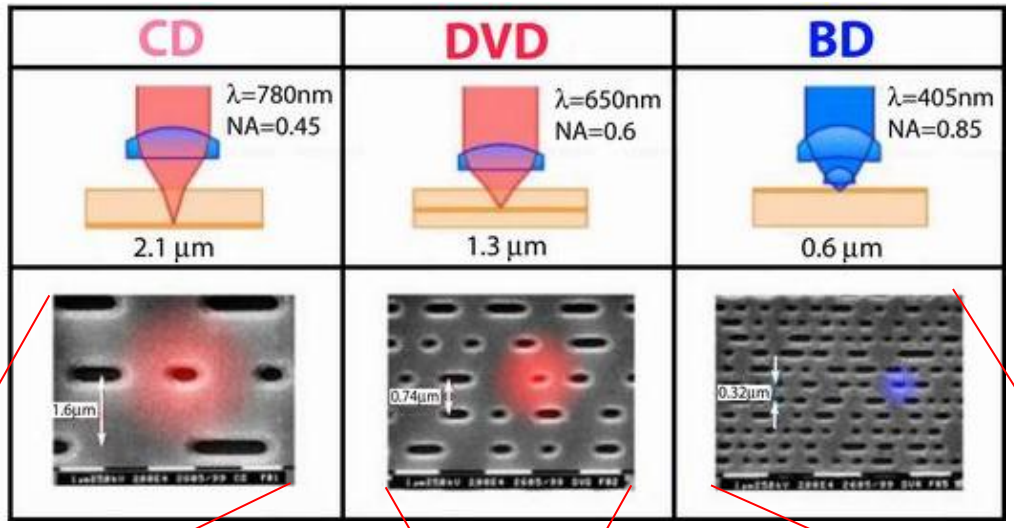


FIG. 4. Reconstructed images: (a) reconstructed image from Fig. 3(a) and (b) reconstructed image from hologram in Fig. 3(b).

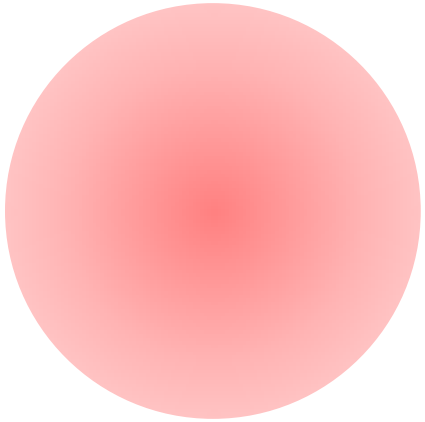
C. Liu, Z. Liu, F. Bo, Y. Wang, and J. Zhu, "Super-resolution digital holograhpic imaging method," Appl. Phys. Lett. **81**, 3143-3145 (2002).

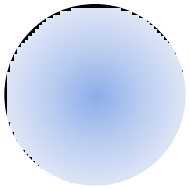
Optical Data Storage



http://www.imperial.ac.uk/research/photonics/pt_group/research/ODS.htm

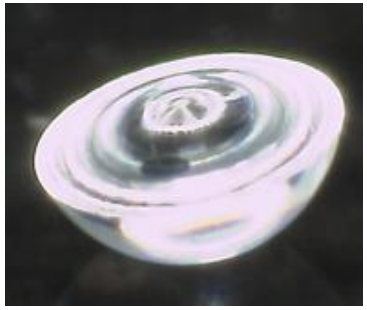
Near-field Optical Data Storage

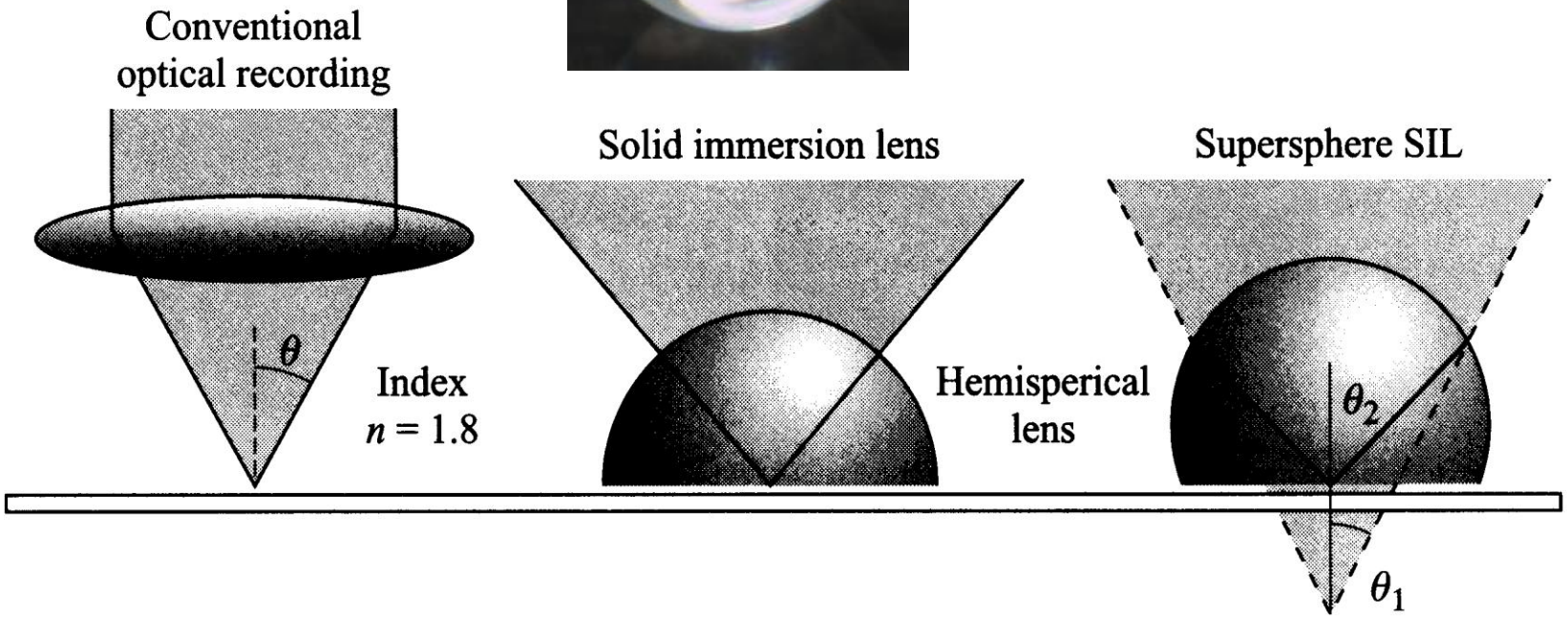




	Digital Versatile Disk (DVD)	Blu-ray Disk (BD)	Near-field storage (Theory)
	4.7 GB	25 GB	1,600 GB
MP3	~940 songs	~5000 songs	~320,000 songs
	6~7 movies	35 movies	~2,300 movies

Solid Immersion Lens (SIL)



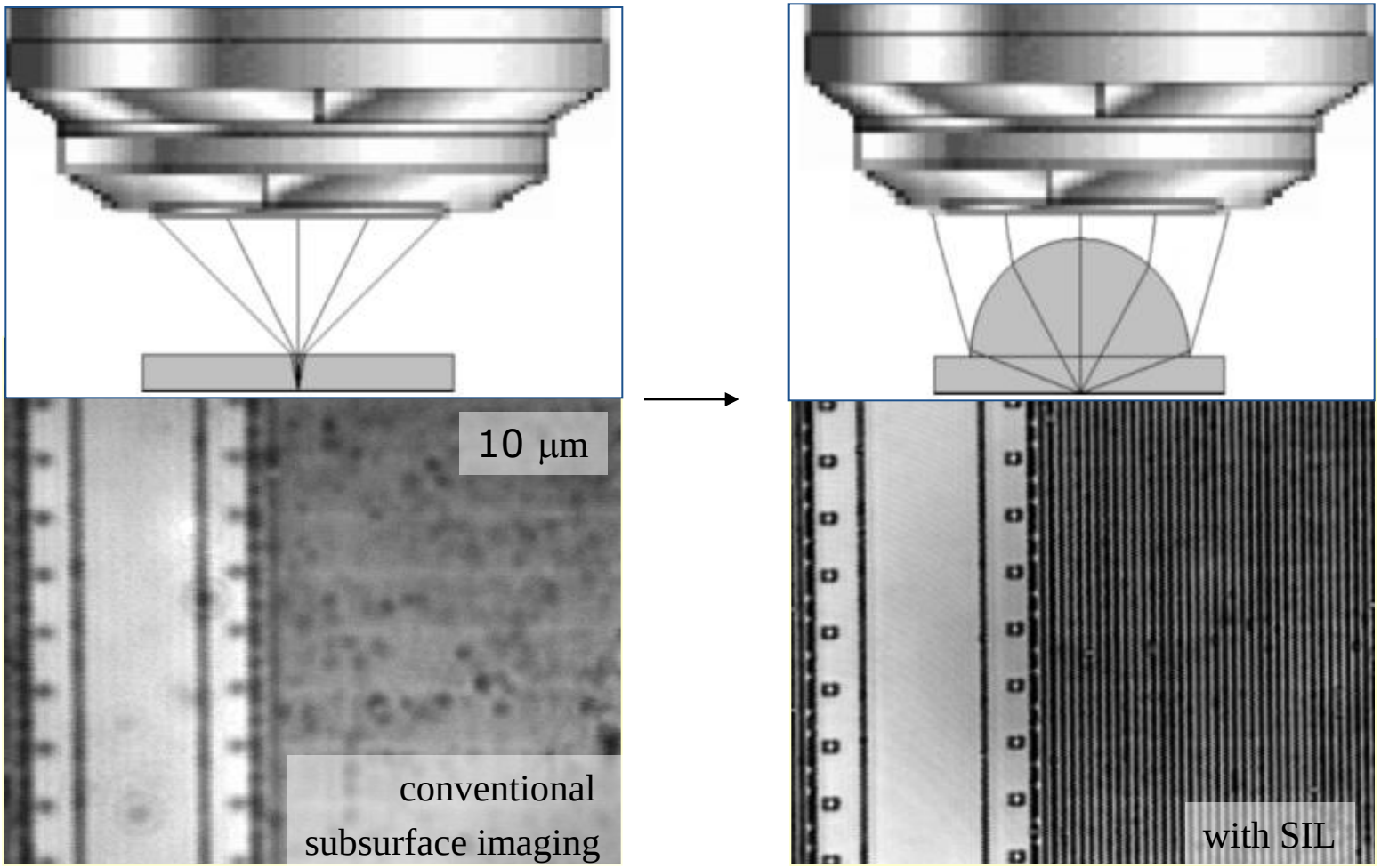


$$\text{Spot size} = \frac{\lambda}{2\sin\theta}$$

$$\text{Spot size} = \frac{\lambda}{2n\sin\theta}$$

$$\text{Spot size} = \frac{\lambda}{2n^2\sin\theta_1}$$

Solid Immersion Lens (SIL)



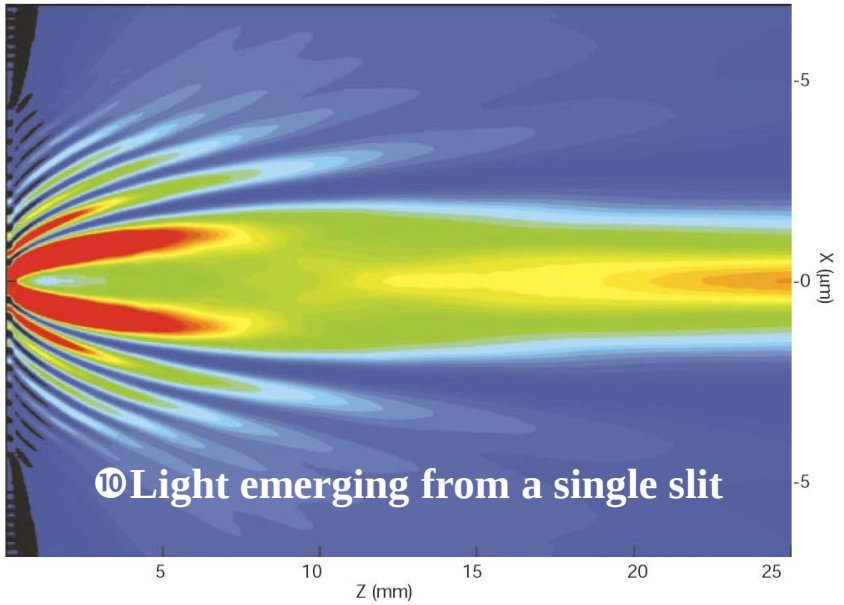
S. Unlu & B. Goldberg, Boston University

Introduction: Plasmonics

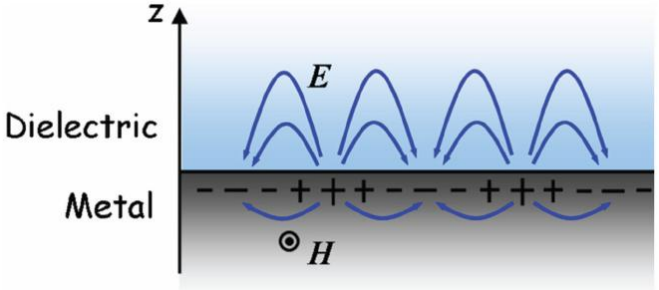
- **Surface Plasmon Polariton (SPP)**
- **Localized SPP**

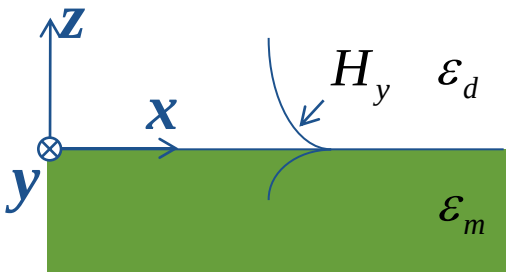
The Lycurgus Cup (glass)
British Museum
4th century A.D.

Labors of the Months"
Norwich, England
ca. 1480



W. L. Barnes *et al.*, *Nature* 424, 824-830 (2003).

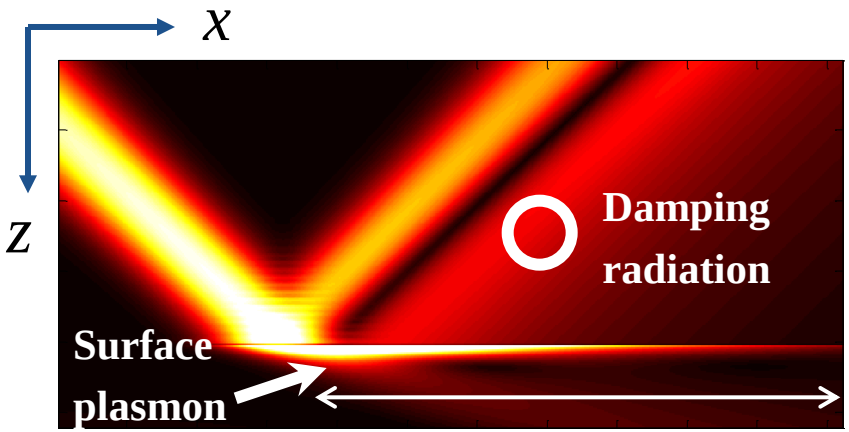




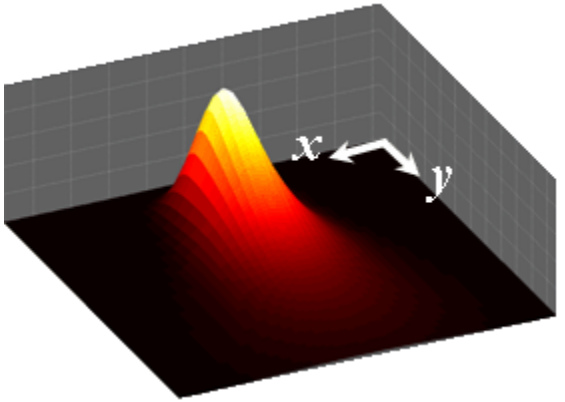
$$k_{SP} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

Surface plasmon polaritons

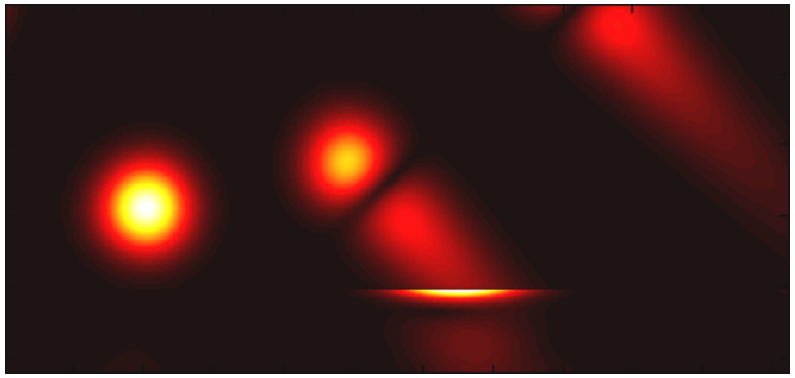
- **Potential for sub-wavelength optics**



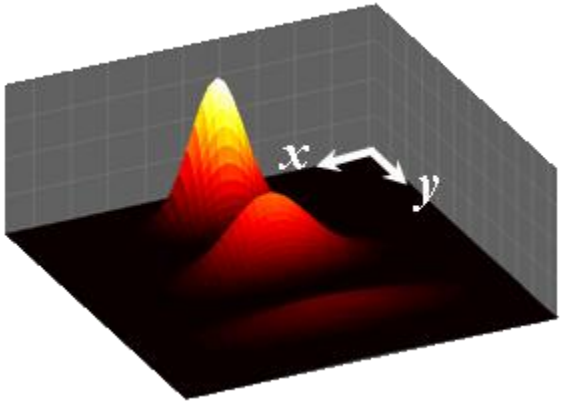
Surface plasmon excited by Gaussian beam



At metal surface



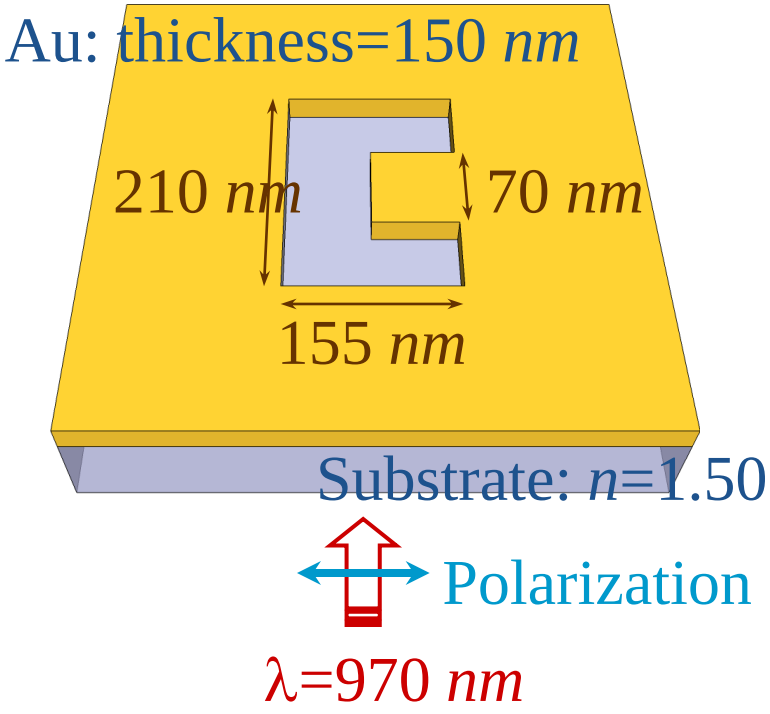
Surface plasmon excited by Gaussian pulse beam

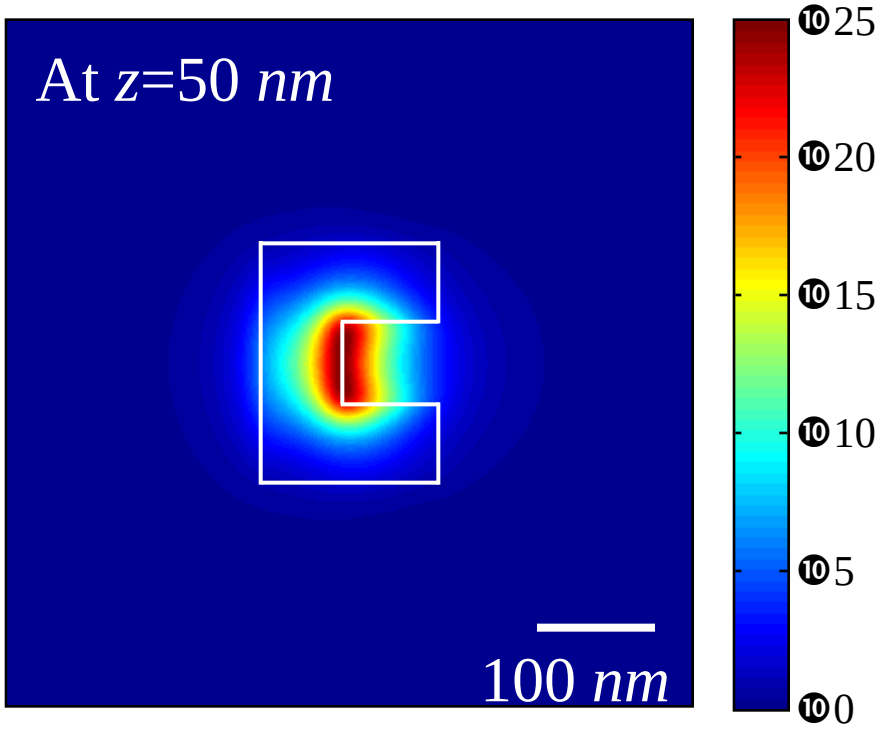


At metal surface

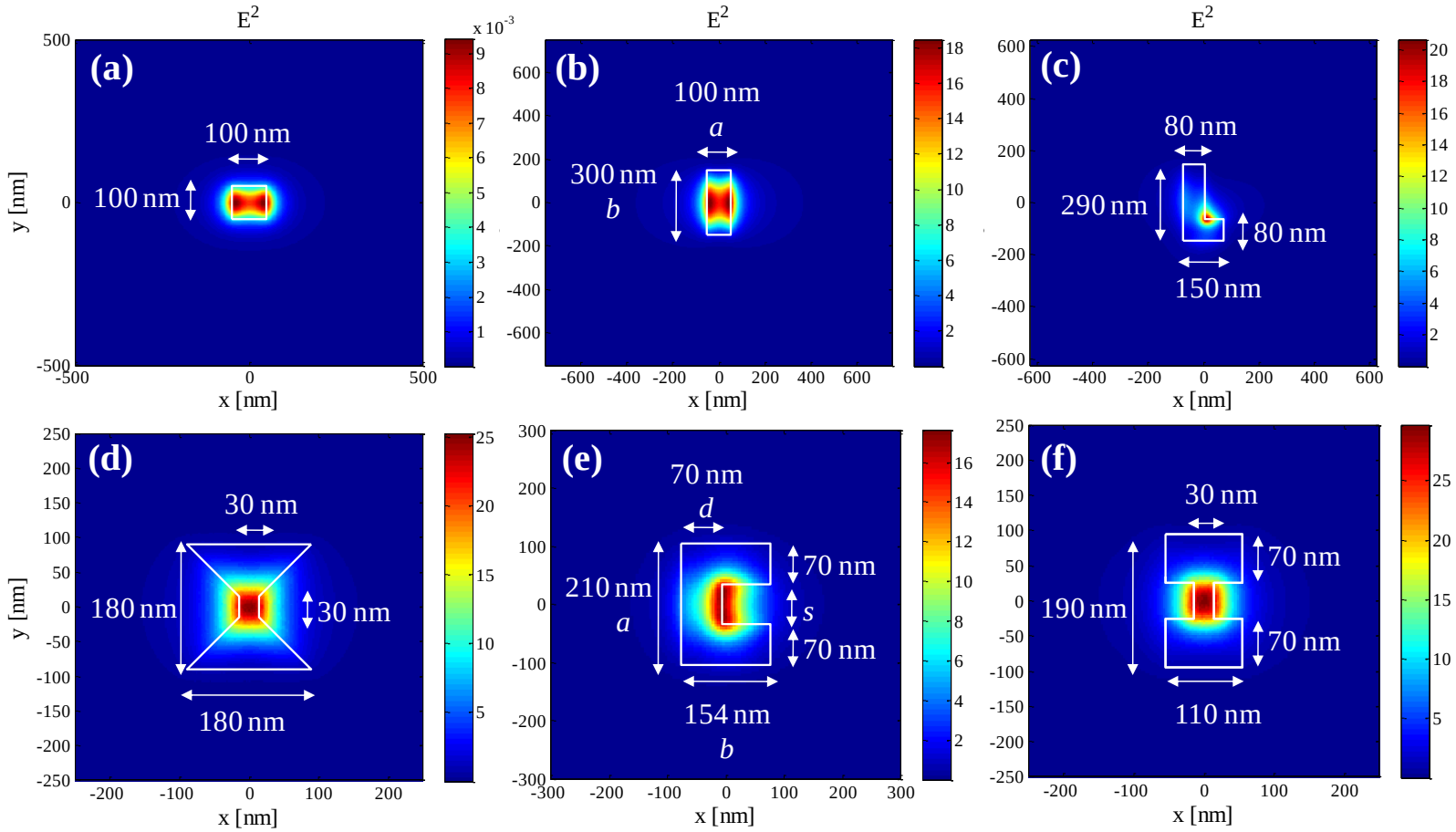
B. Lee, S. Kim, H. Kim, and Y. Lim, Progress in Quantum Electronics, vol. 34, no. 2, pp. 47-87, 2010 (invited paper).

Subwavelength 'Hot-Spot'





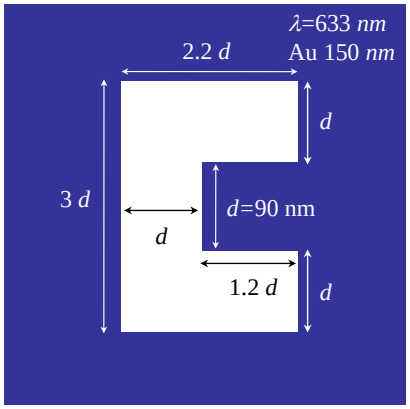
Plasmonic Hot Spots

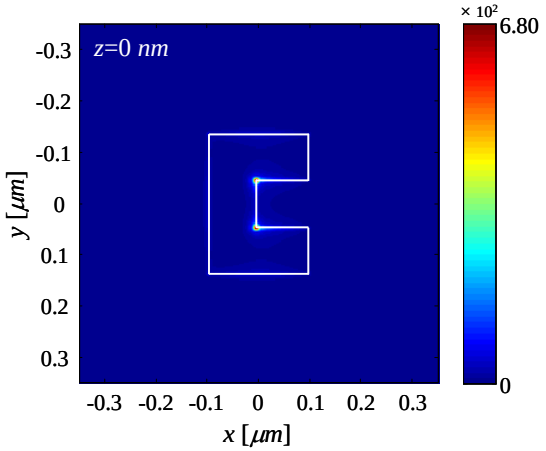


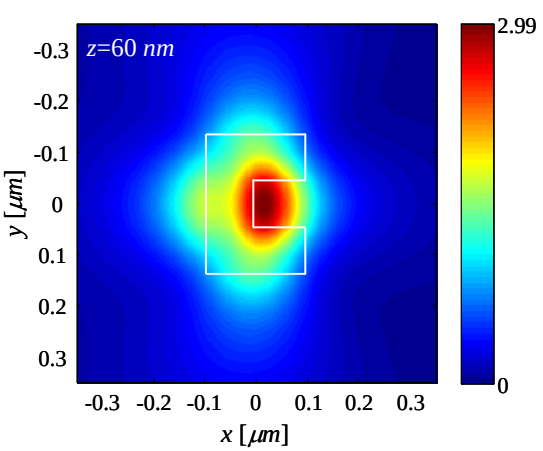
B. Lee, I.-M. Lee, S. Kim, D.-H. Oh, and L. Hesselink, Journal of Modern Optics, vol. 57, no. 16, pp. 1479-1497 (2010) (invited paper).

C-shaped Aperture

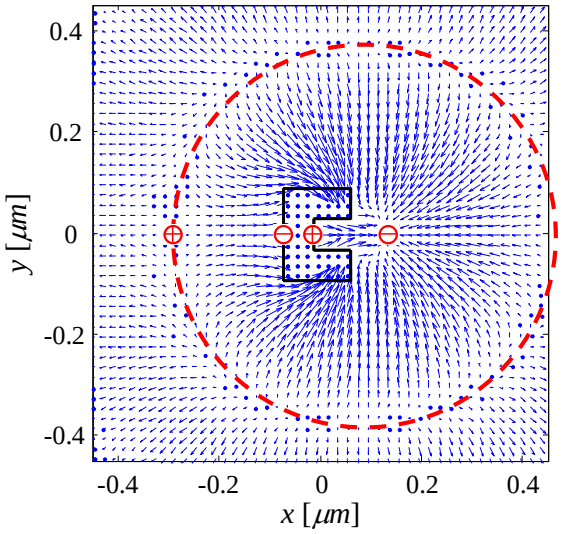
Intensity distribution & surface current distribution



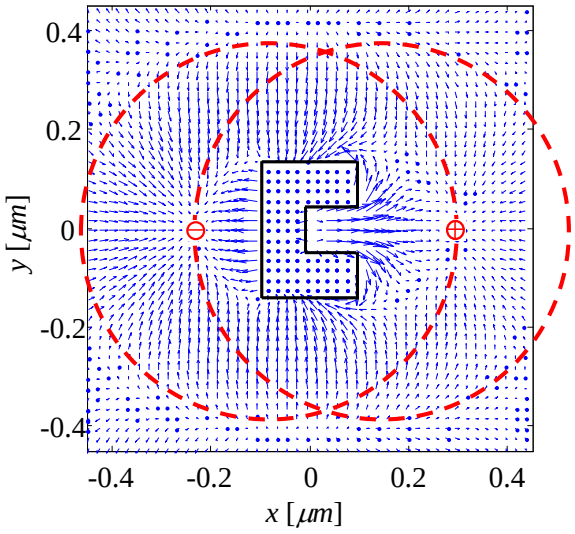




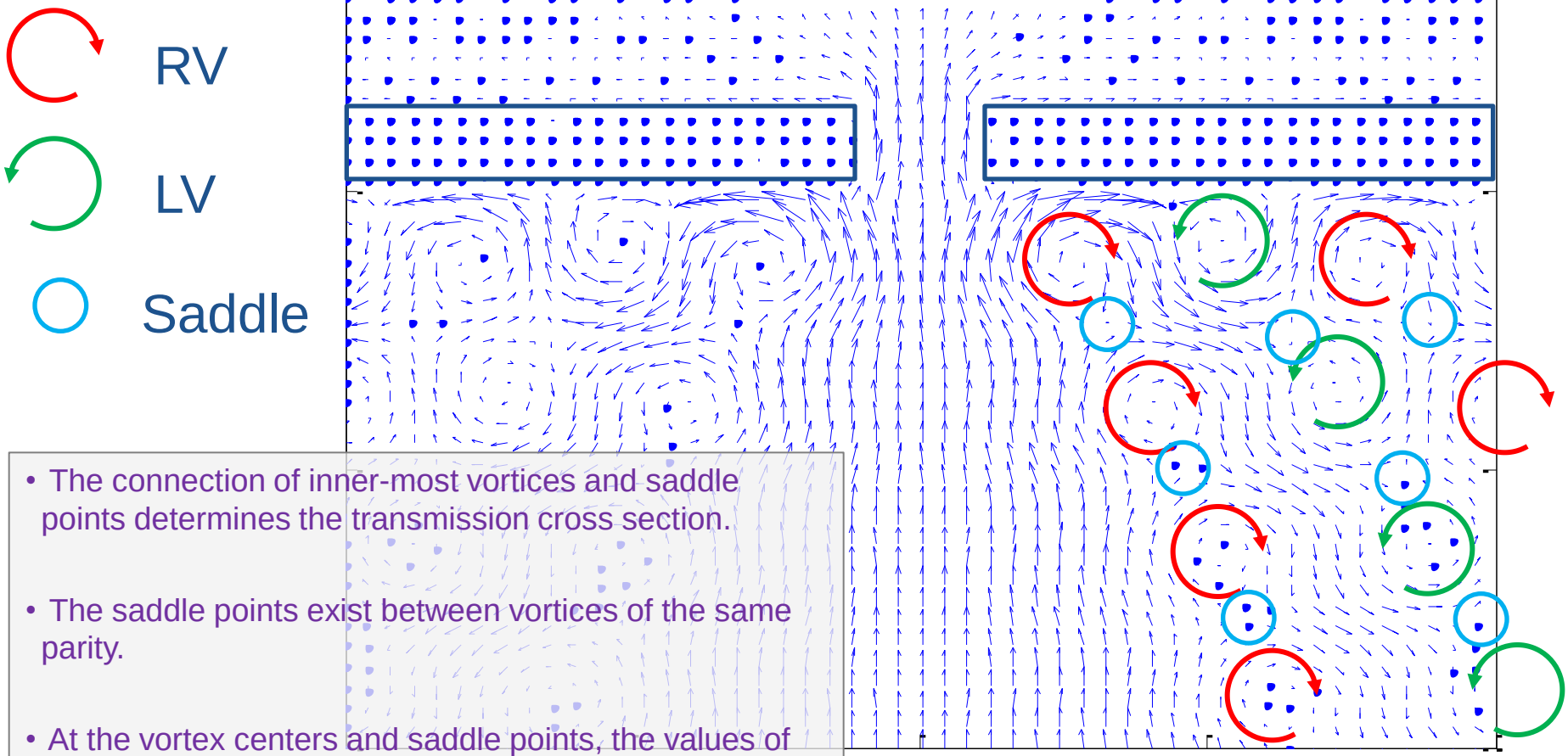
(b) $d = 60nm, \quad \omega t = \pi / 2$



(d) $d = 160nm, \quad \omega t = \pi / 2$

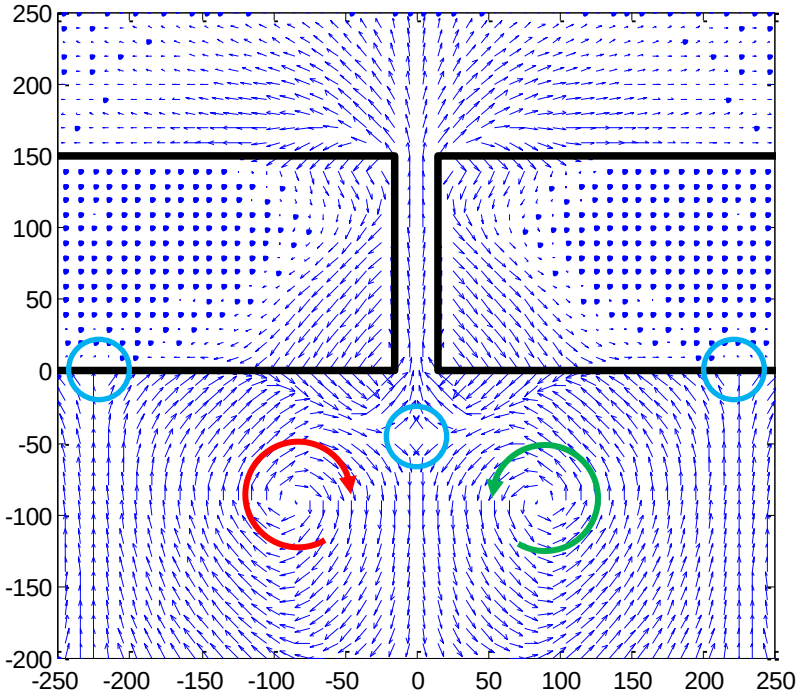


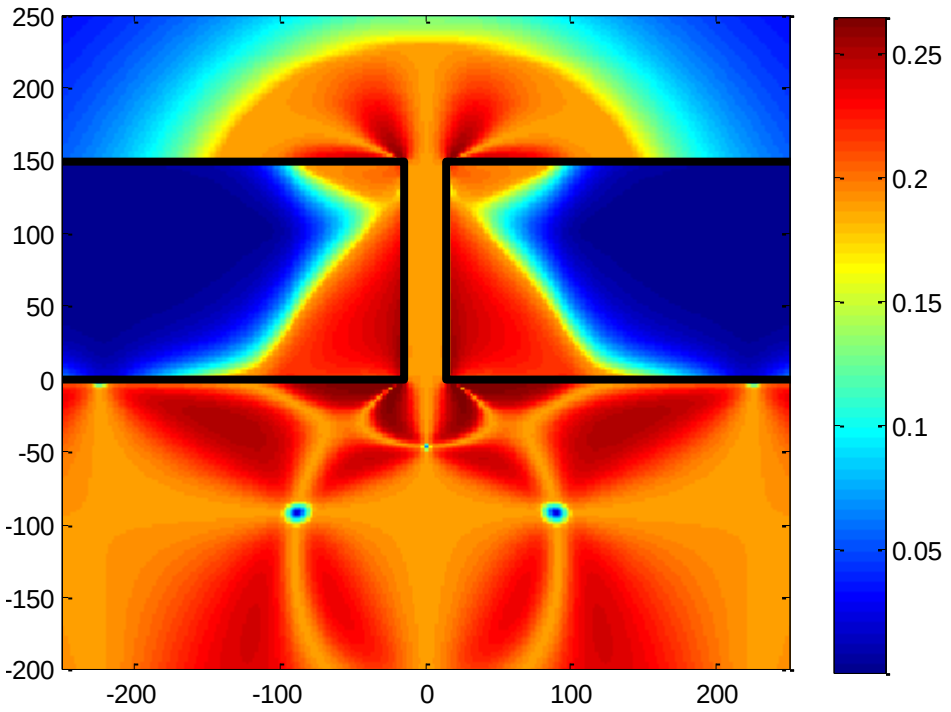
Vortex and Saddle in 2D Slit



- The connection of inner-most vortices and saddle points determines the transmission cross section.
- The saddle points exist between vortices of the same parity.
- At the vortex centers and saddle points, the values of the time-averaged Poynting vector reduce to zero.

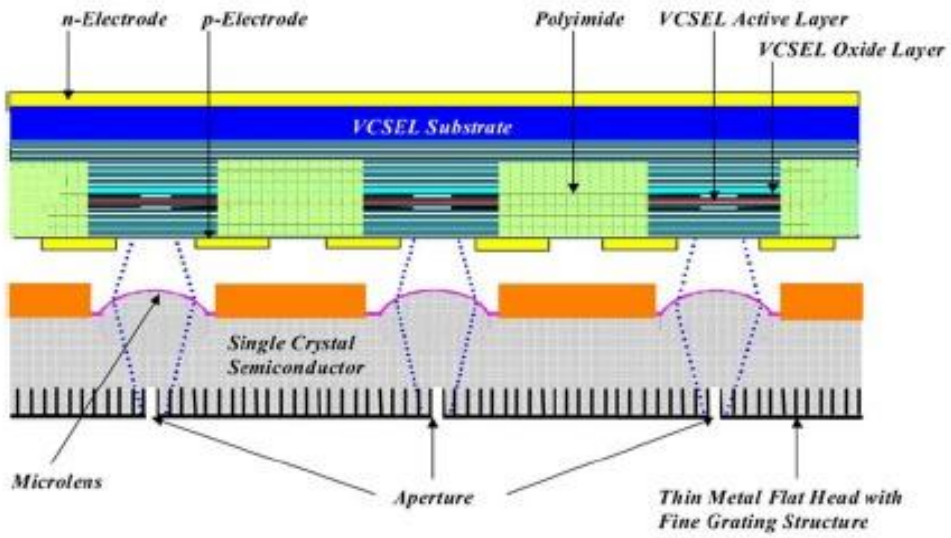
Optical Power Flow: H-aperture (3D)





Plasmonic Data Storage

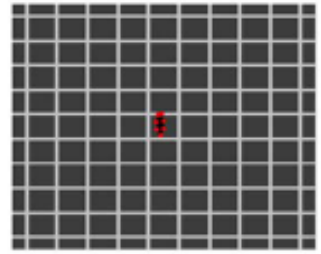
Optical memory head with VCSEL array

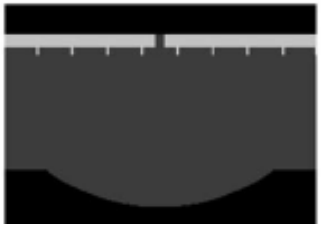


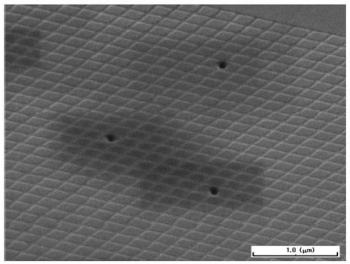
Optical efficiency enhancement at the nano aperture by the surface plasmon polariton with surface corrugation (aperture size : 30nm)

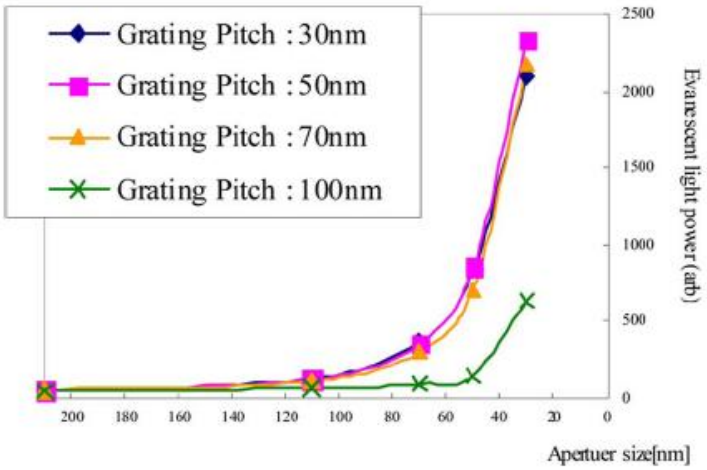
K. Goto *et al.*, *IEEE Trans. Magnet.* 43, 851 (2007).

Corrugation structure



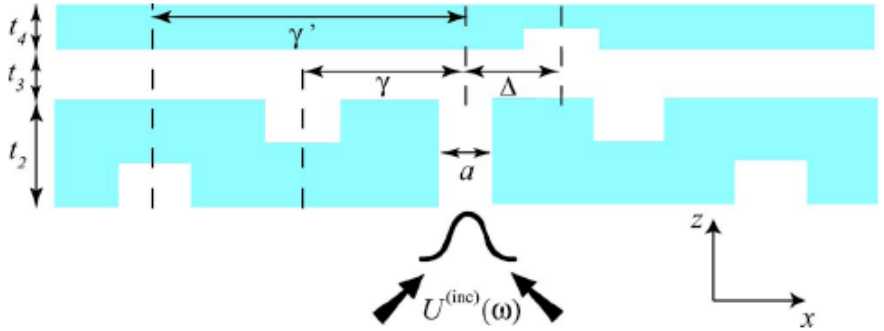






Plasmonic Data Storage

Near field transmission optical readout system

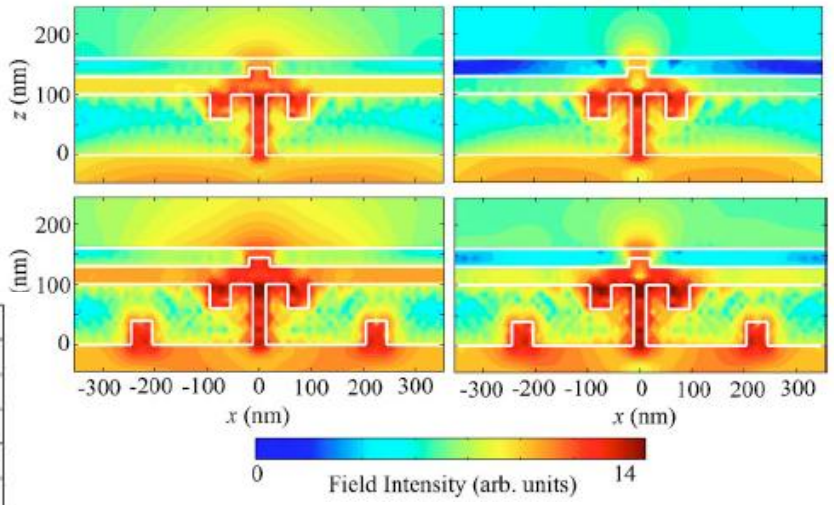


Recorded data

Moving metal plate

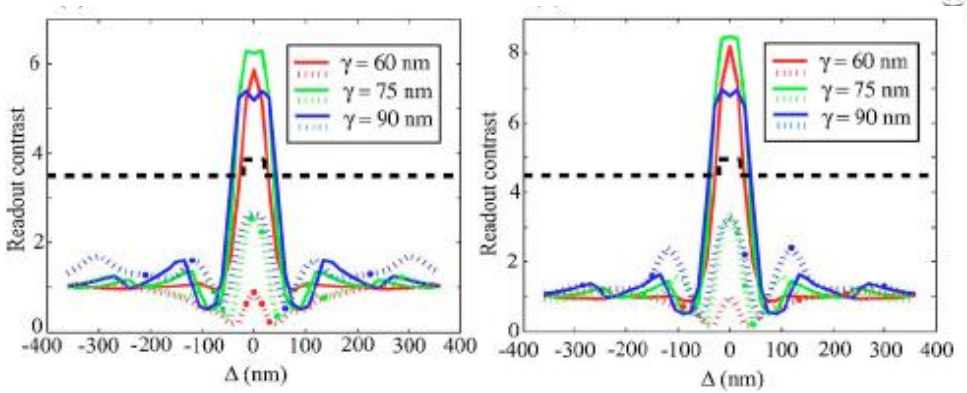
Air pit in Ag plate

Ag line in Si plate



Solid line : Air pit in Ag plate

Dashed line : Ag line in Si plate

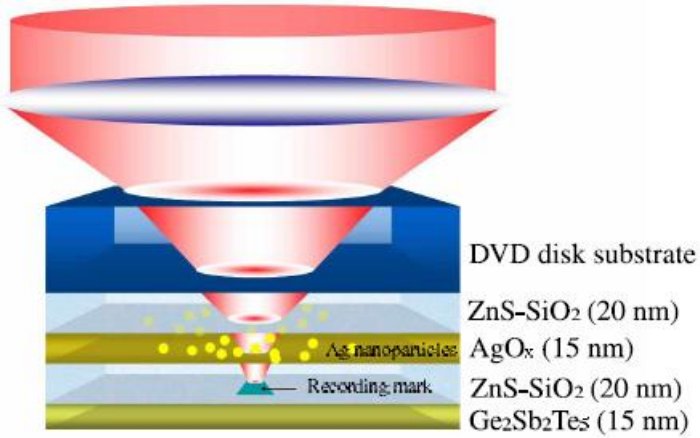


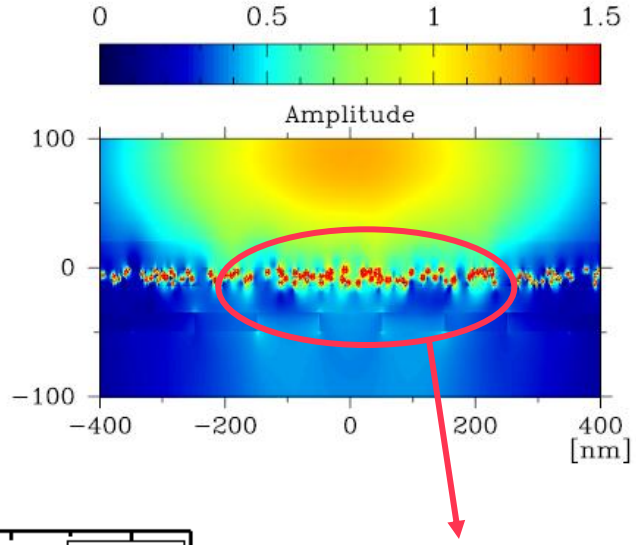
C. H. Gan et al., *Opt Express* 14, 2385 (2006).

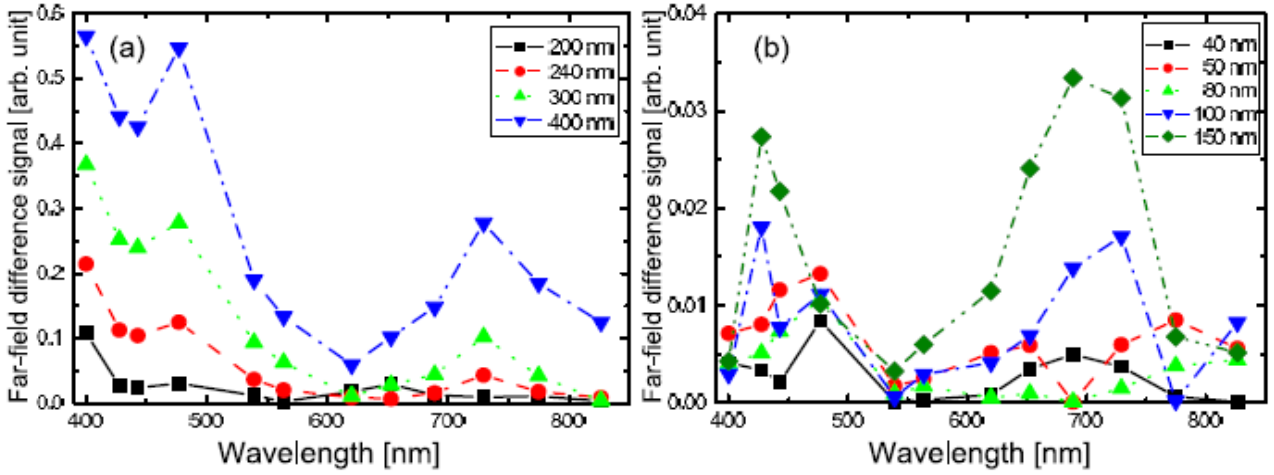
C. H. Gan *et al.*, *App. Phys. Lett. 91*, 131109 (2007).

Plasmonic Data Storage

Near field optical disk with silver nanoparticles





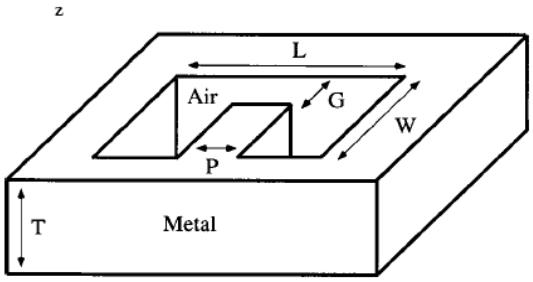


Local field enhancement near the silver nanoparticle

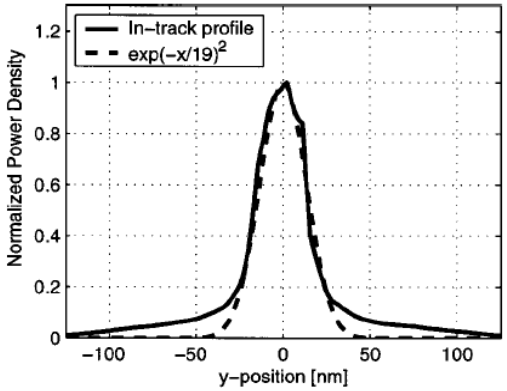
M.-Y. Ng et al., *Opt Express* 13, 9422 (2005).

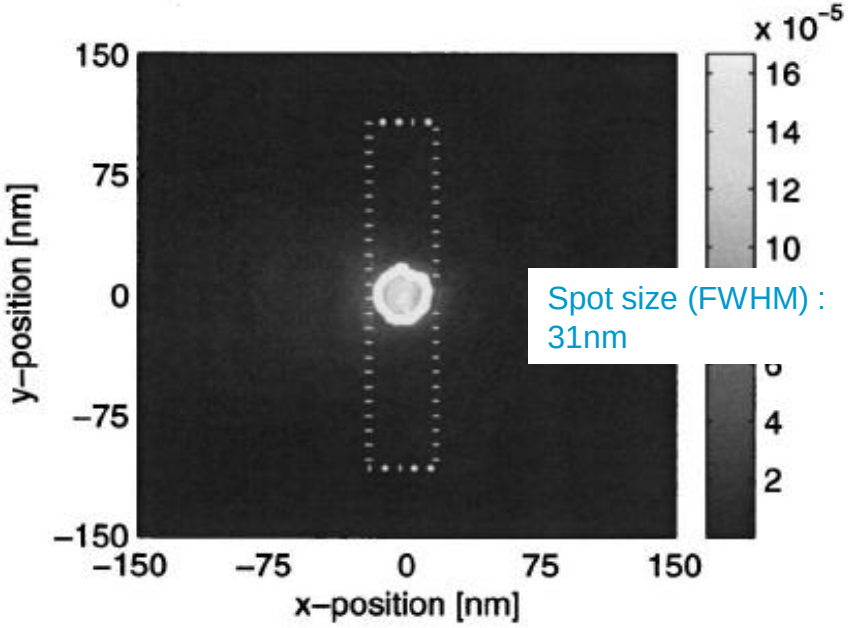
Plasmonic Data Storage

Ridge waveguides near field aperture for high density data storage

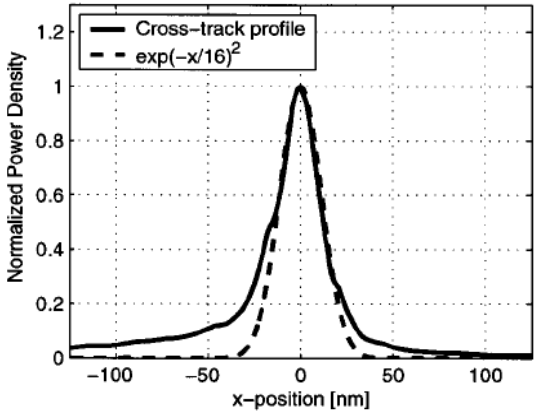


Ridge waveguide transducer





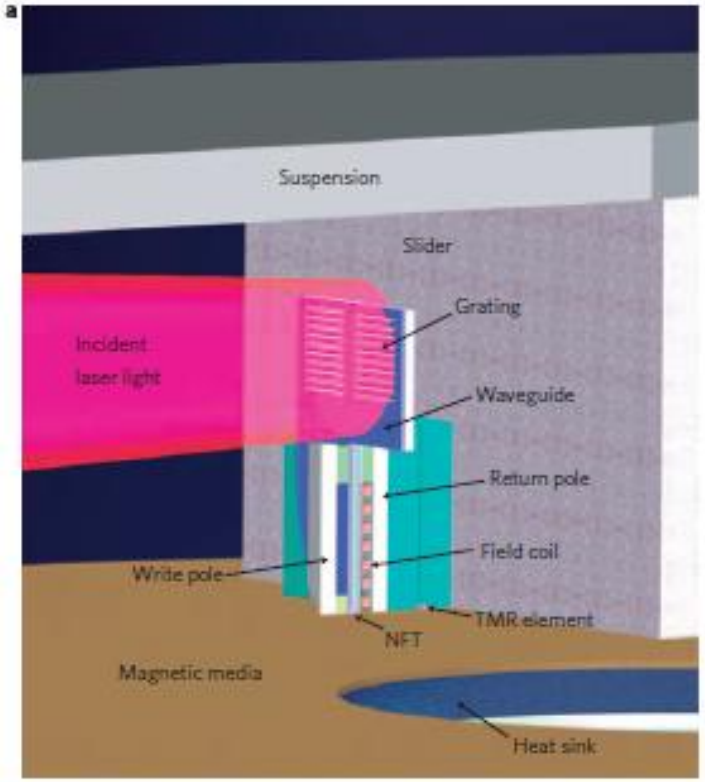
Spot size (FWHM) : 31nm

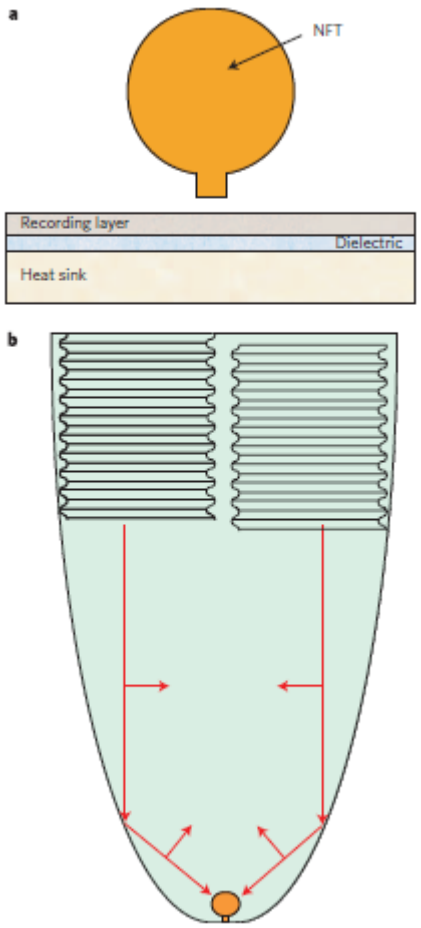


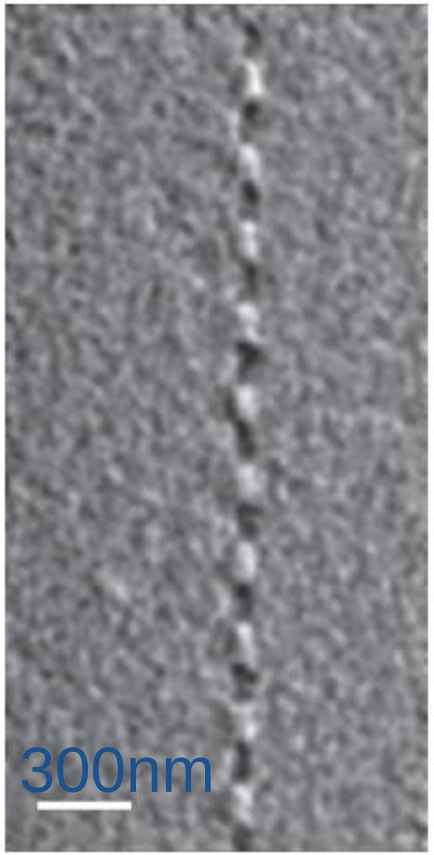
K. Sendur et al., *J. App. Phys.* 96, 2743 (2004).

Heat Assisted Magnetic Recording (HAMR)

Plasmonic transducer for local heating source

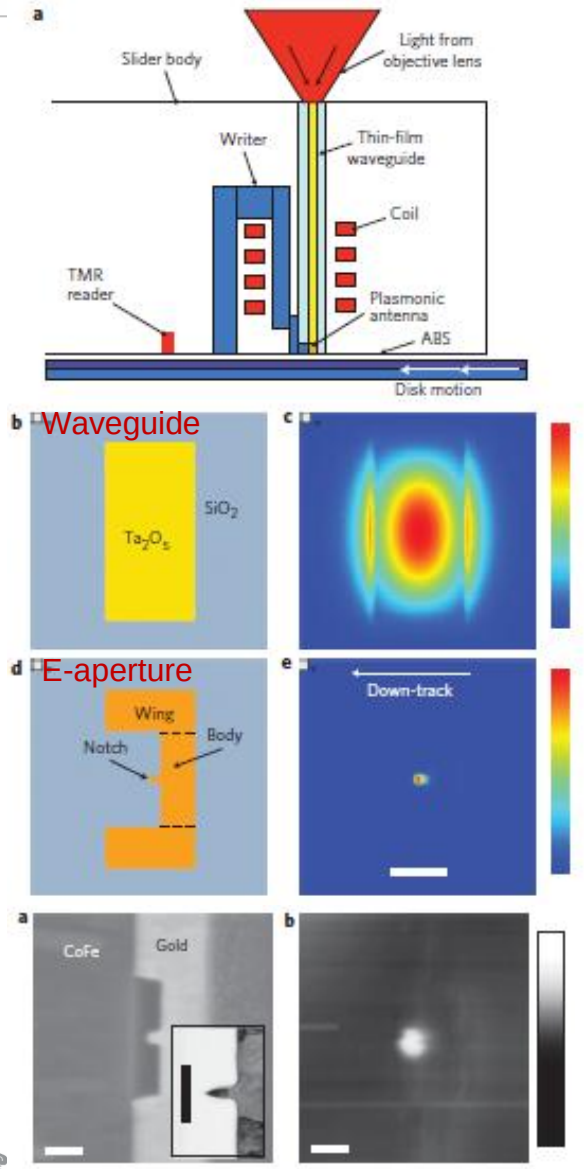






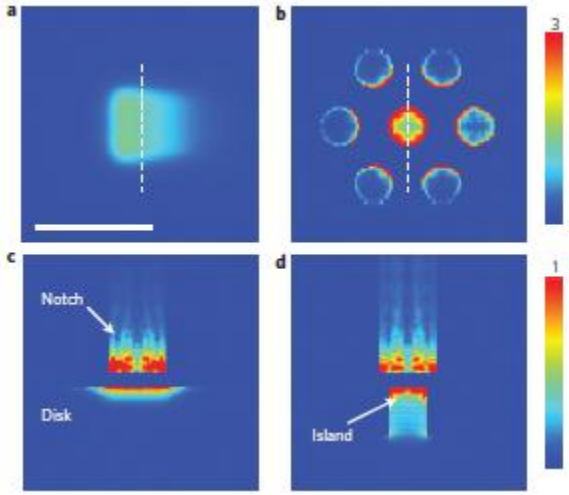
W. A. Challener *et al.*, *Nature Photon.*, 3, 220 (2009)

Bit Patterned Media with HAMR

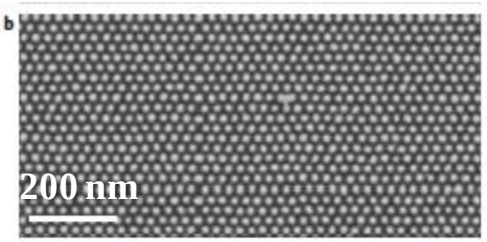


'E'-shaped plasmonic antenna for BPM + HAMR

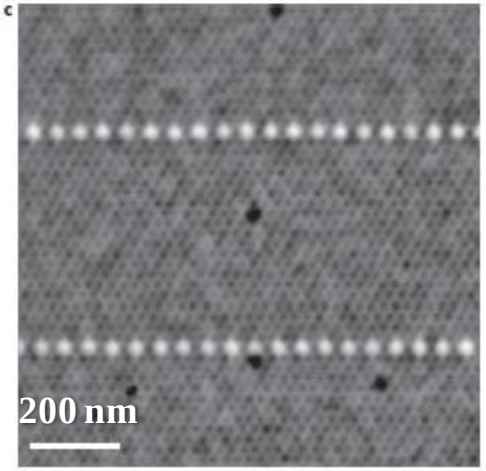
- Disk surface absorption profile



24 nm bit-pitch



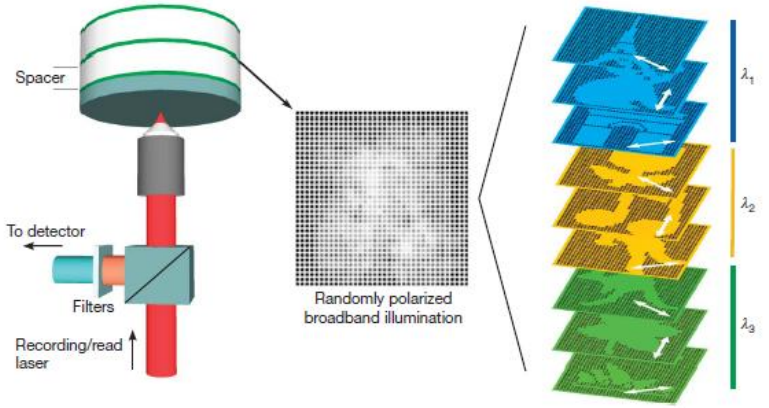
28 nm bit-pitch recorded track
(1.5 Pb m^{-2} (1 Tb in^{-2}))

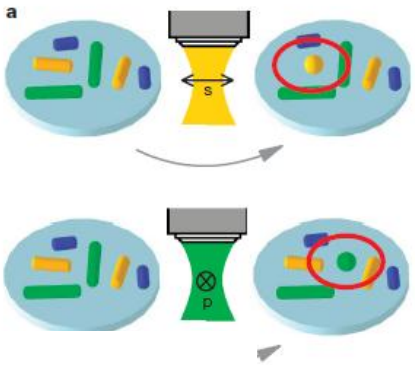


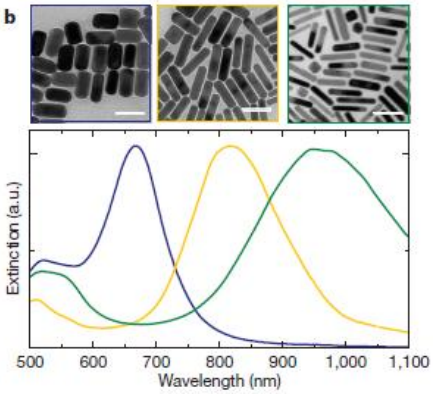
B. C. Stipe *et al.*, *Nature Photon.*, 4, 484 (2010)

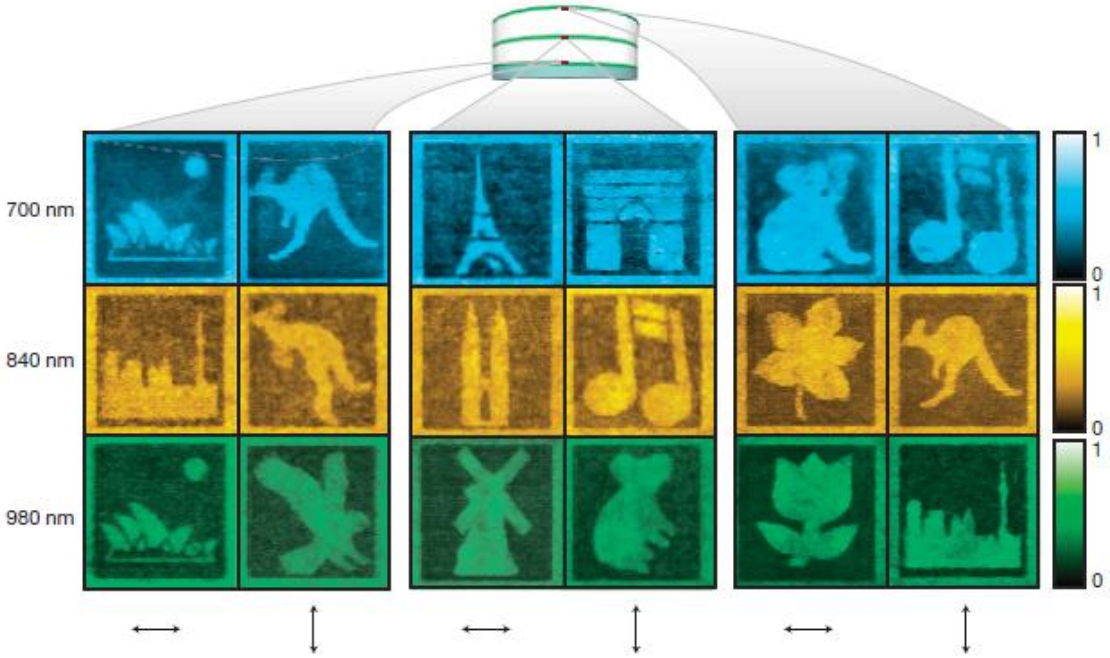
Other Plasmonic Storage – 5D Storage

position (3D) + polarization + wavelength







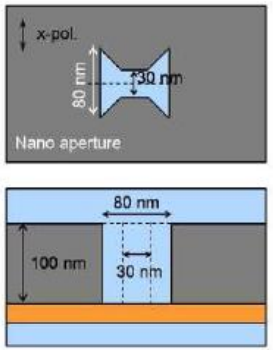


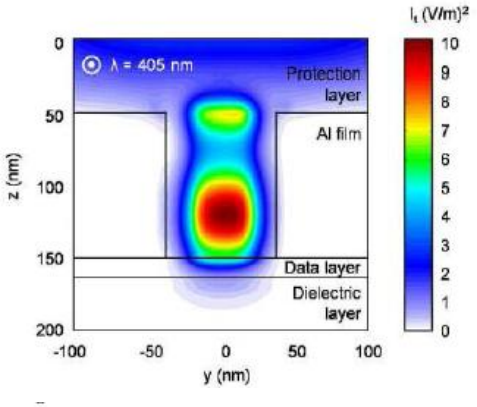
$1.1\ \mathrm{Tb\ cm^{-3}}$ ($\sim 16.4\ \mathrm{Tb\ in^{-3}}$)

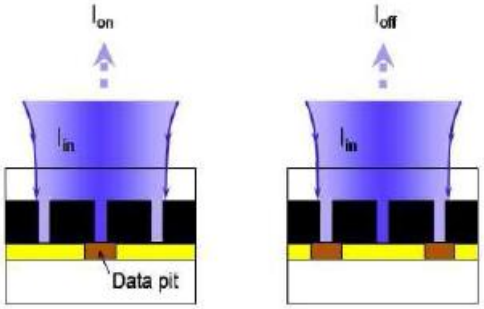
P. Zijlstra *et al.*, *Nature*, 459, 410 (2009)

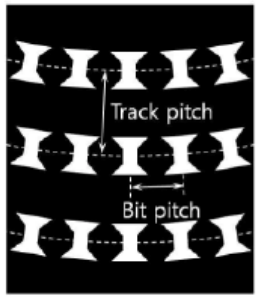
Other Plasmonic Storage – Nano Aperture Pattern

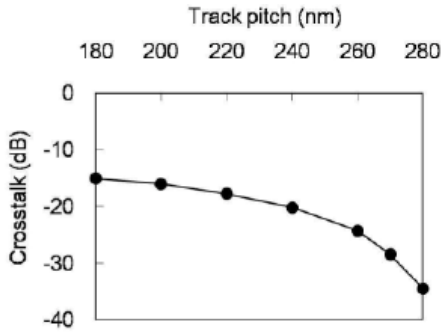
Aperture attached on recording medium

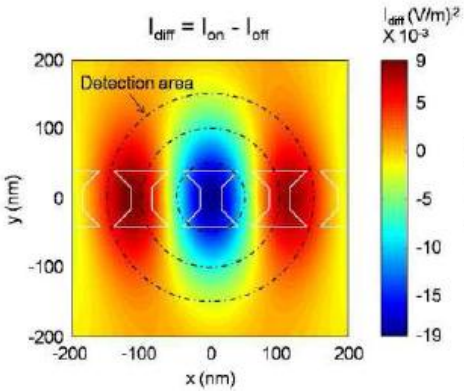


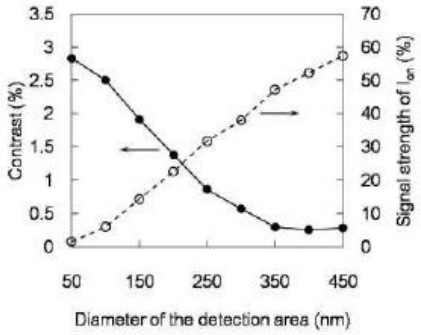












on-off state contrast

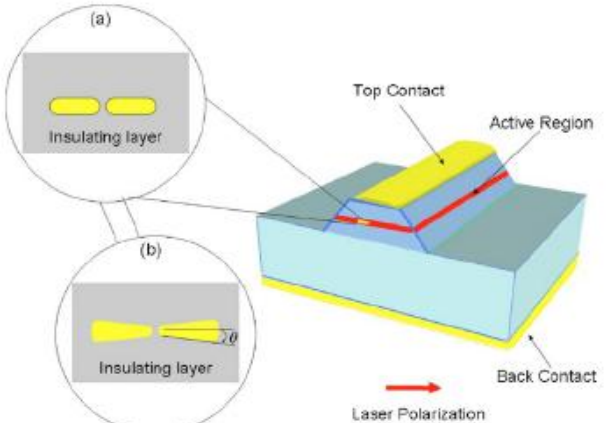
50 nm bit cell with 280 nm pitch

~ 1.2 times denser than conventional Blu-ray

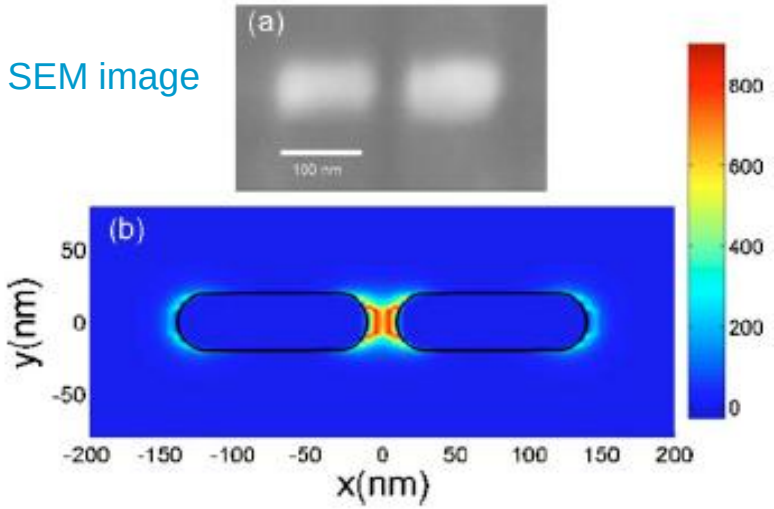
S. Park *et al.*, *Opt. Express*, 17,20203 (2009)

Very Small Aperture Lasers

Optical resonant antenna integrated on the facet of diode laser

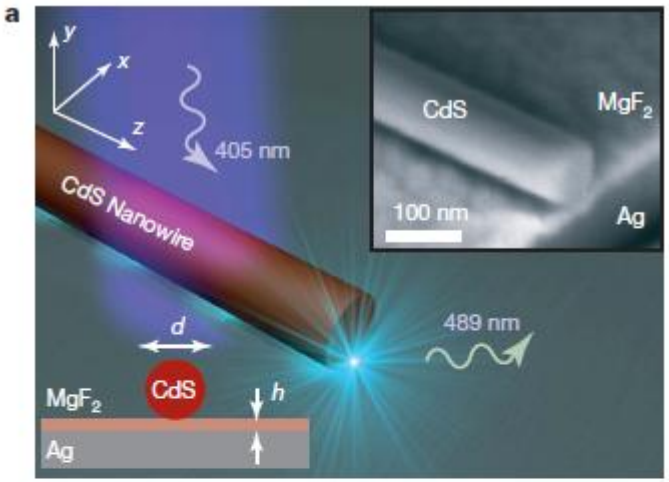


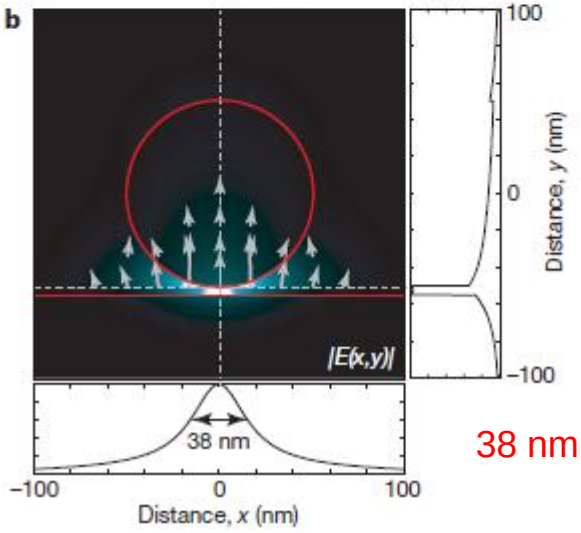
SEM image



E. Cubukcu et al., *App. Phys. Lett.* 89, 093120 (2006).

Plasmonic laser

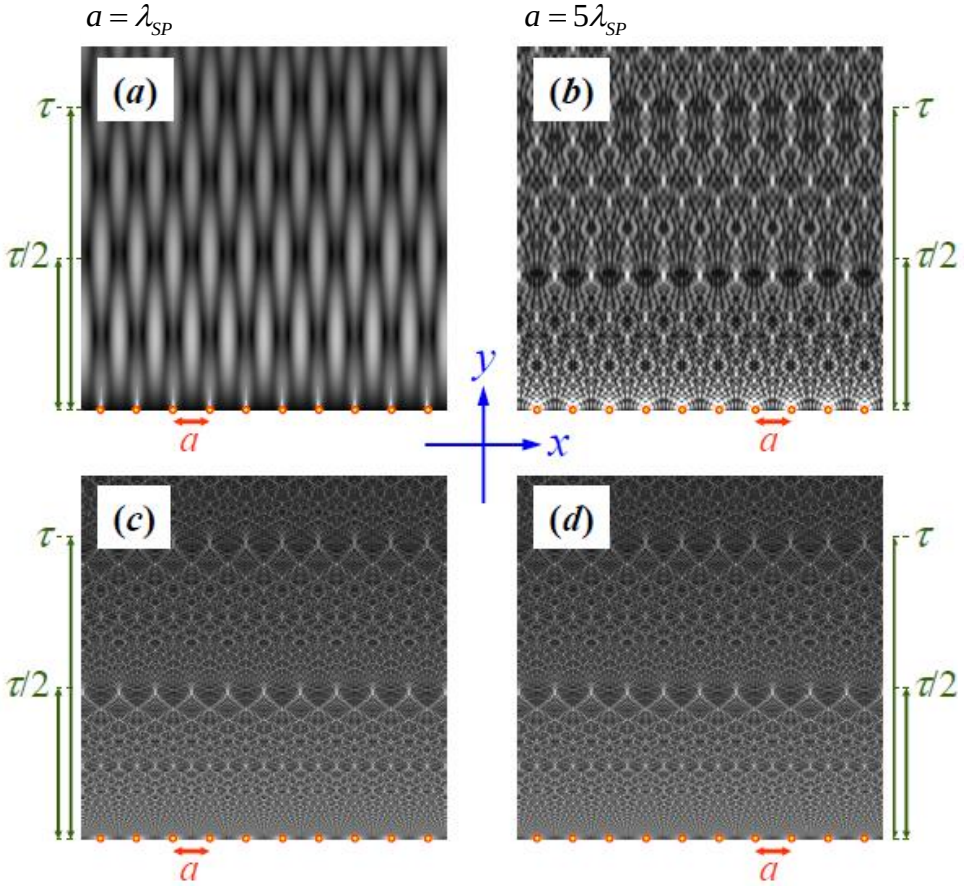




38 nm spot size

R. F. Oulton et al., *Nature* 461, 629 (2009).

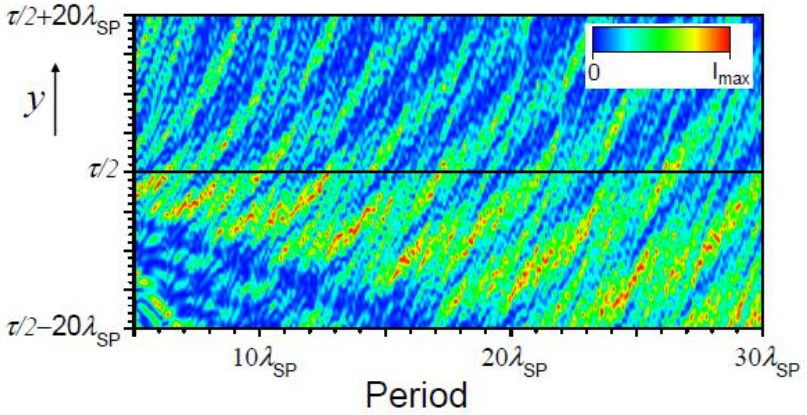
Plasmon Talbot Effect



$a = 20\lambda_{SP}$
(Full-wave simulation)

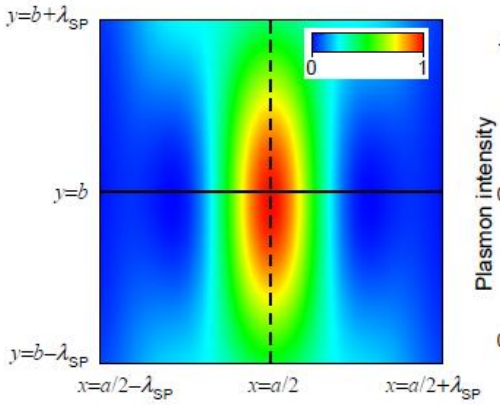
$a = 20\lambda_{SP}$
(Analytical approximation)

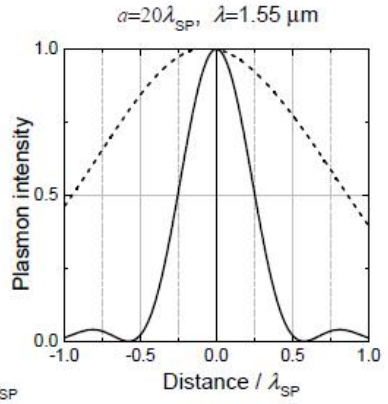
Intensity vs. period a



$\tau = 2a^2 / \lambda_{SP}$: Talbot distance

$b = \tau / 2 - 5\lambda_{SP}$





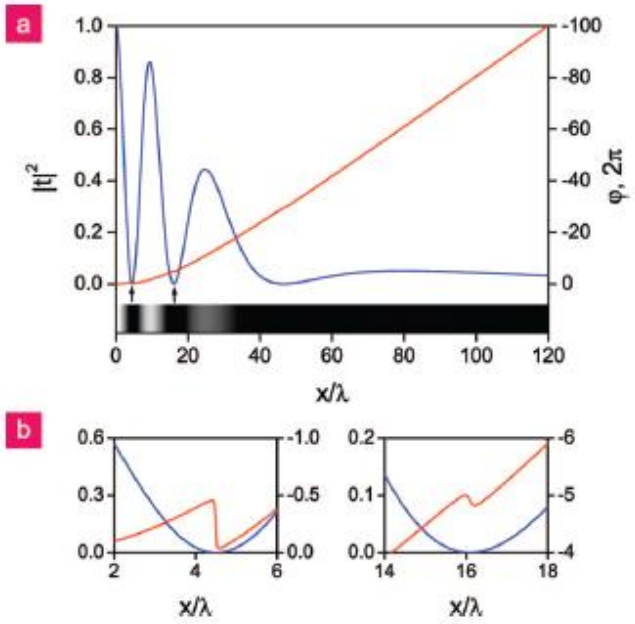
M. R. Dennis, N. I. Zheludev, and F. J. Garcia de Abajo, *Opt. Express* **15** 9692 (2006).

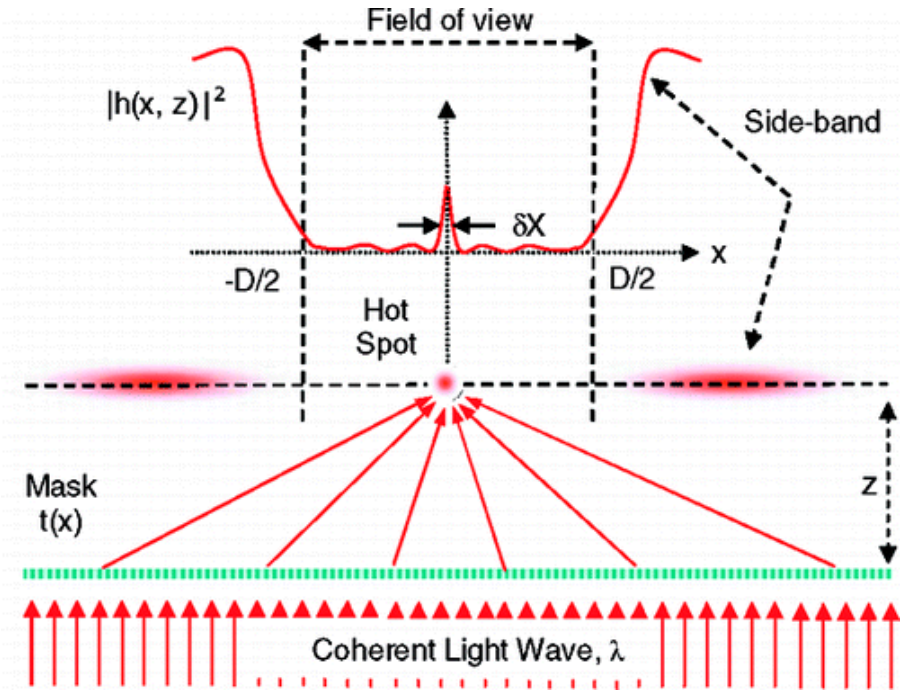
Super-Resolution without Evanescent Waves

Mask profile

Red: phase

Blue: intensity





F. M. Huang and N. I. Zheludev, *Nano Lett.* **9** 1249 (2009).