



Surface plasmons: beam engineering, active integration, and nonlinear process

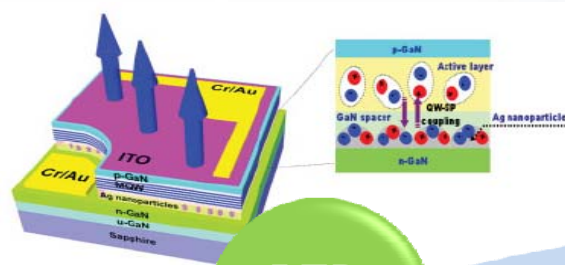
Tao LI (李涛)

taoli@nju.edu.cn

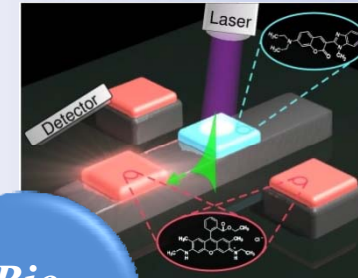
National Laboratory of Microstructures,
College of Engineering and Applied Sciences,
Nanjing University



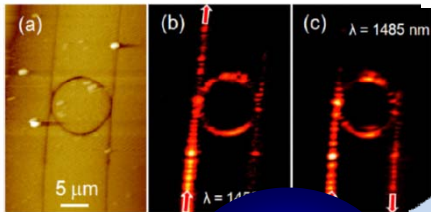
Introduction



LED
Solar cell



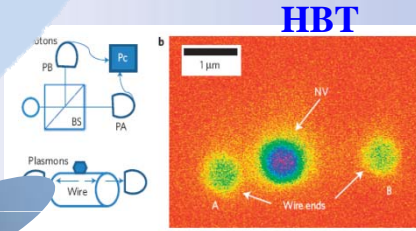
Bio
Sensor



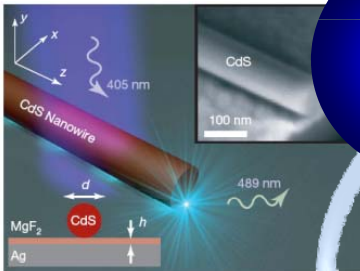
Sub-λ
optics

Plasmonics

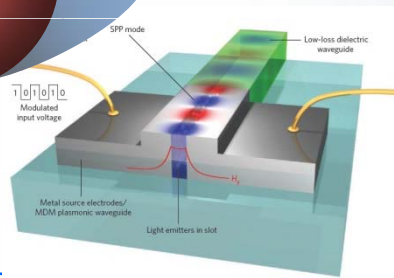
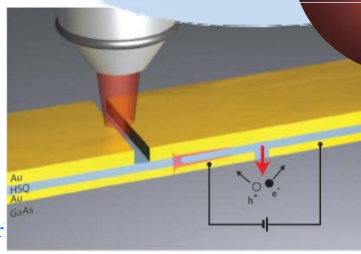
Quantum
property



HBT

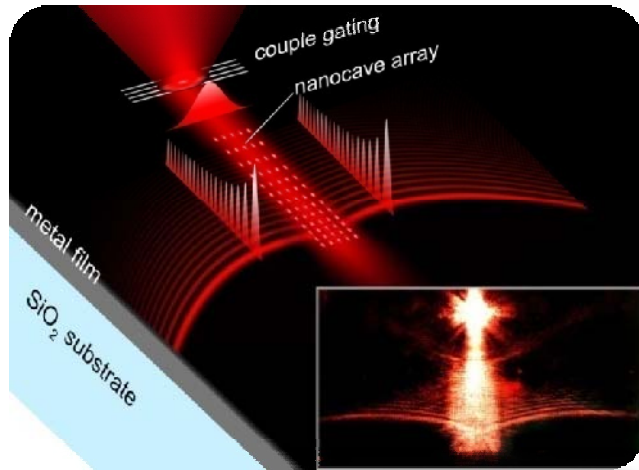


Others

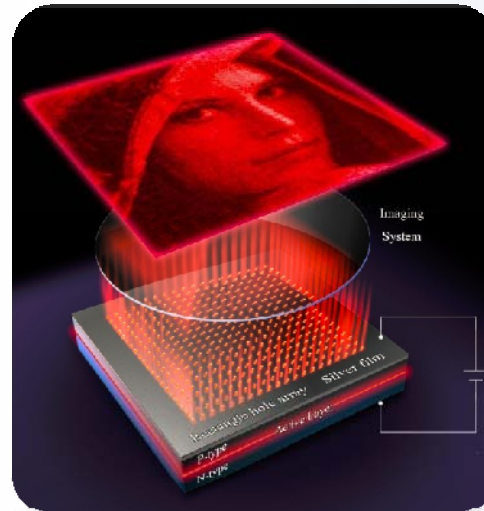




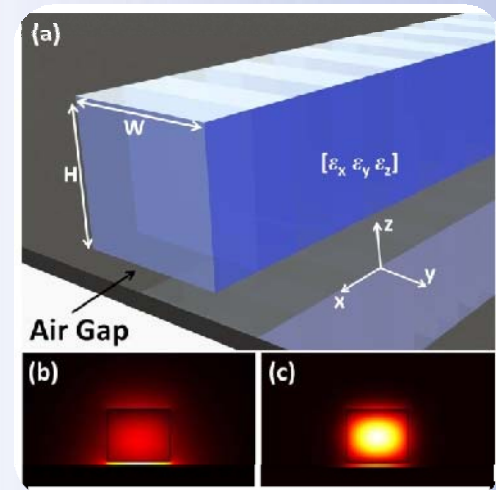
Content



In-plane manipulation
SPP propagation



Plasmonic active
integration



Nonlinear process of
hybrid SPP waveguide



Part I

Steering SPP beam by in-plane diffraction (phase game)

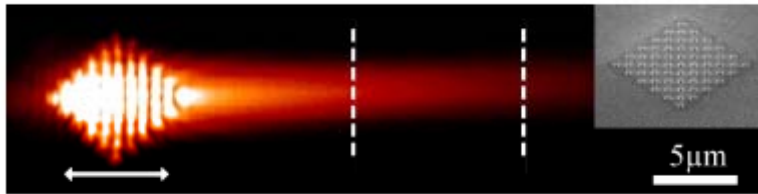


Outline

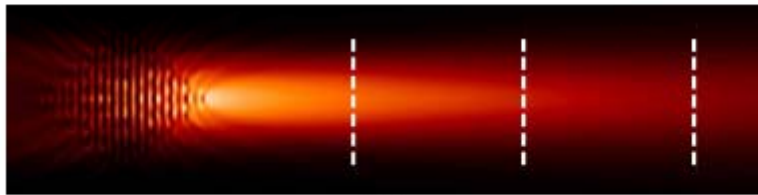
- Background
- In-plane manipulation of SPP
 - (I) Airy Plasmon
 - (II) Broadband SPP focusing
 - (III) Collimated SPP beam
- Conclusion and perspective



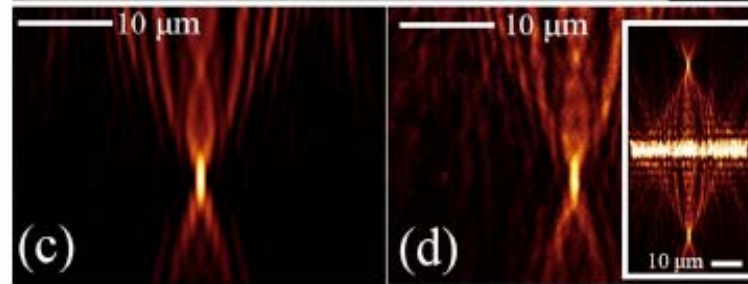
Manipulation of SPP



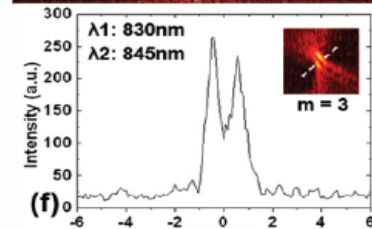
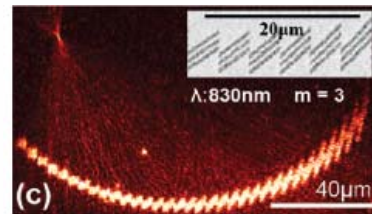
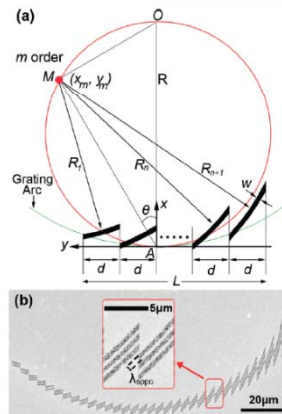
(a)



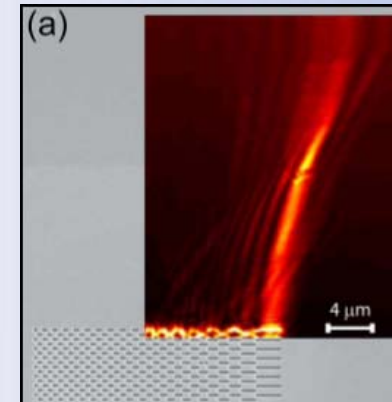
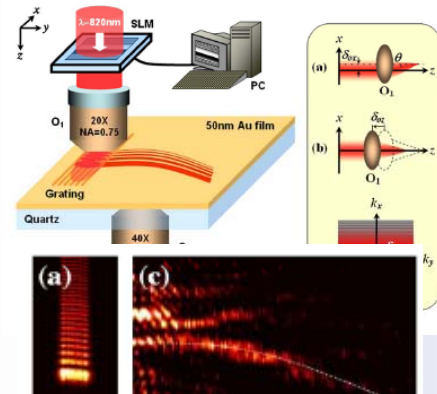
Collimate beam, OE 15, 3488 (2007)



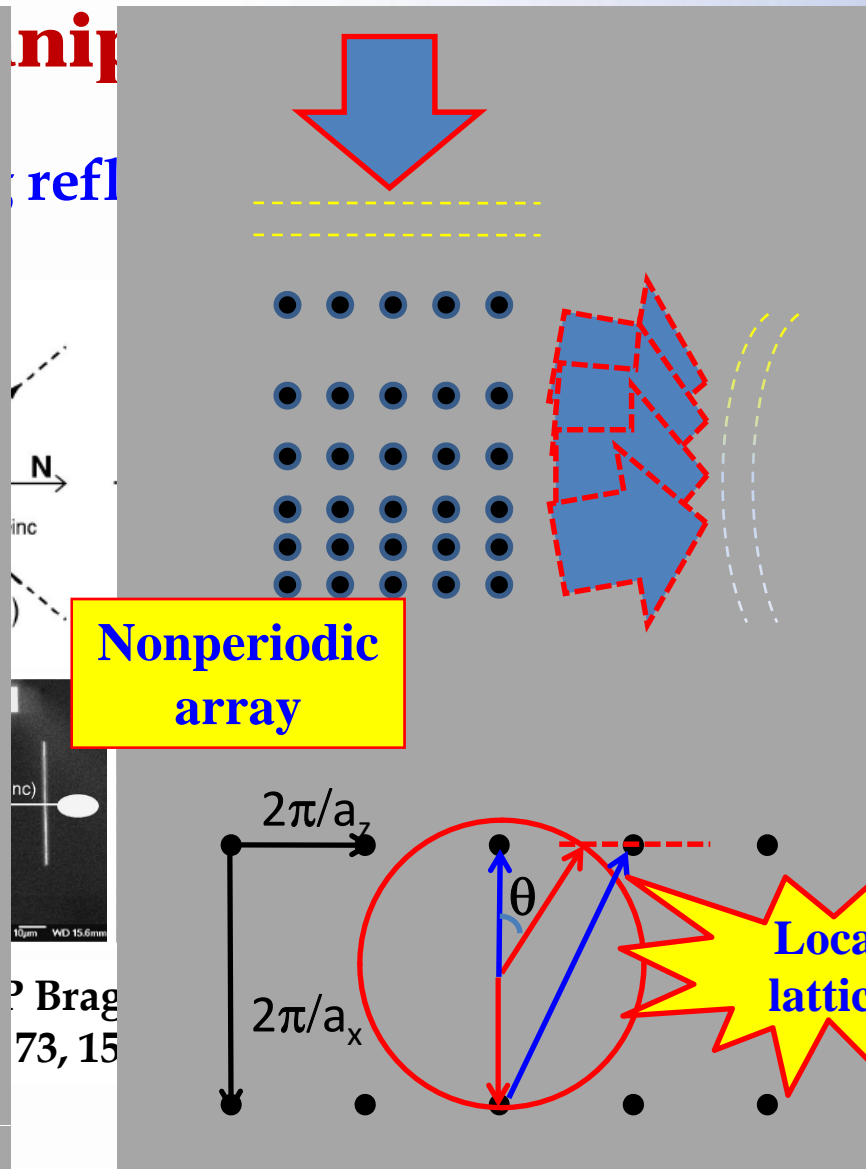
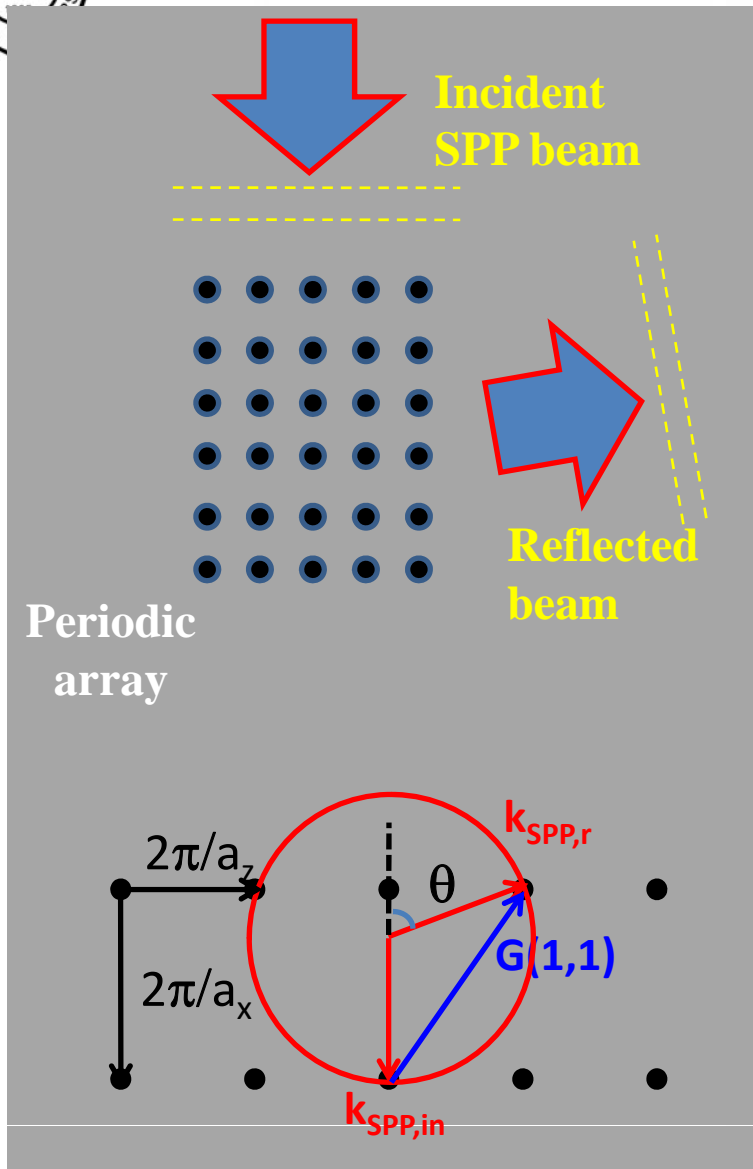
SPP focusing, OL 16, 2417 (2009)



SPP WDM, ACS Nano 4, 6433 (2010)

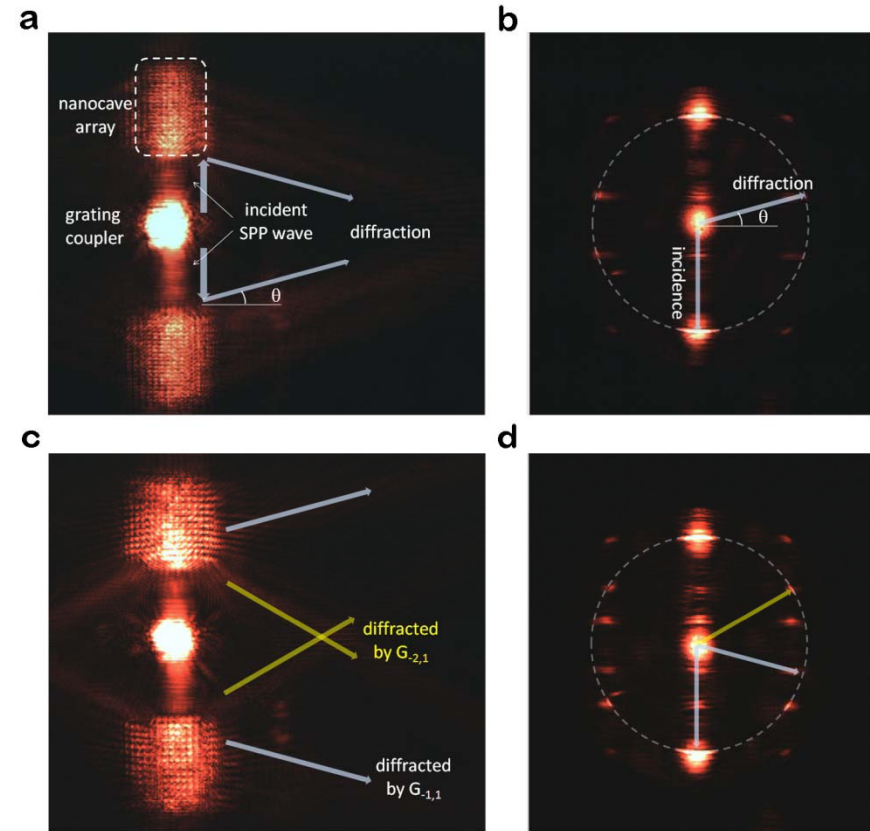
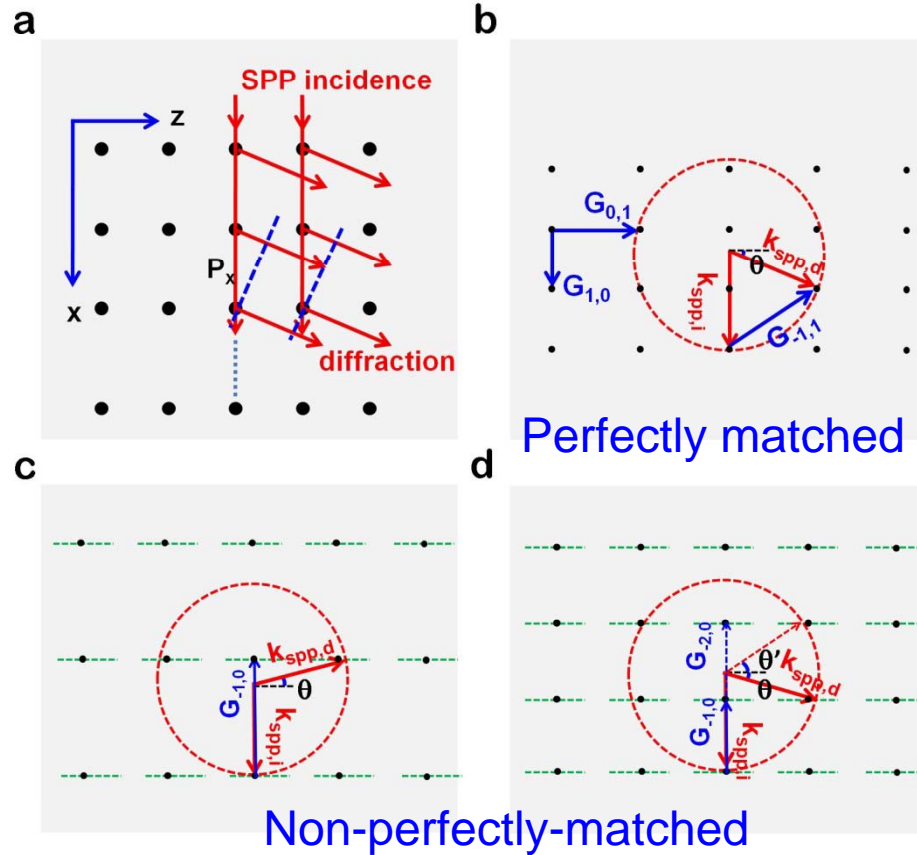


Airy Plasmon
OL 36, 3191 (2011), PRL 107, 116802 (2011)





Verification

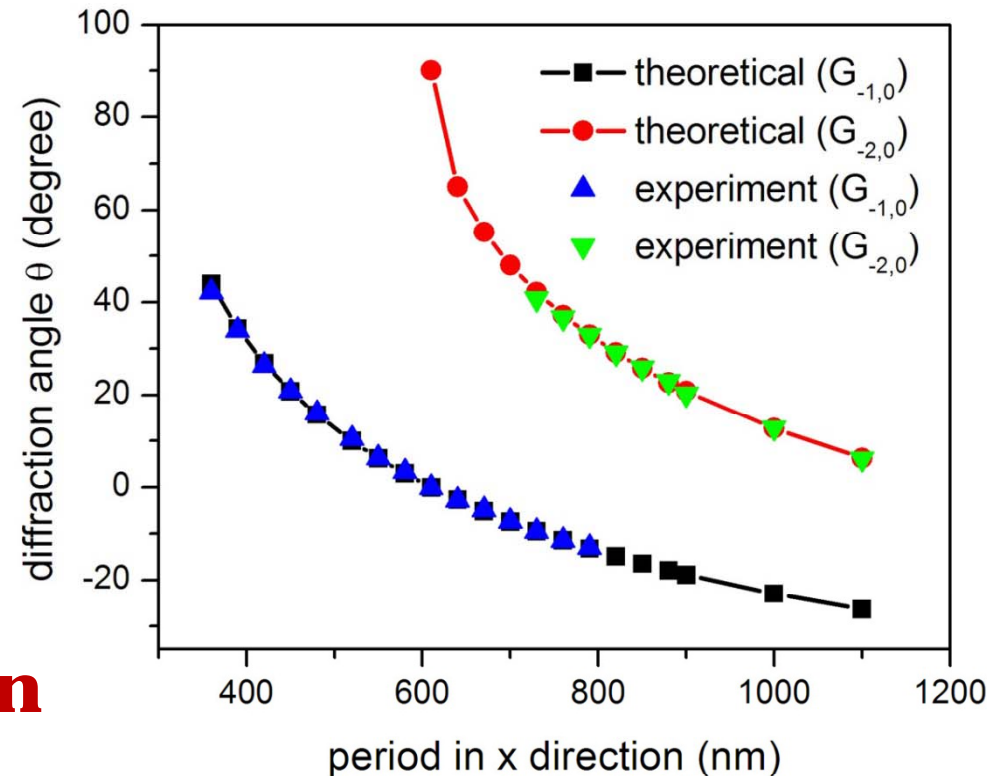


**Elongated reciprocal lattice
due to the finite nanoarray**

LRM observation



further verification



- Non-perfectly-matched conditions do *have* constructive diffraction.
- Constructive diffraction means 2π phase difference between every neighbor units.
- It is possible to design *the local lattices* to tailor the beaming angles, as well as the complicated phase.



(a) SPP Airy beam

For a 2D paraxial wave equation

$$\frac{\partial^2 \phi}{\partial x^2} + 2ik \frac{\partial \phi}{\partial z} = 0$$

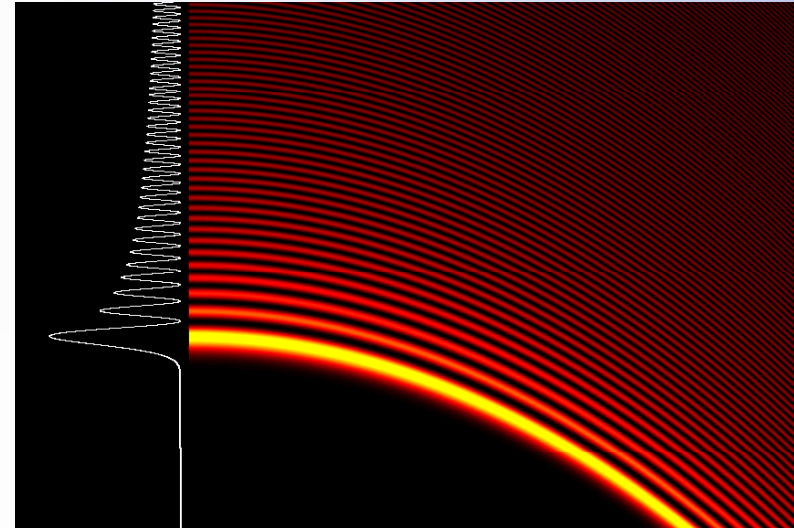
Schrödinger Eq.

$$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} = i\hbar \frac{\partial \psi}{\partial t}$$

$$\text{Ai}(x) = \begin{cases} \frac{1}{\pi} \sqrt{\frac{x}{3}} \text{K}_{1/3} \left(\frac{2}{3} x^{3/2} \right), & (x > 0) \\ \frac{\sqrt{-x}}{3} \left[\text{J}_{1/3} \left(\frac{2}{3} (-x)^{3/2} \right) + \text{J}_{-1/3} \left(\frac{2}{3} (-x)^{3/2} \right) \right], & (x < 0) \end{cases}$$

Phase modulation

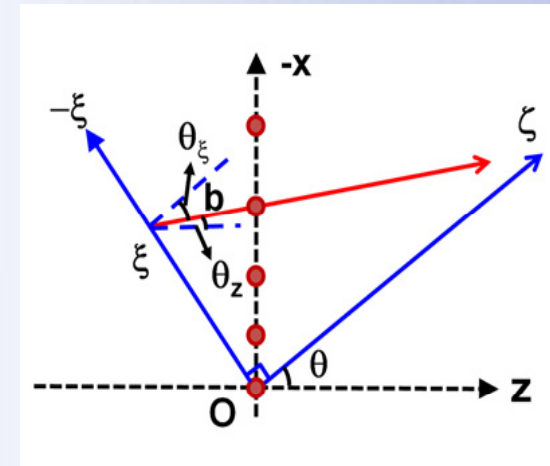
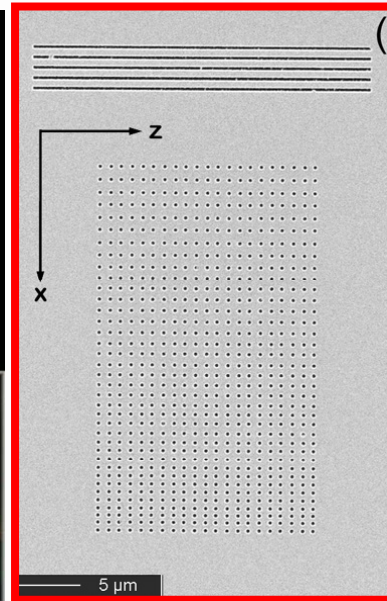
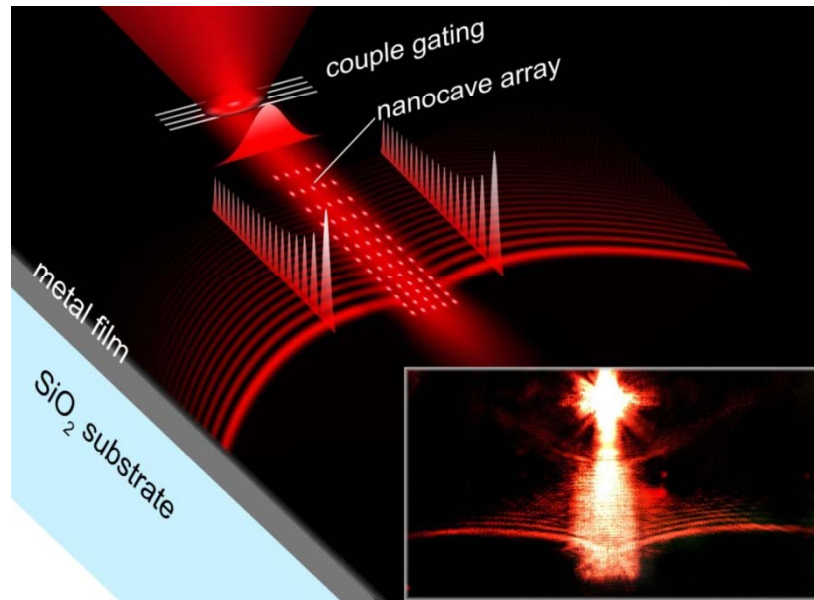
$$\psi(x) = -\frac{2}{3} \left(-\frac{\xi}{\xi_0} \right)^{3/2} - \frac{\pi}{4} - k \frac{\xi \sin \theta}{\cos(\theta - \theta_\xi)}$$



non-spreading,
non-diffraction
self-bending,
self-accelerating,
self-healing



Phase design for Airy plasmon



$$\phi(\xi) = \phi(x) - k_{spp}b = 2m\pi + k_{spp}x - k_{spp}b,$$

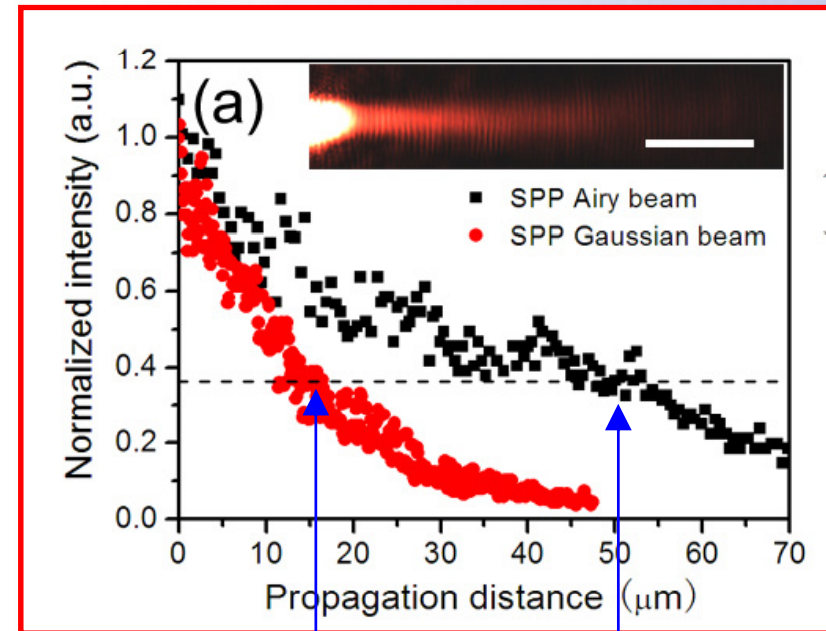
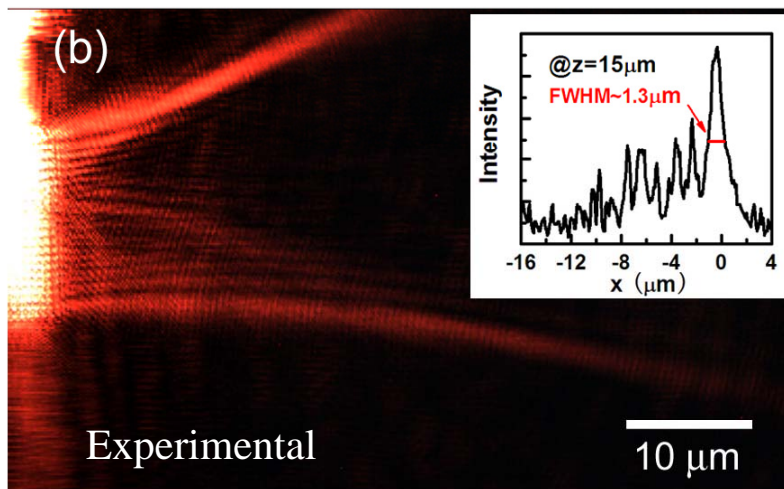
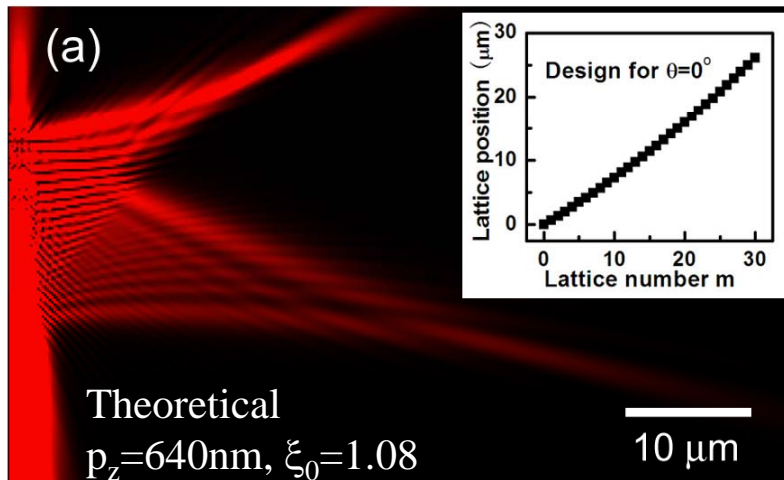
Airy beam requires

$$\psi(x) = -\frac{2}{3} \left(-\frac{\xi}{\xi_0} \right)^{3/2} - \frac{\pi}{4} - k \frac{\xi \sin\theta}{\cos(\theta - \theta_\xi)},$$

Solving $\phi(\xi)=\psi(x)$, we can get the lattice parameter $a(x)$!



Generation of Airy beam

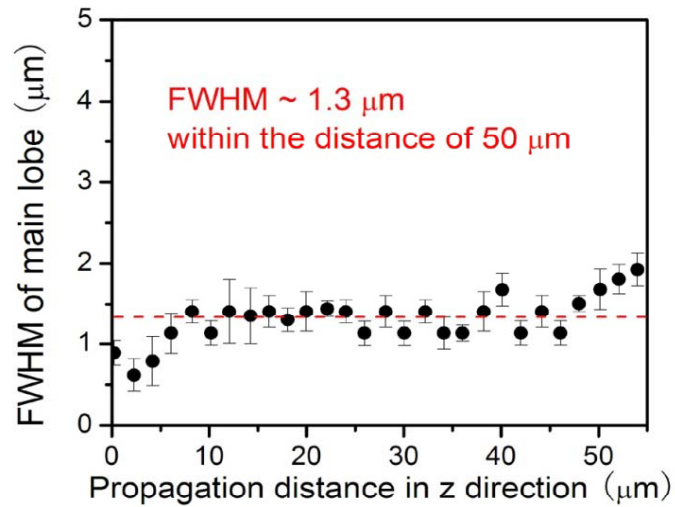


$L \approx 15\mu\text{m}$

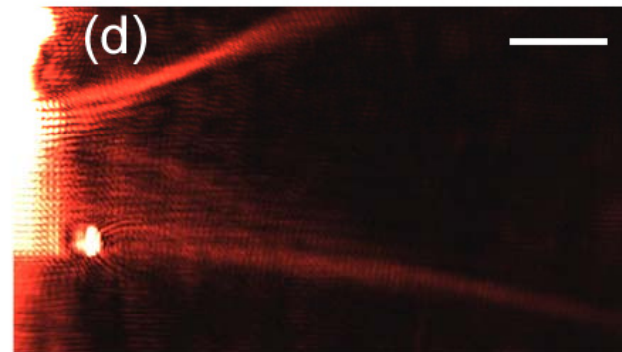
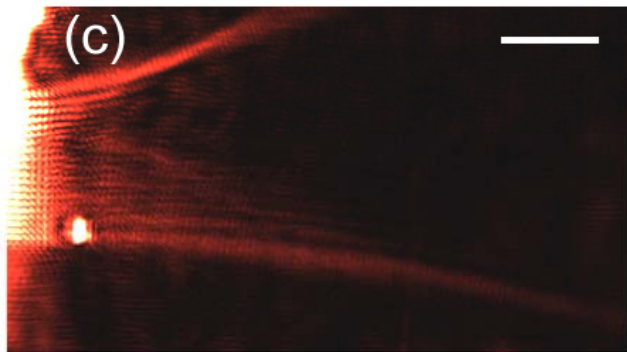
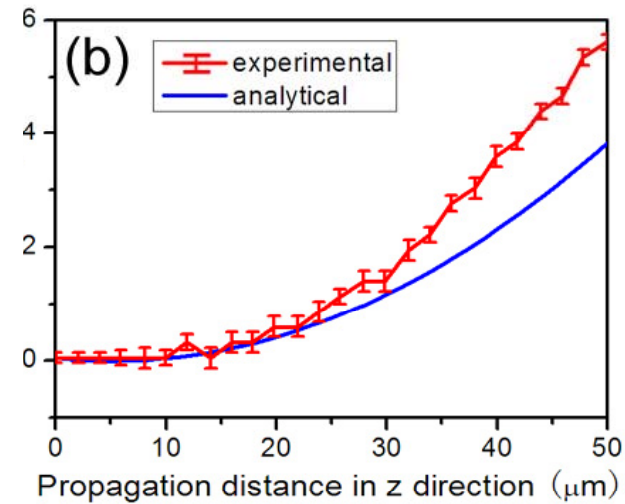
$L \approx 50\mu\text{m}$,
>3 times than the Gaussian beam



Non-spreading beam



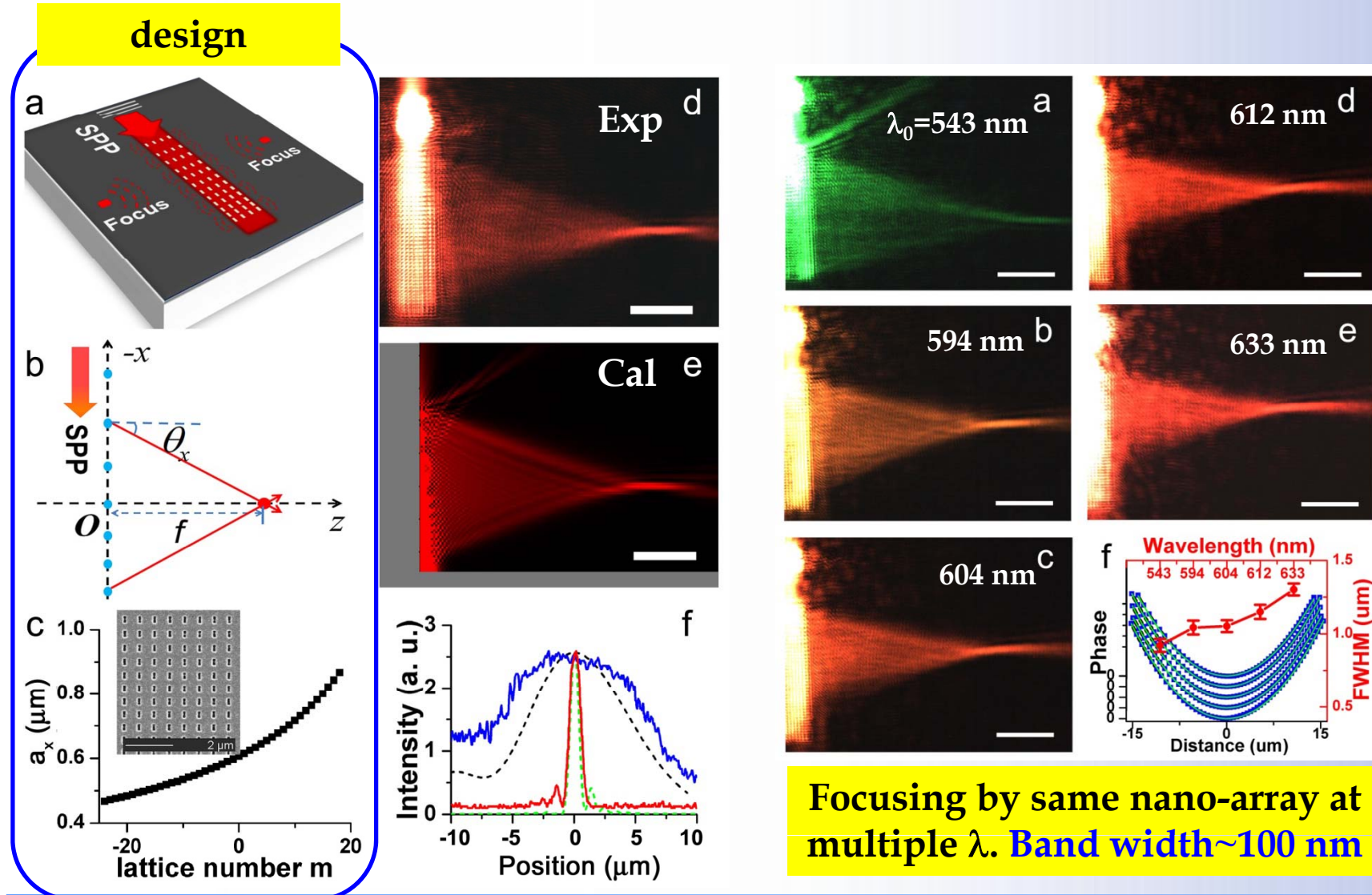
Parabolic trajectory



Self-healing property

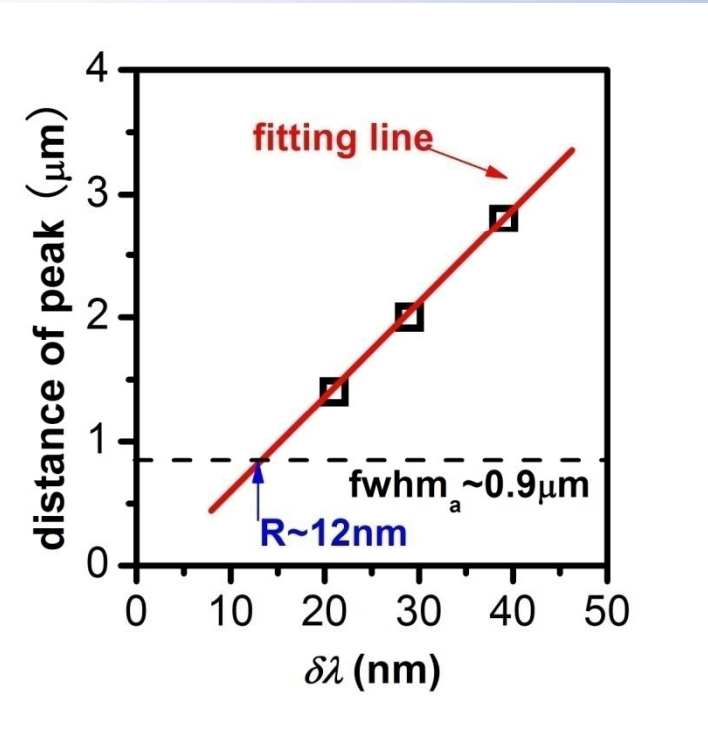
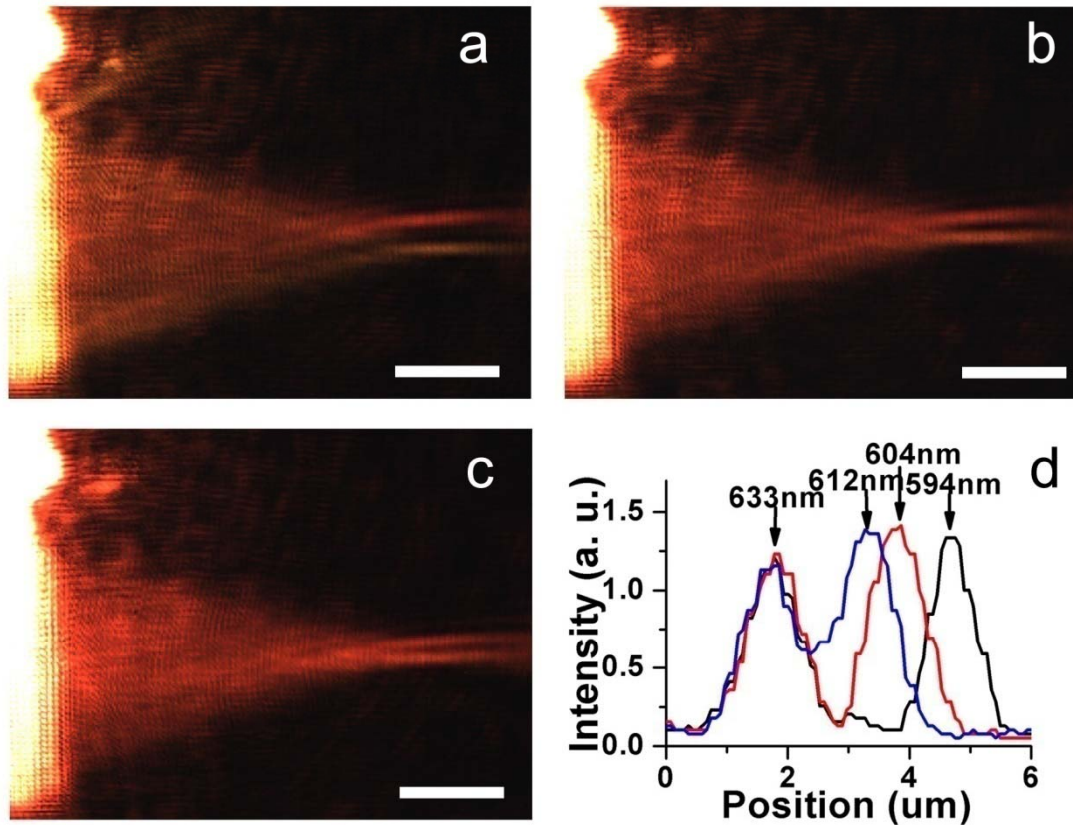


(II) Broadband SPP focusing





Working as SPP demultiplexer



WDM resolution $\sim 12 \text{ nm}$

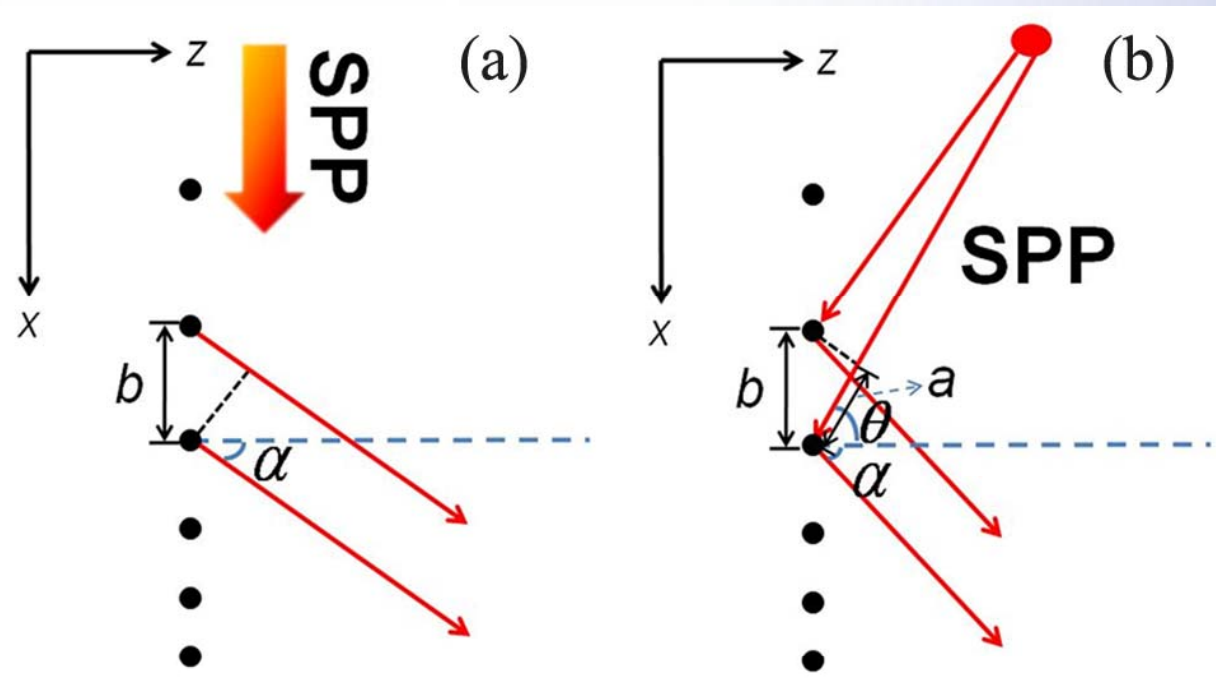
$$R = \Delta\lambda(d = \text{fwhm}_a)$$

Nano Lett. 11, 4357 (2011)



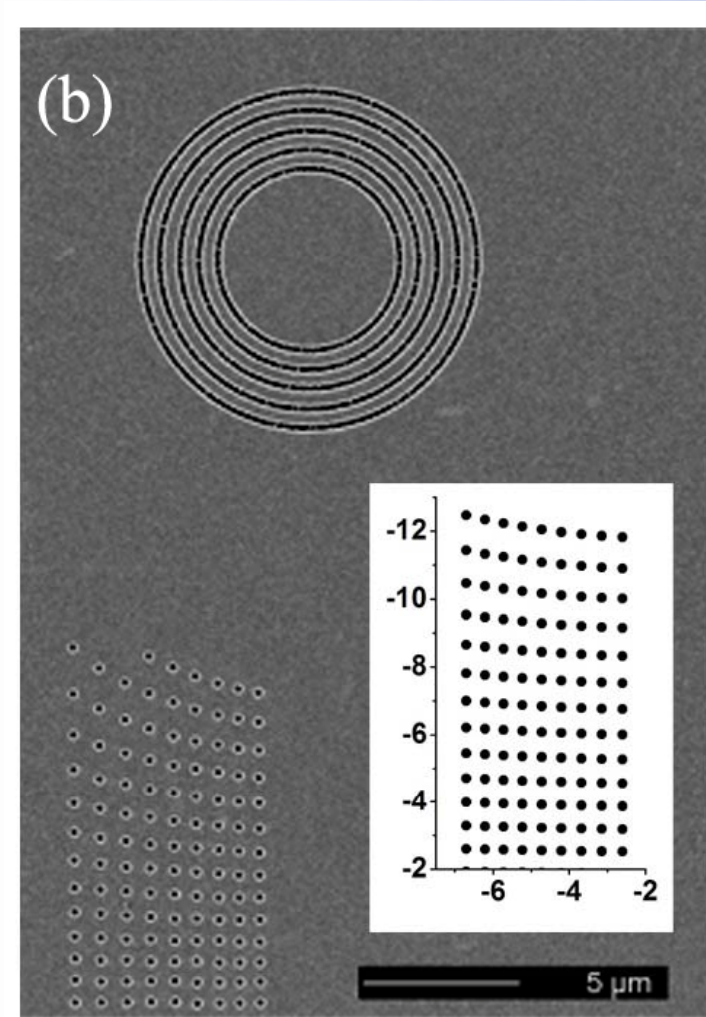
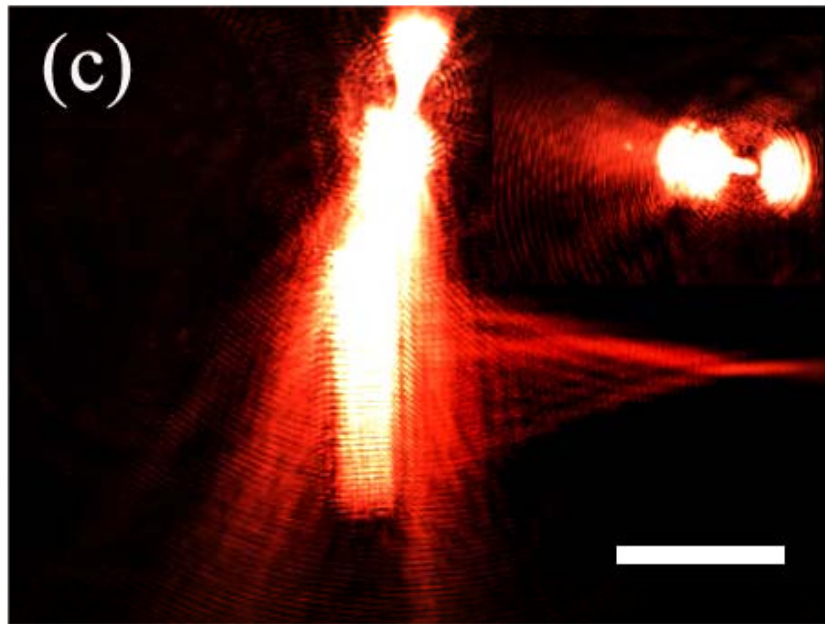
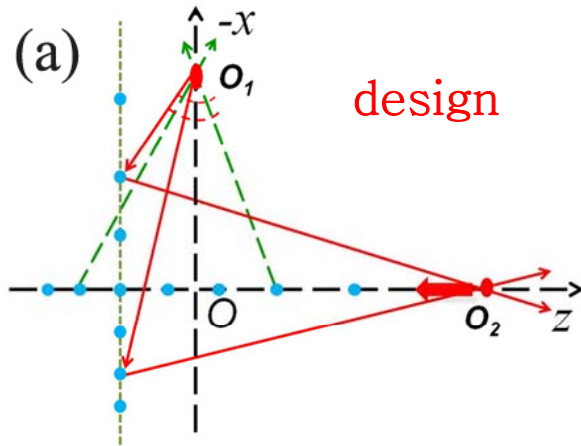
Further step: Steering SPP from point source

Point source: quantum dot, end face of fiber, etc
More practical application than the design for plane wave





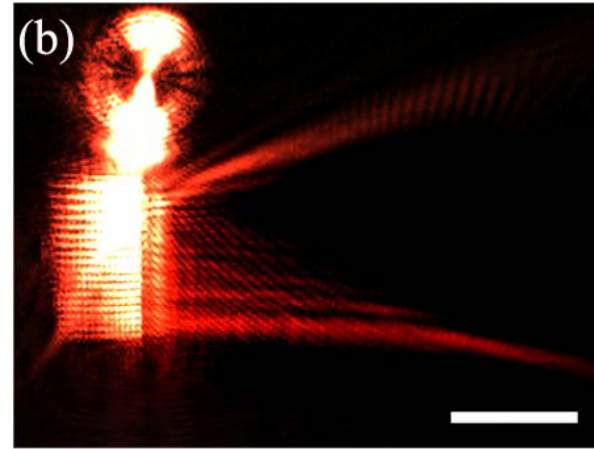
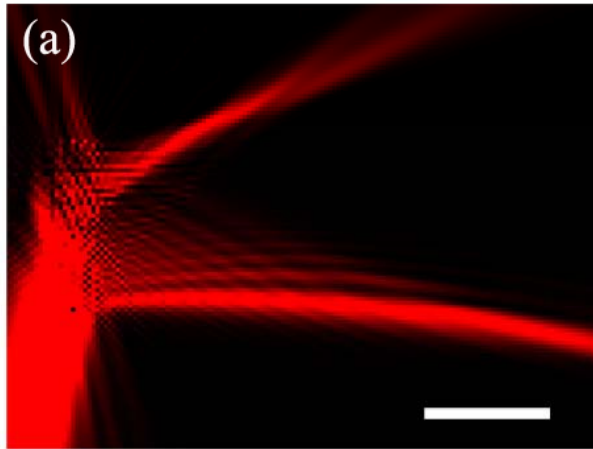
Point to point (phase 2→2)



Microstructure Laboratory

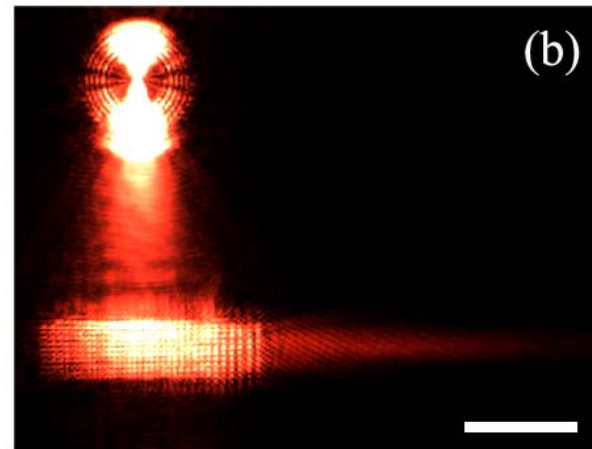
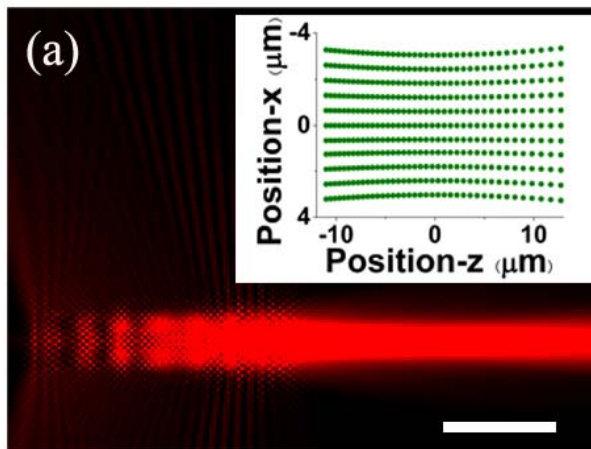


Point source to Airy and plane plasmons



Phase

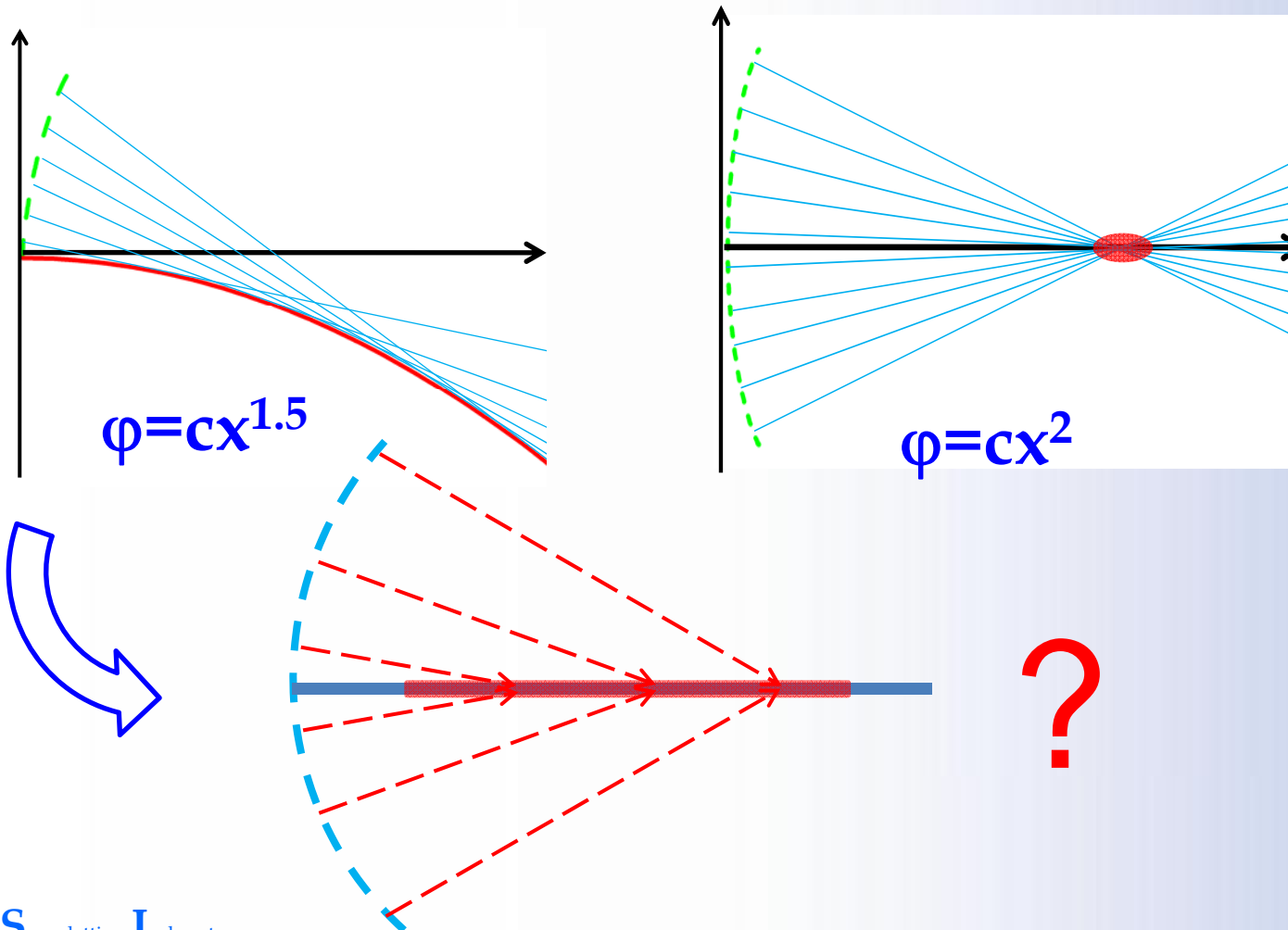
$2 \rightarrow 1.5$



$2 \rightarrow 1$

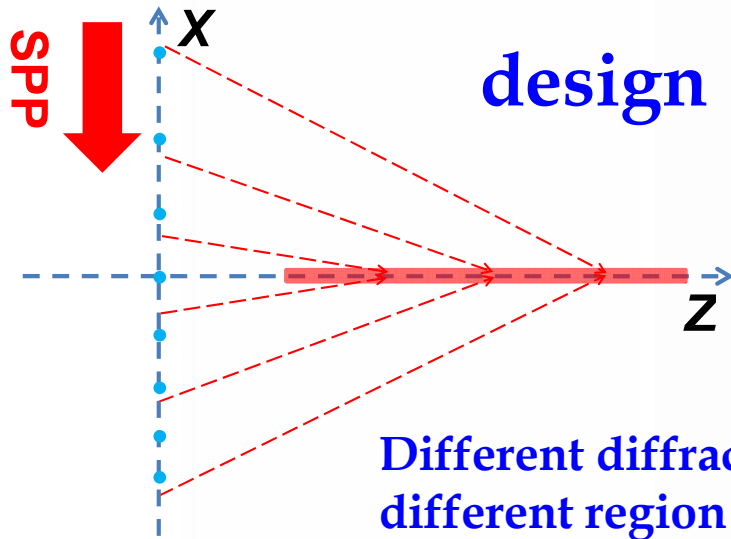


(III) Collimated plasmon beam



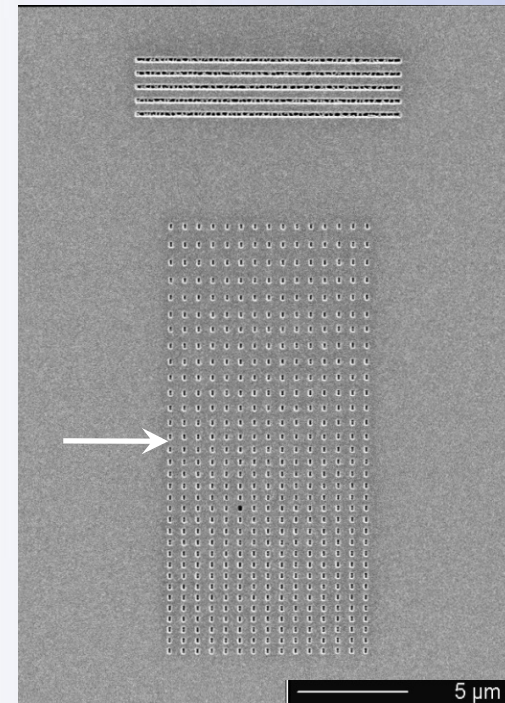
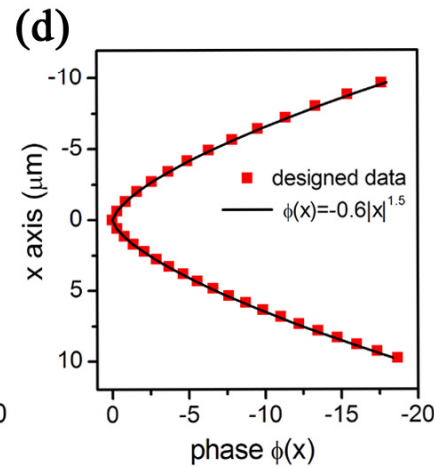
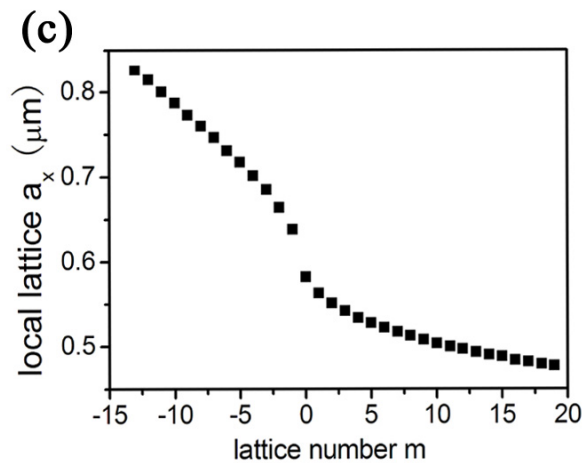


Experimental



$$z_{length} = \frac{k}{cn} x_l^{2-n} \sqrt{1 - \left(\frac{cn}{k} x_l^{n-1} \right)^2}$$

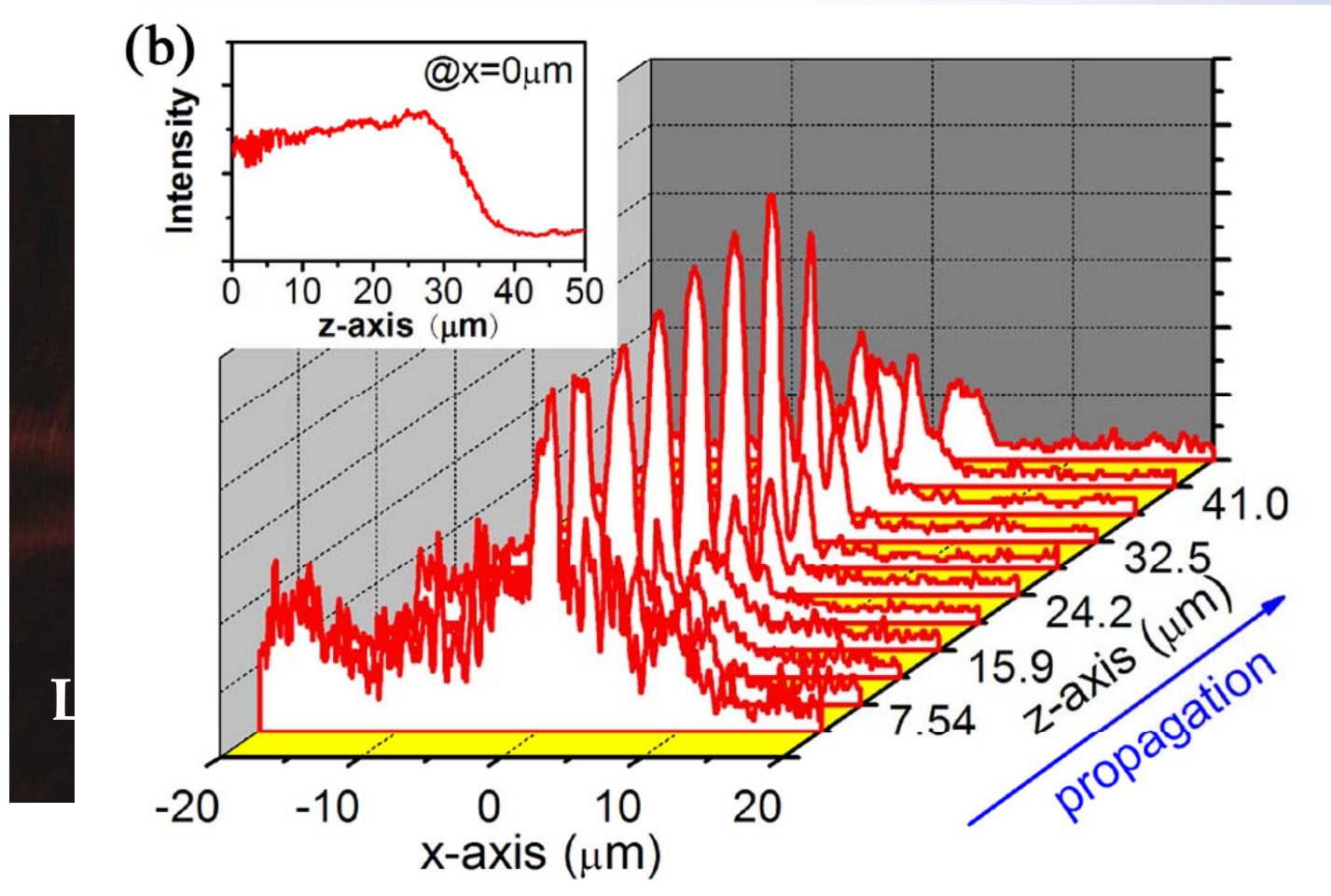
Different diffracted ray crosses different region of z axis



I



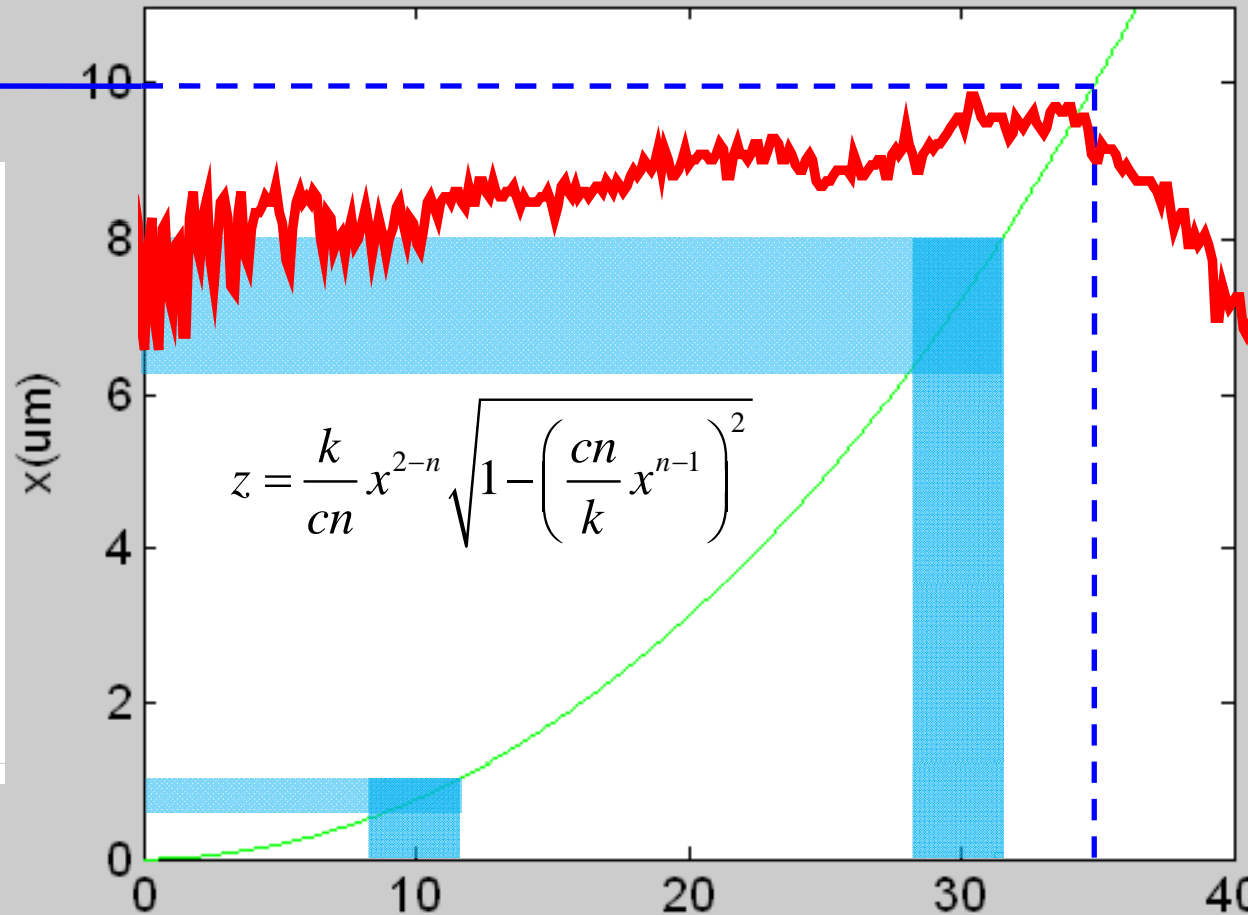
less-dispersive straight beam





How to explain the profile?

diffraction source
(limited by ~10 um)

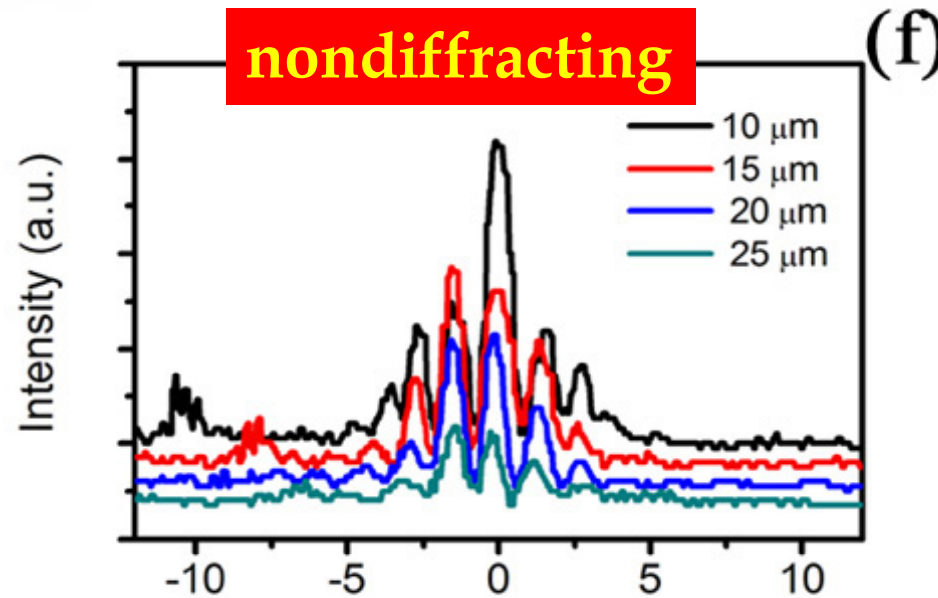
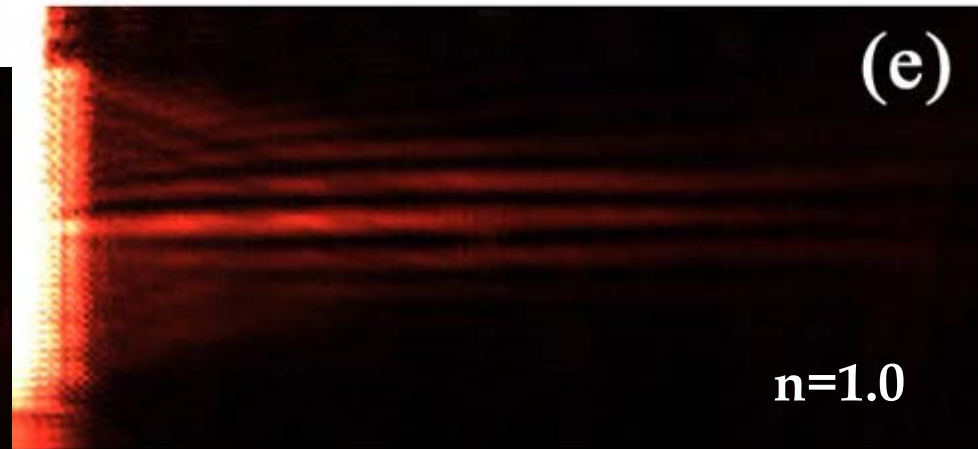


beam propagating



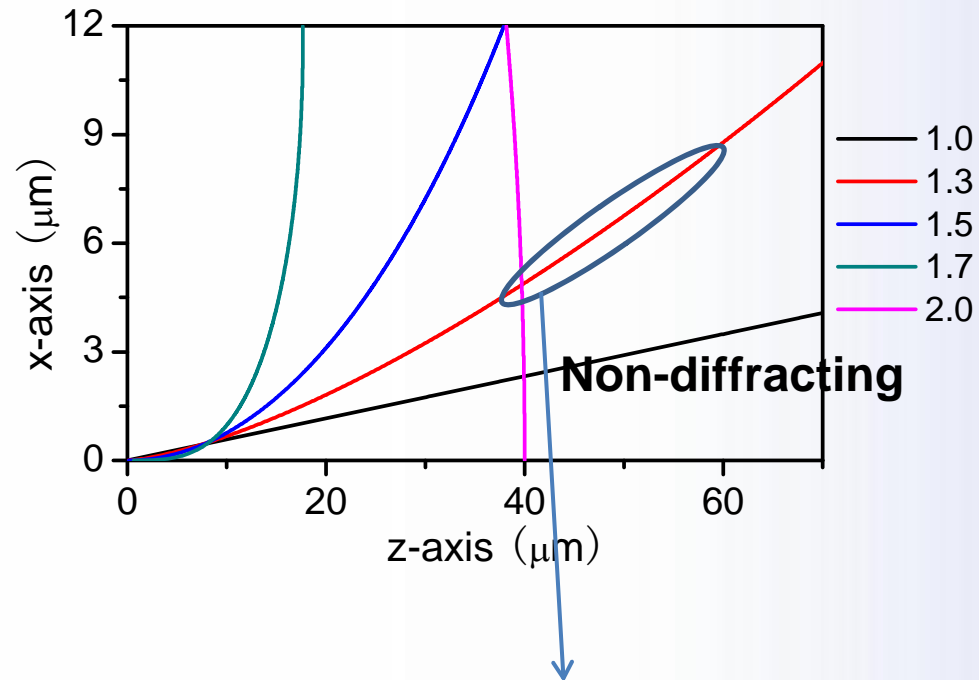
Other phase cases

Z





Only $n=1$ case is the strict non-diffracting



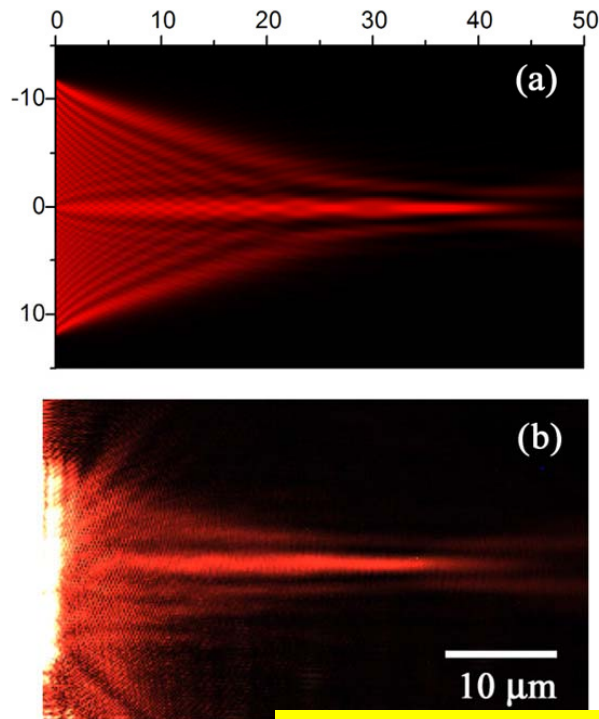
Almost linear within a certain region, can act as nearly non-diffracting beam!



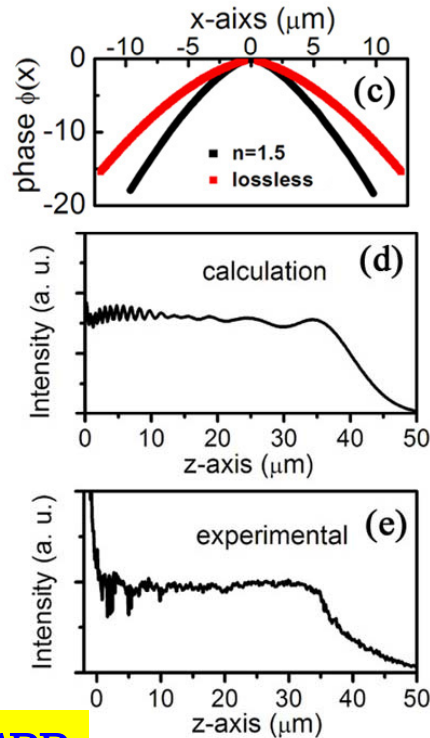
Strong tool controlling beam intensity

defining $\rho \propto \frac{dx}{dz}$, considering $I_i \propto \exp(-\frac{r}{l}) = \exp(-\frac{x}{l \sin \theta})$

We can get a “lossless” SPP by solving $I(z) = \rho I_i = c$

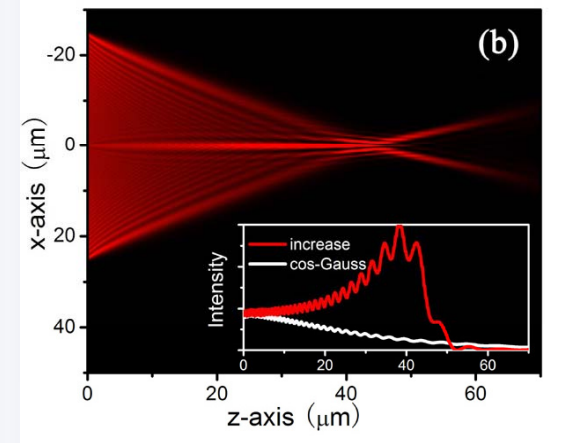


“Lossless” SPP



$$I(z) = \rho I_u = c F(z)$$

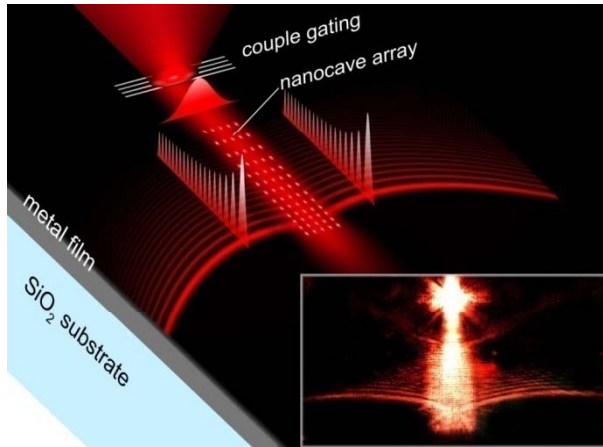
$$F(z) = \exp\left(\frac{z - z_0}{l'}\right)$$



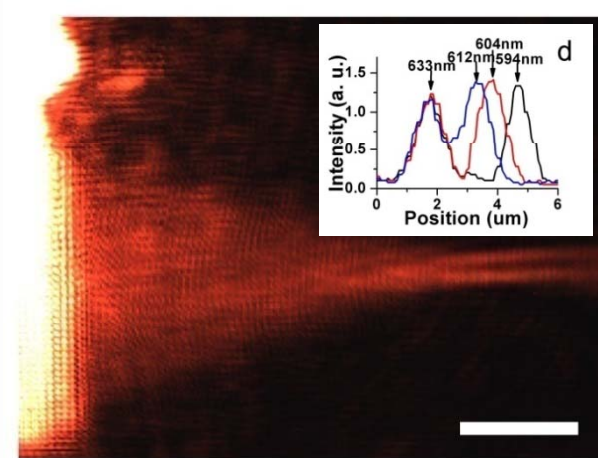
Phys. Rev. Lett. 110, 046807 (2013)



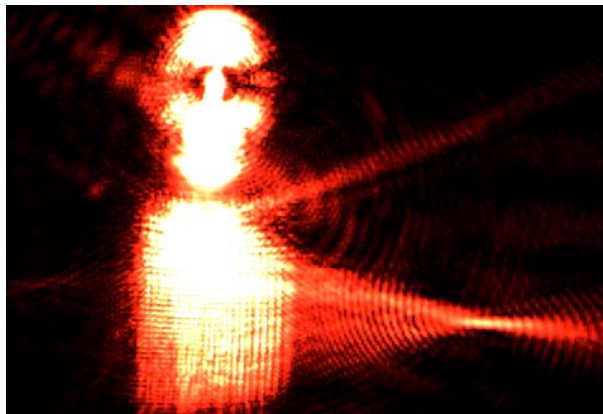
Conclusion



Nondiffracting SPP Airy beam,
Phys. Rev. Lett. **107**, 126804 (2011)

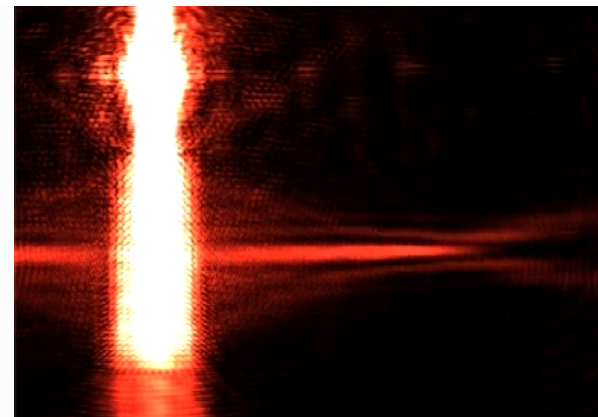


Broadband SPP focusing and WDM,
Nano Lett. **11**, 4357 (2011)



D

Steering SPP from a point source,
Opt. Lett. **37**, 5091 (2012)



Collimated "lossless" SPP beam,
Phys. Rev Lett. **110**, 046807 (2013)



Part II

Plasmonic active integration



plasmonics

Information
Photonic integration

Energy
Light emission

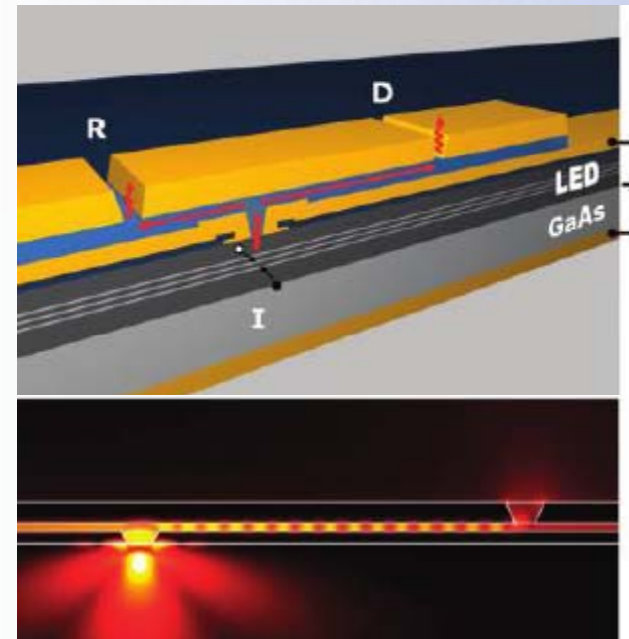
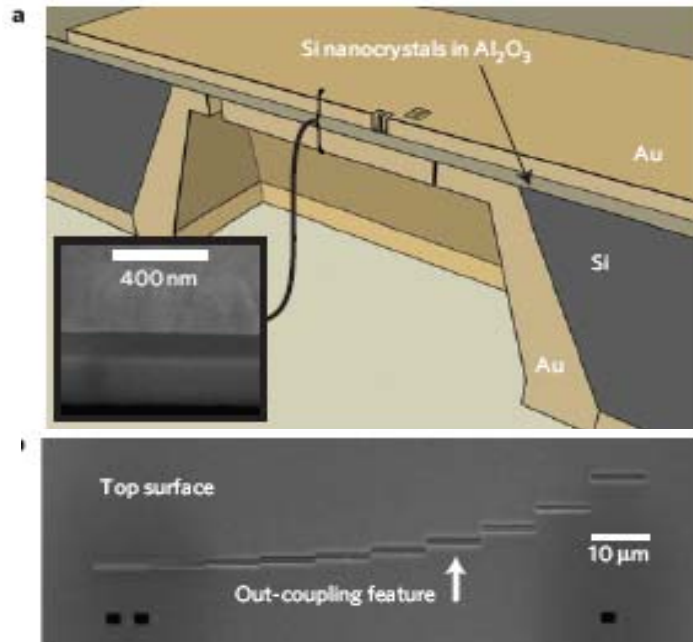
1. Electrical pumped unidirectional **SPP source**
2. Active display of **polarized SPP-LED**



(I) Electrical pumped SPP source

Why electrical pump?

Compact integration



Si Nano-particle embedded in
MIM plasmon waveguide
Nat. Material 9, 21 (2010)

LED based electro-plasmon source
Nano Lett. 10, 1429 (2010)

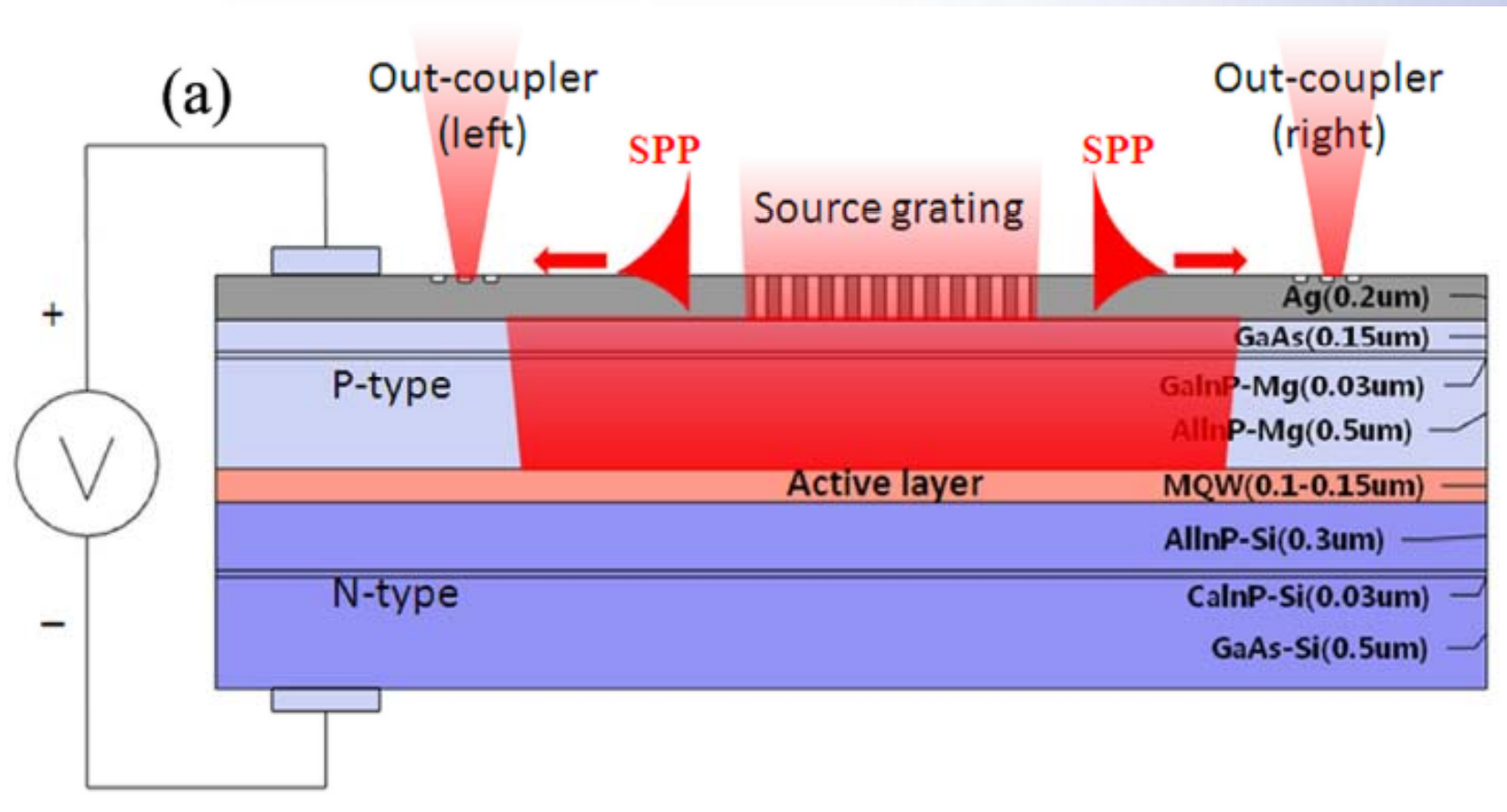


Two challenges

- Propagation length
(MIM structure \rightarrow large loss mode, $l \sim 3-4 \mu\text{m}!$)
- Coupling efficiency
(single-slit; bidirectional SPP)



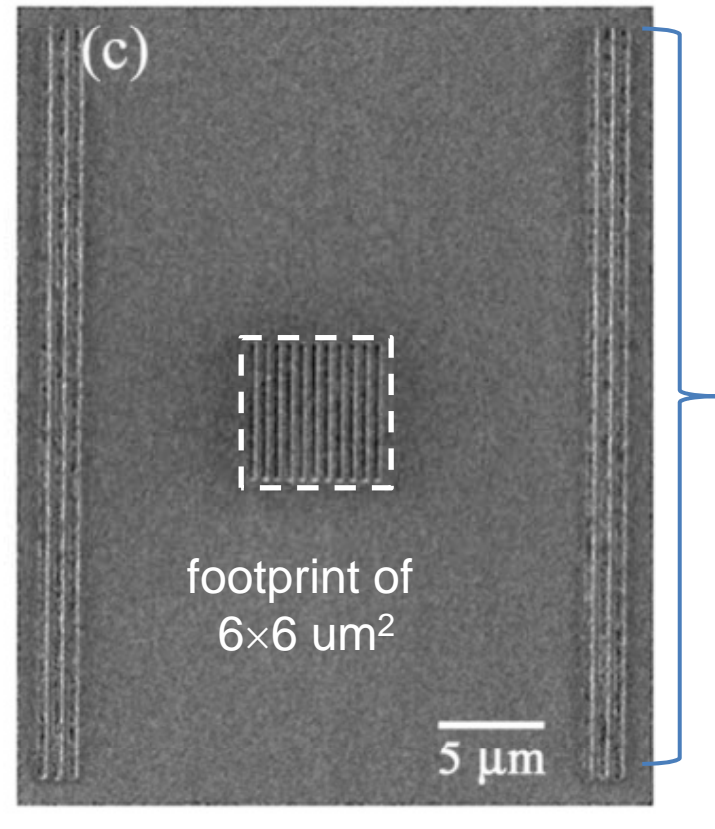
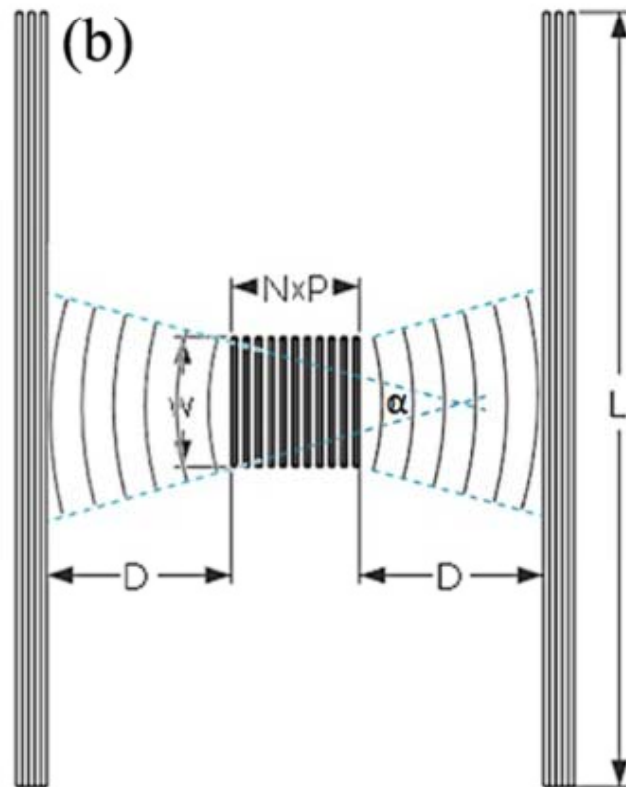
Our design



Wavelength~633 nm



Sample and parameters



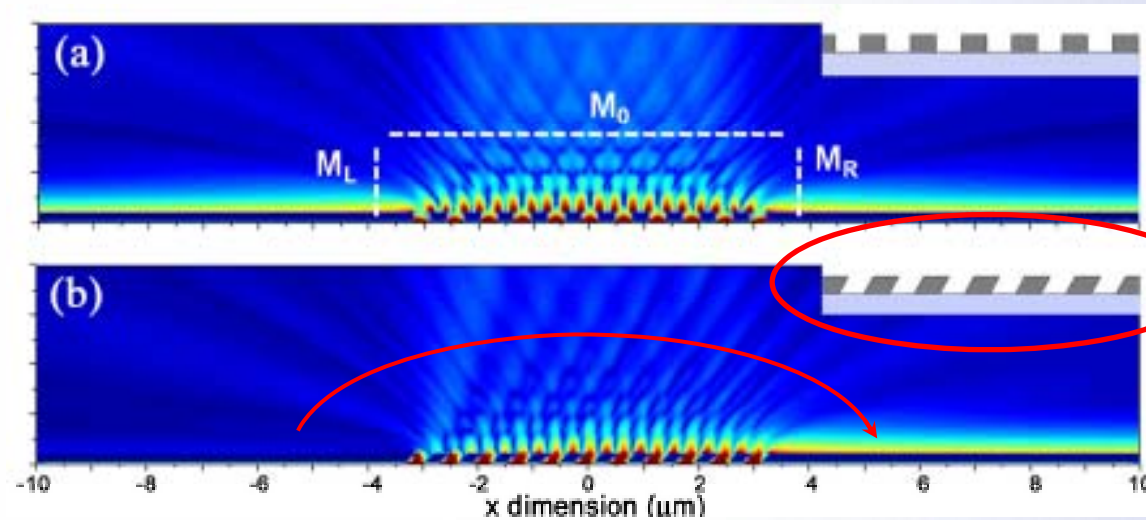
long out-coupler for SPP beam analysis

footprint of $6 \times 6 \mu\text{m}^2$

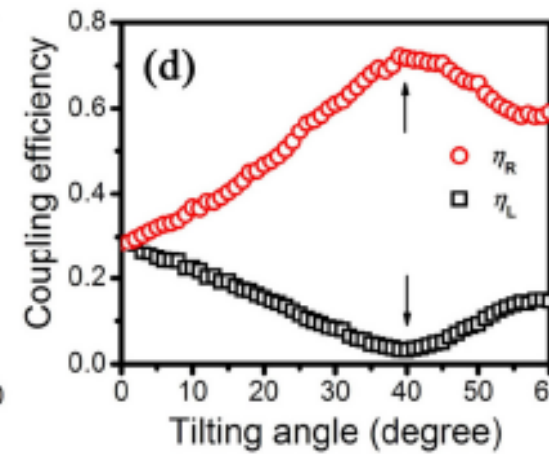
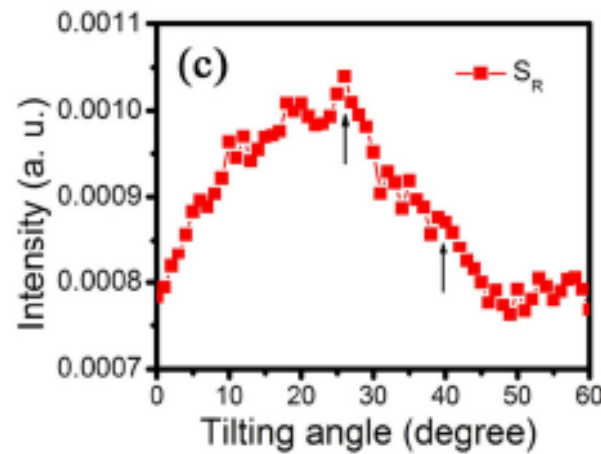
5 μm



Simulation results

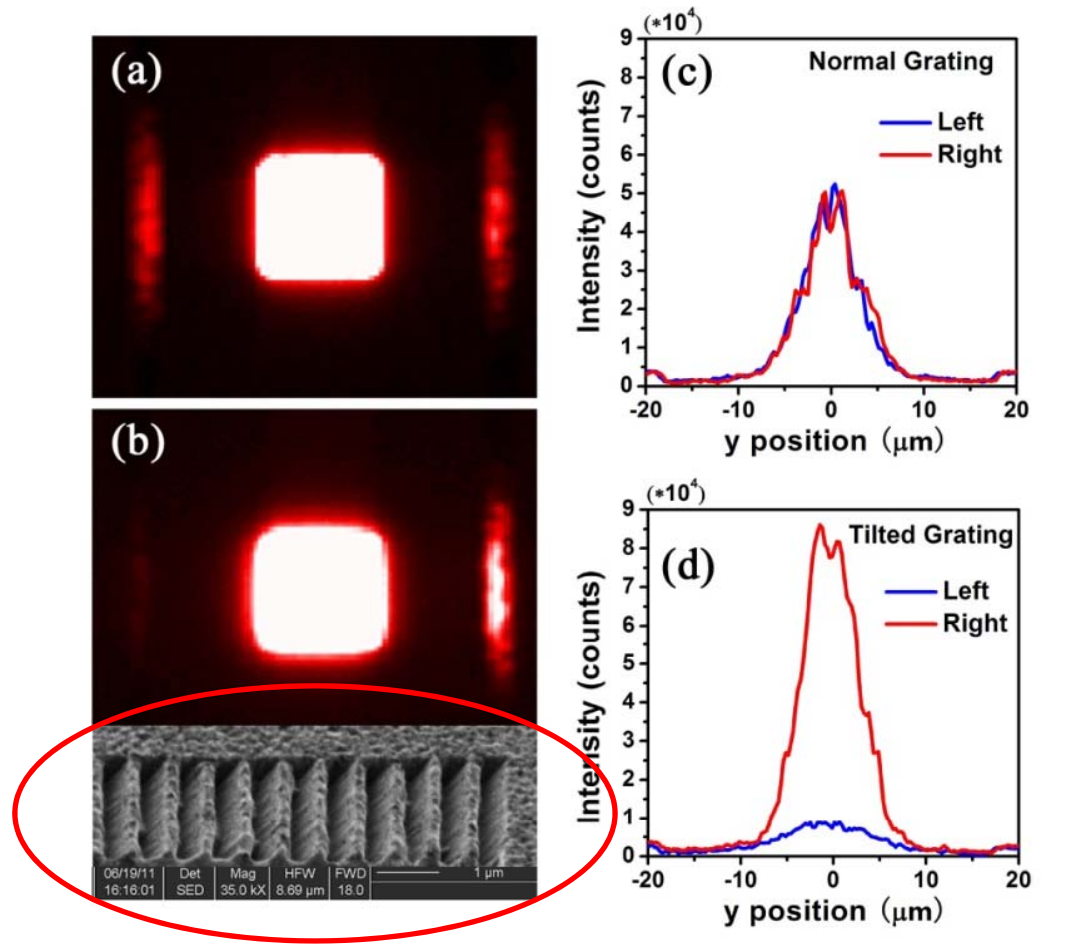


tilted grating





Experimentally generated SPP



Bidirectional case

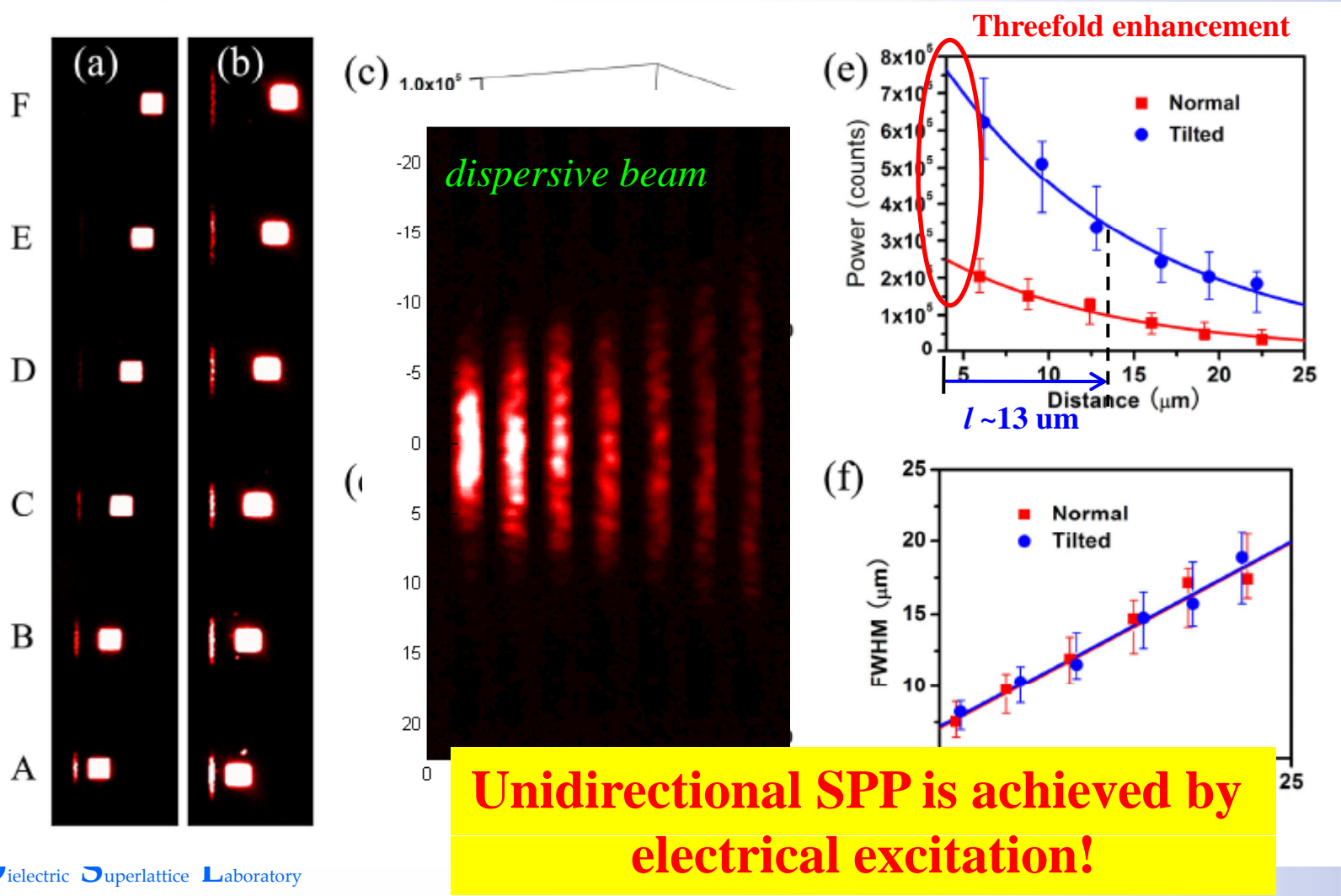
Unidirectional case

FIB fabricated tilted sample
angle $\sim 40^\circ$, period ~ 600 nm

Opt. Express 20, 8710 (2012)



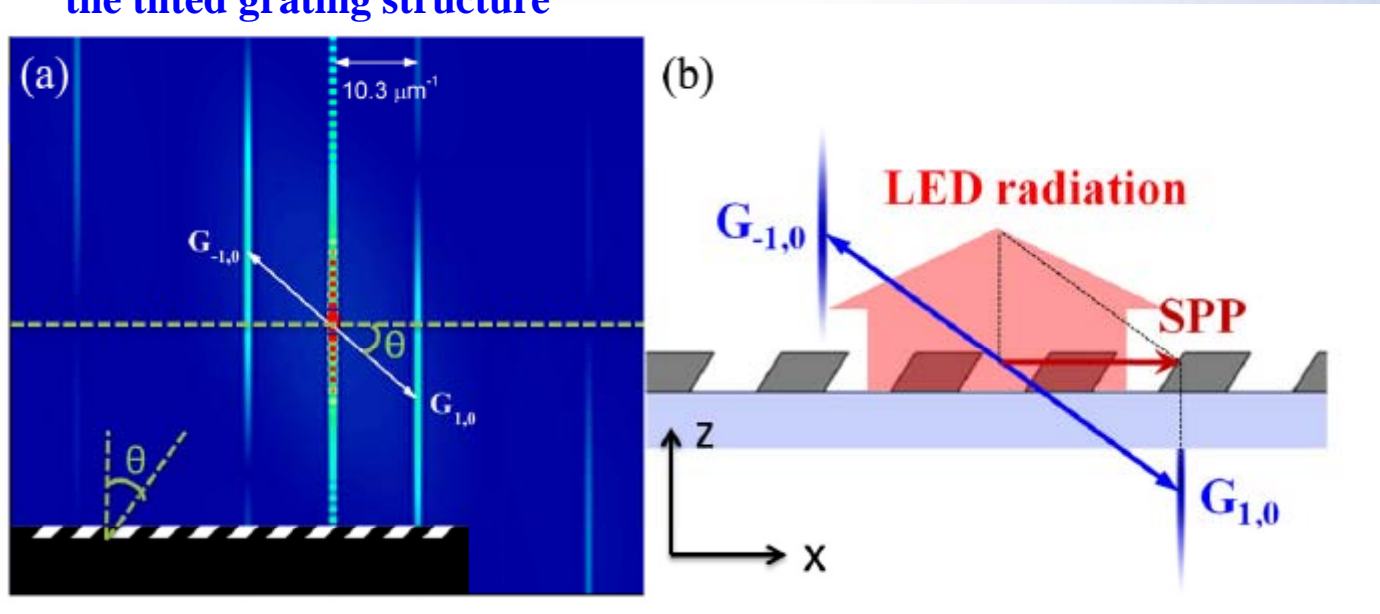
Propagation property of SPP





Explanation on the unidirectional coupling

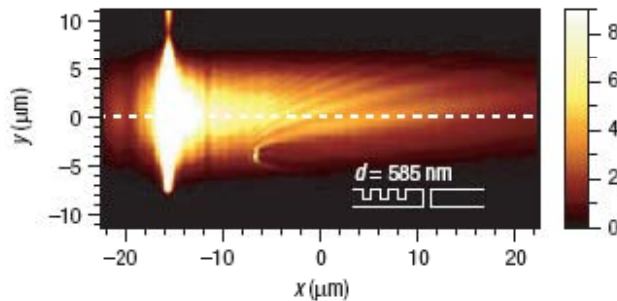
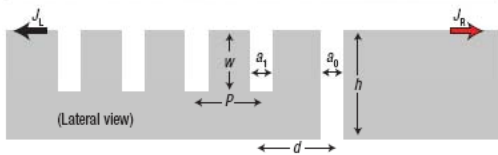
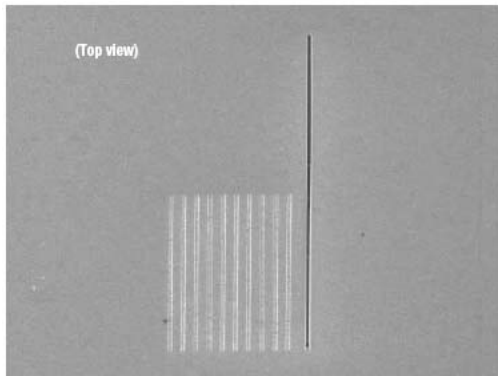
Fourier Transformation of the tilted grating structure



Inclined reciprocal vector is responsible for the asymmetric coupling of SPP

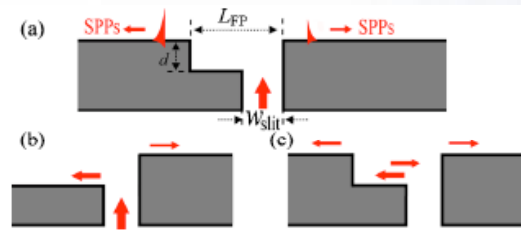


Review the unidirectional strategy

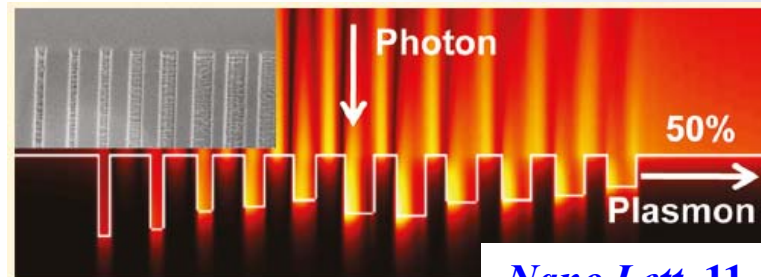
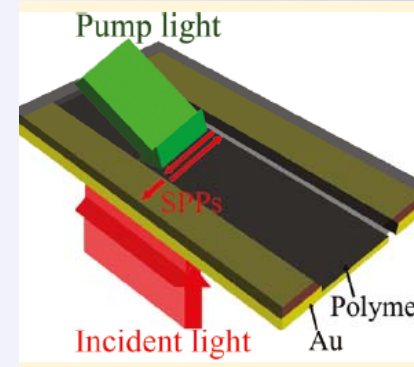


Slit launcher with a Bragg grating beside

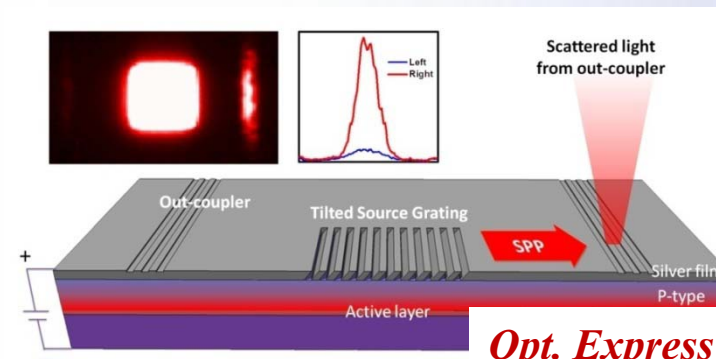
Nat. Physics 3, 324 (2007)



APL 97, 014113 (2010),
Nano Lett. 11, 2933 (2011)



Nano Lett. 11, (2011)



Opt. Express 20, 8710 (2012)

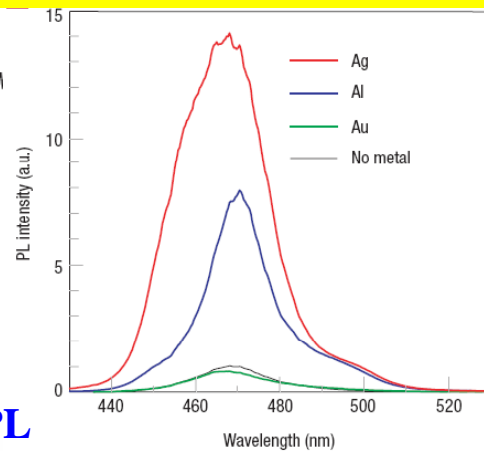
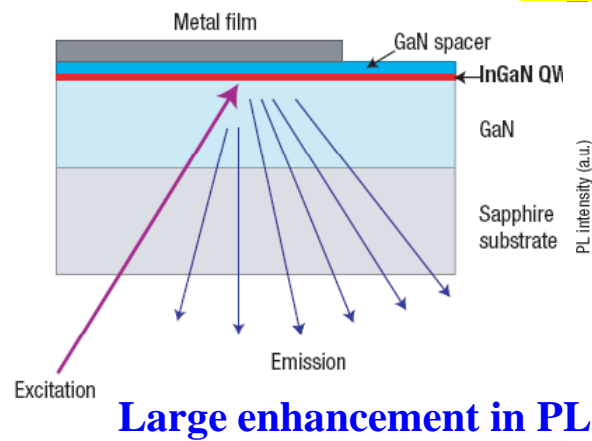


(II) Active display by polarized SPP-LED

Surface-plasmon-enhanced light emitters based on InGaN quantum wells

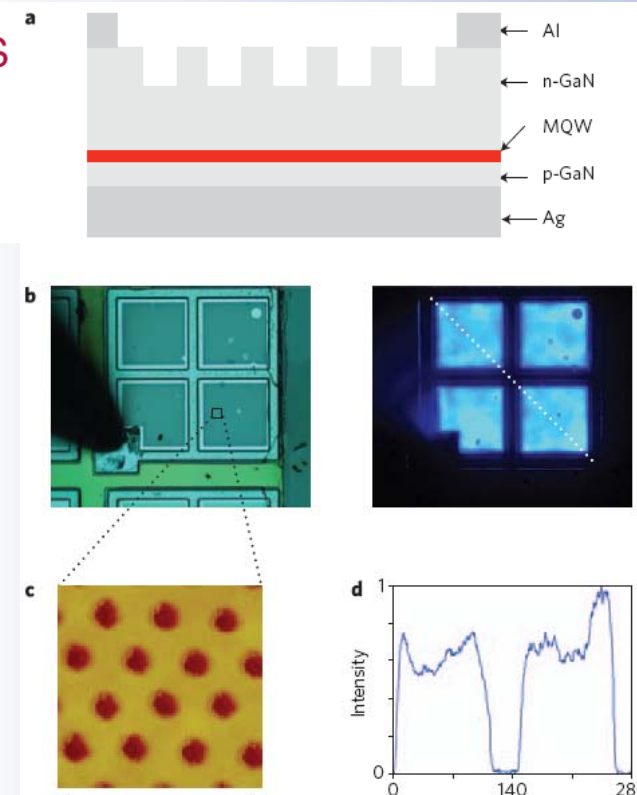
KOICHI OKAMOTO¹, ISAMU NIKI^{1,2}, ALEXANDER SHVARTSER¹, YUKIO NARUKAWA², TAKASHI MUKAI² AND AXEL SCHERER^{1*}

Nat. Mater. 3, 601 (2004)



How about

Few report of enhancement by SPP in practical electrical pumping!



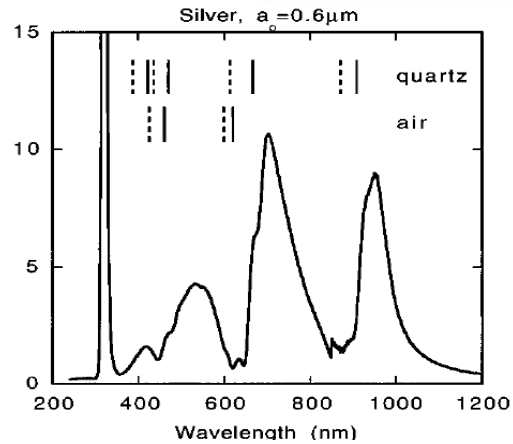
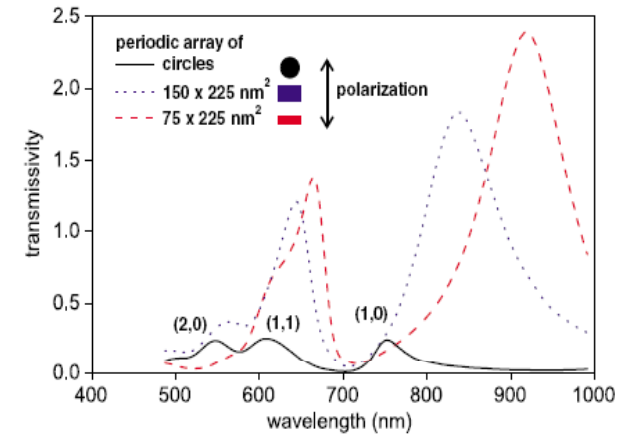
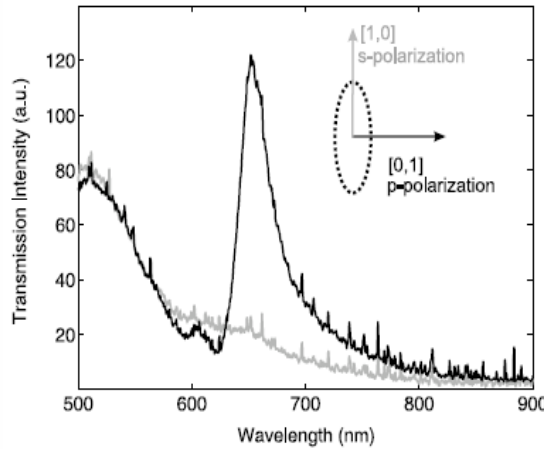
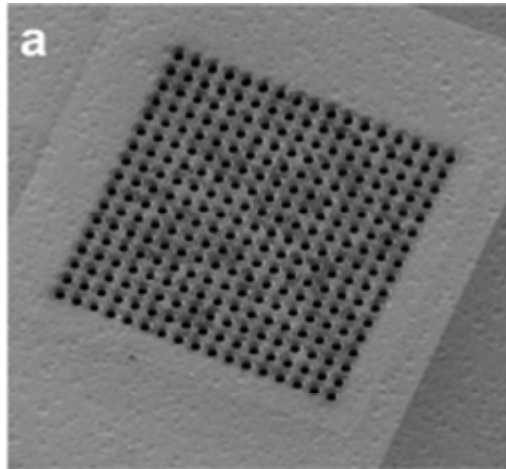
Nat. Photonics 3, 163 (2009)

Improved light extraction by PhC

Possible reason: big metal loss kills the extracted internal reflection



Background- extraordinary optical transmission



PRL 92, 037401 (2004), PRL 92 (2004), PRB 72 (2005)

EOT-assisted Polarizer

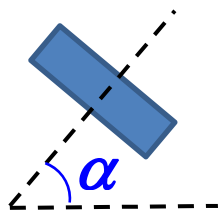
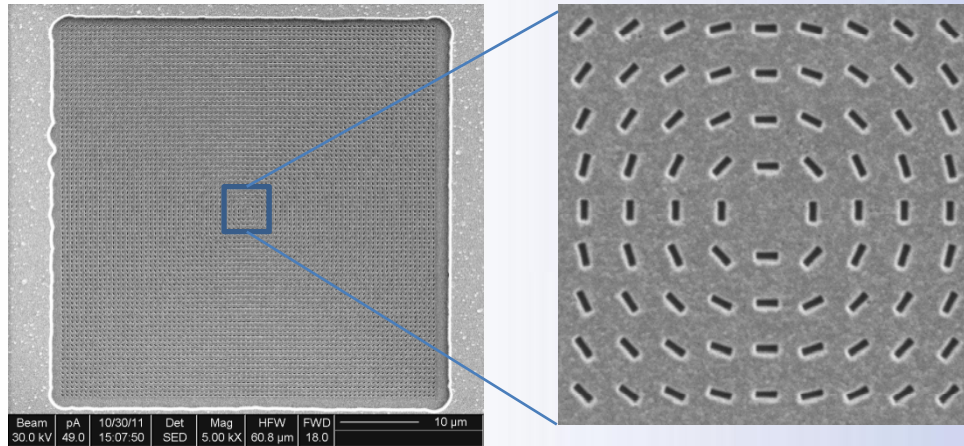
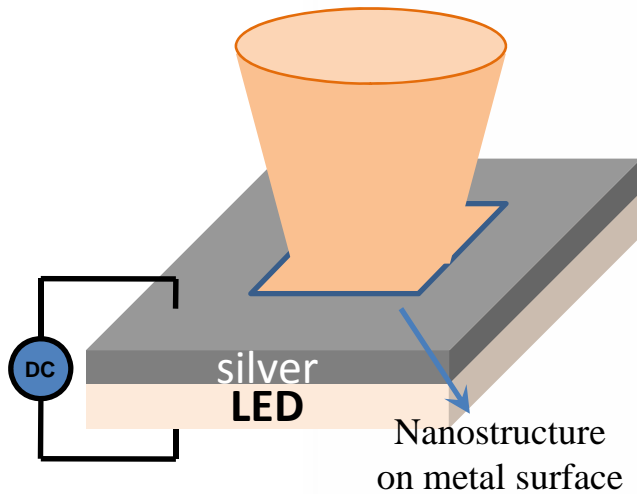
**Nano hole array can
work as good polarizer!**

LSP+SPP

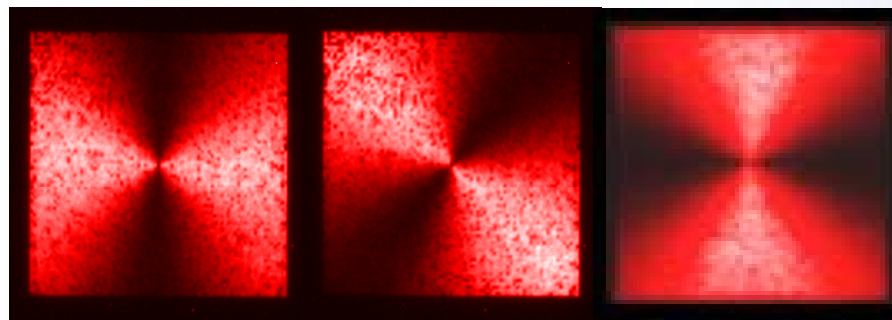
Nature 391, 667 (1998)



Vetorial beam - radial



LED emission



checked in

$\varphi=0^\circ$

45°

90°

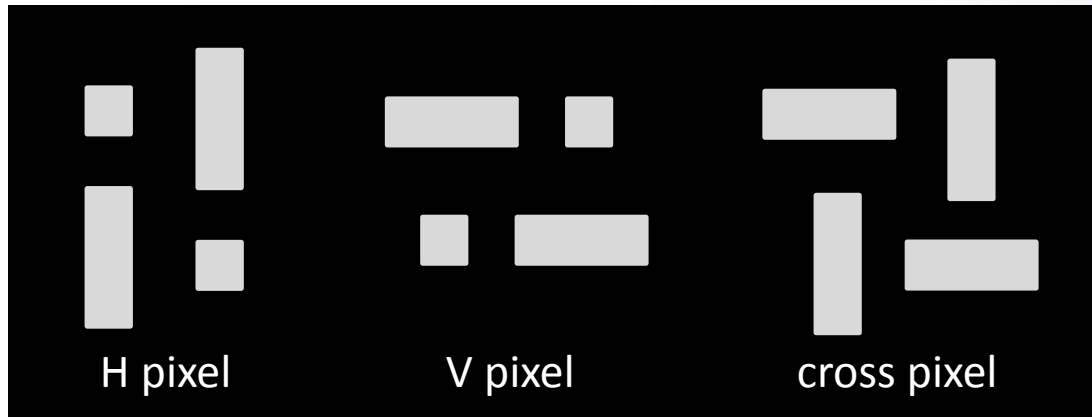
radial beam

LSP+SPP

$$I = I_0 \cos^2(\varphi - \alpha)$$

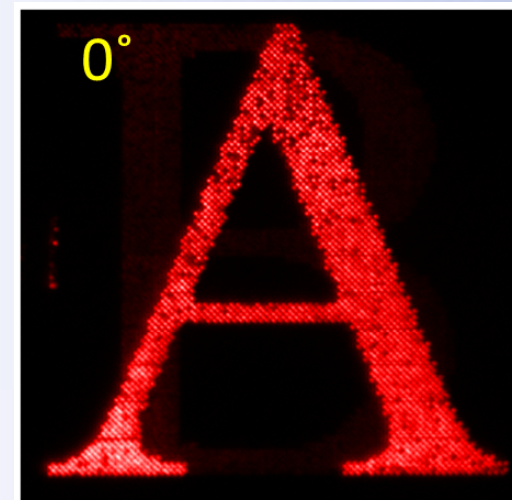
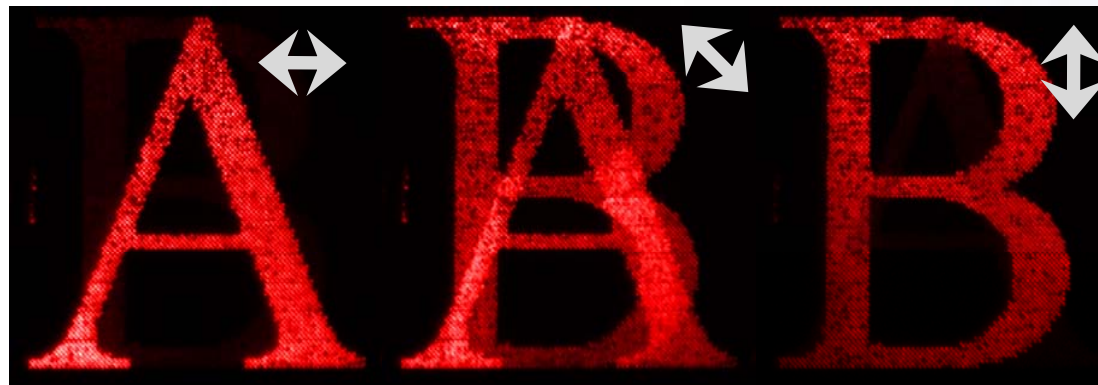


Polarization encoding



Pixels defined corresponding to H-V polarization states for encoding

Experimental result





SPP (Period) influence

Sub-pixel

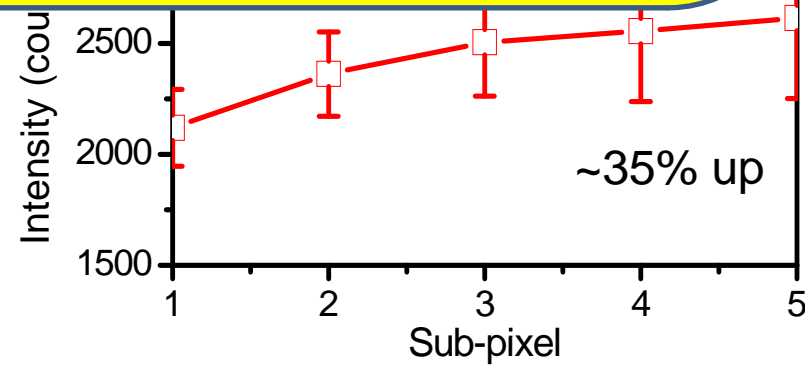
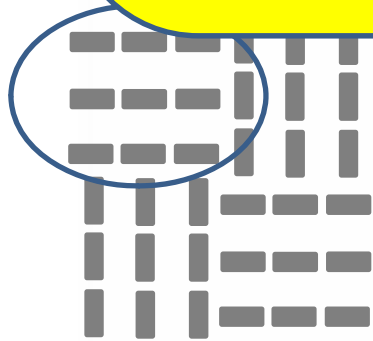
1×1

3×3

5×5



Resolution VS brightness





For complex images

For any defined intensity distribution $I(x, y)$

We can design the orientation of rect-holes with distribution

$$\alpha(x, y) = \frac{1}{2} \arccos\left(\frac{2I(x, y)}{I_0} - 1\right)$$

so as to achieve a gray scale image!

Moreover, hole size can be used to tune the pixel intensity

$$I(x, y) = \underline{u(x, y)} \cos^2(\varphi - \alpha(x, y))$$

by adopting $\varphi_1=0$ and $\varphi_1=\pi/2$, we have

$$\begin{cases} I_1(x, y) = u(x, y) \cos^2 \alpha \\ I_2(x, y) = u(x, y) \sin^2 \alpha \end{cases}$$

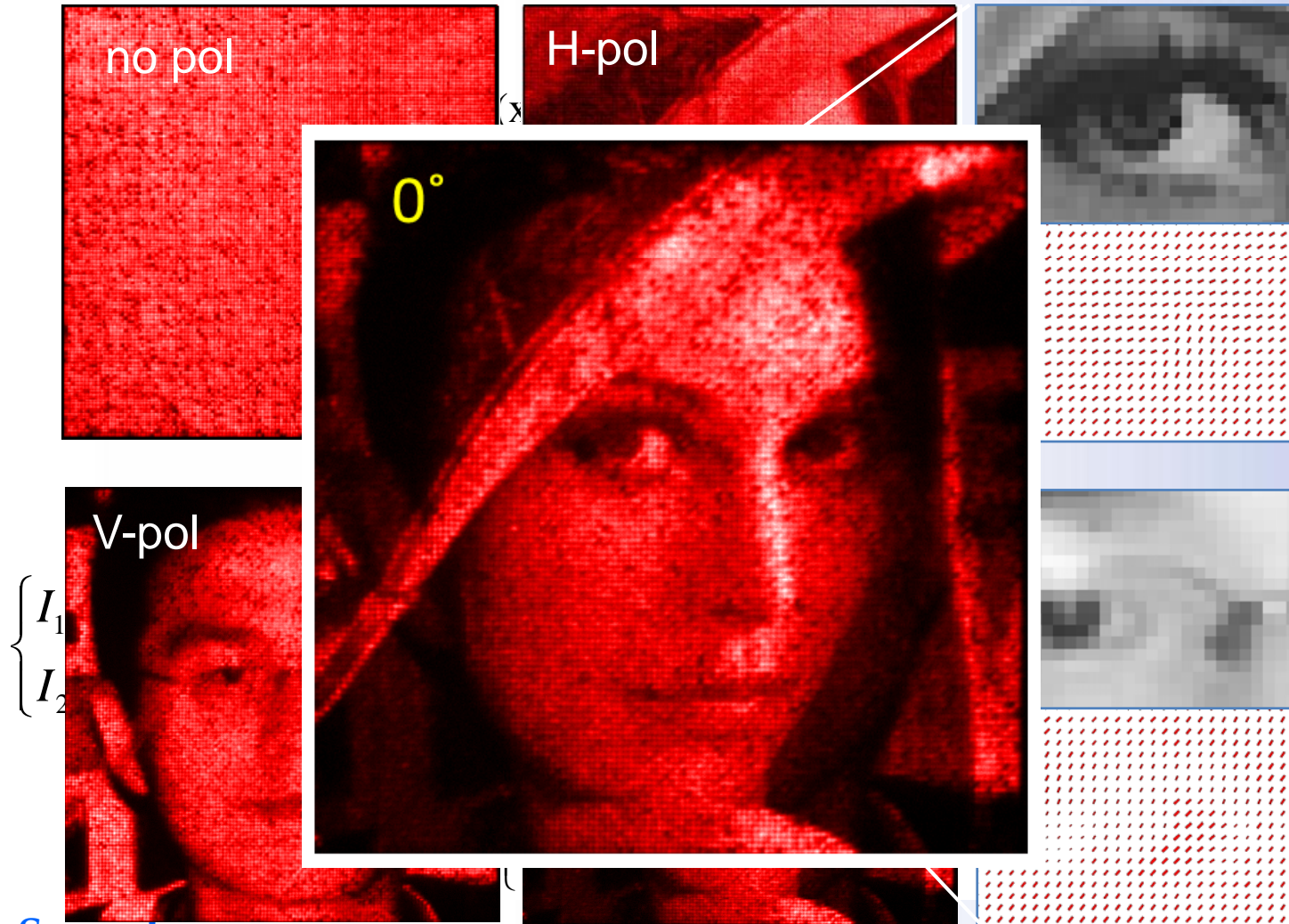
then
$$\begin{cases} \alpha(x, y) = \frac{1}{2} \arccos\left(\frac{I_1 - I_2}{I_1 + I_2}\right) \\ u(x, y) = \frac{I_1 + I_2}{2} \end{cases}$$

given intensity distribution of **two images**
 $I_1(x, y)$ and $I_2(x, y)$

We can calculate the angle and size distribution
 $\alpha(x, y)$ and $u(x, y)$



Grayscale image display



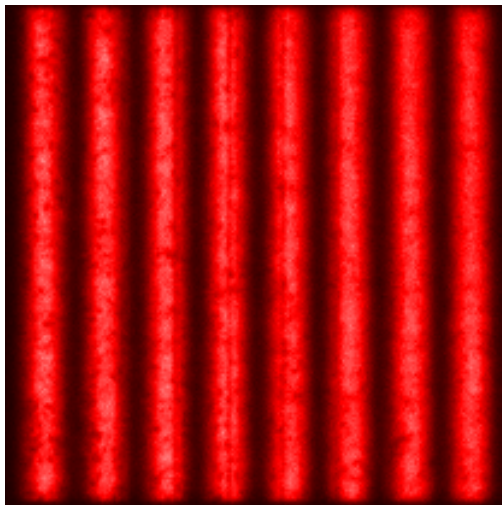


Active animation

For some simple patterns, we can generate dynamic images rotating polarization

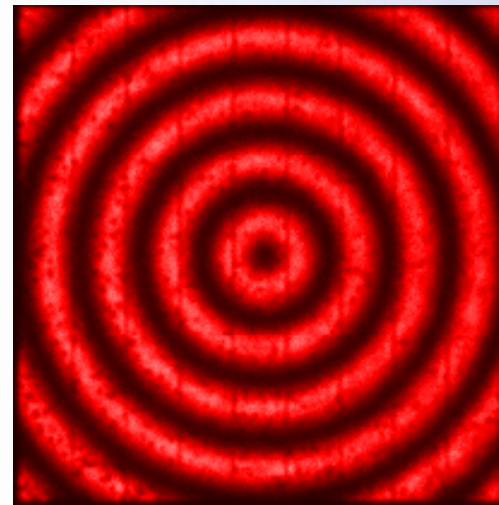
1D moving grating

$$\alpha = n\pi x / L$$



concentric grating

$$\alpha = 8\pi\sqrt{x^2 + y^2} / L$$

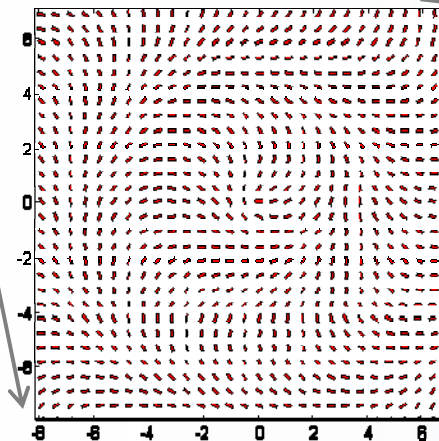
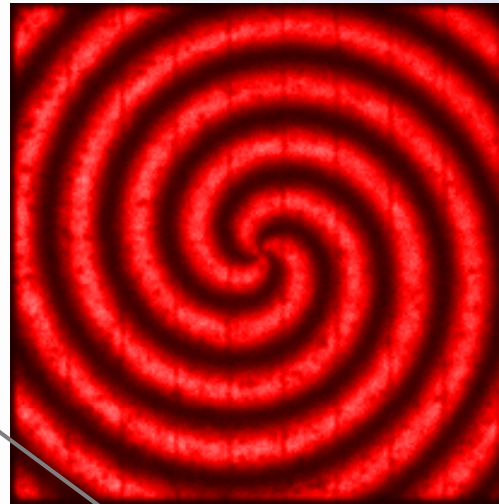
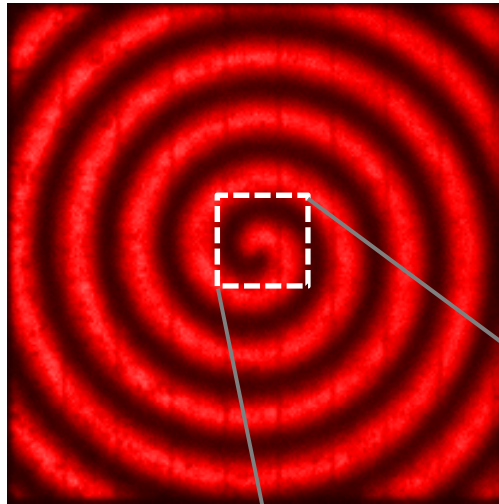




rotating spirals $\alpha = n \left(\theta + \frac{8\pi}{nL} \sqrt{x^2 + y^2} \right)$

n=1

N=3



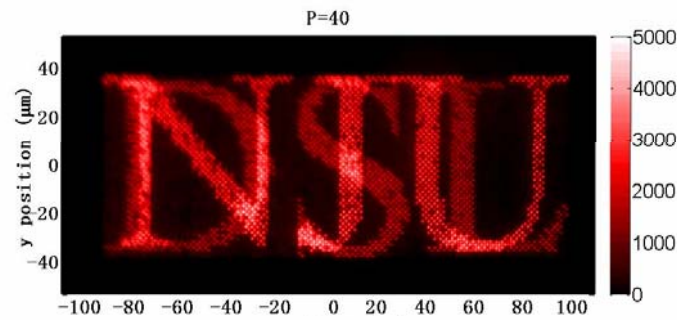
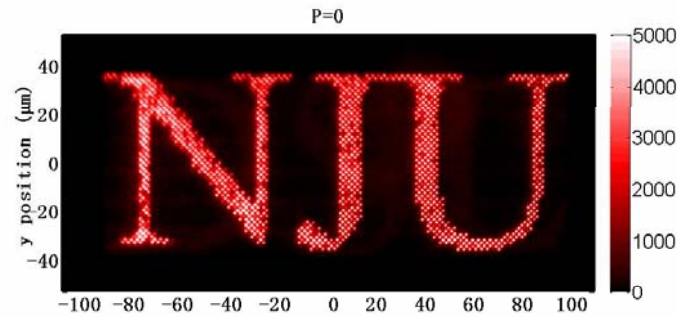
Animation is well achieved!

Sci. Rep. 3, 02603 (2013)

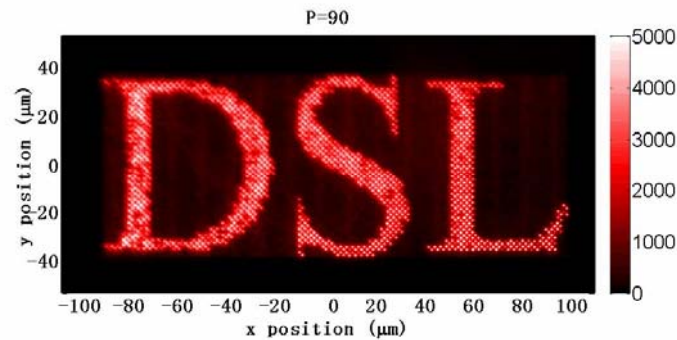


for examples

H-Pol



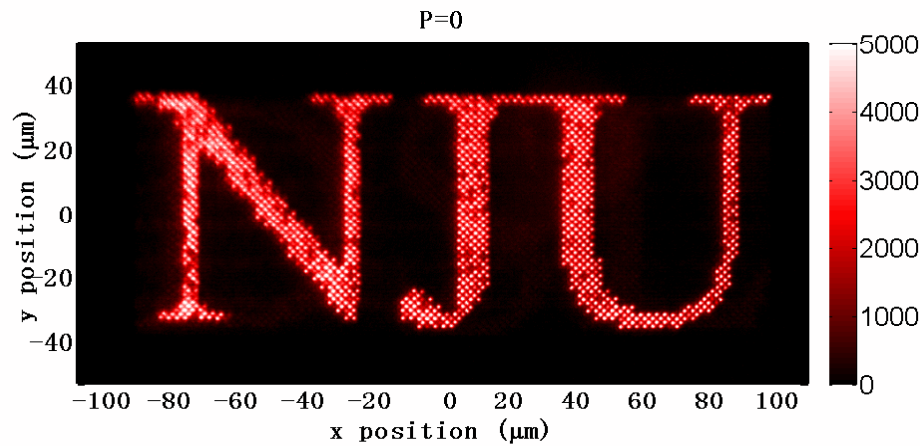
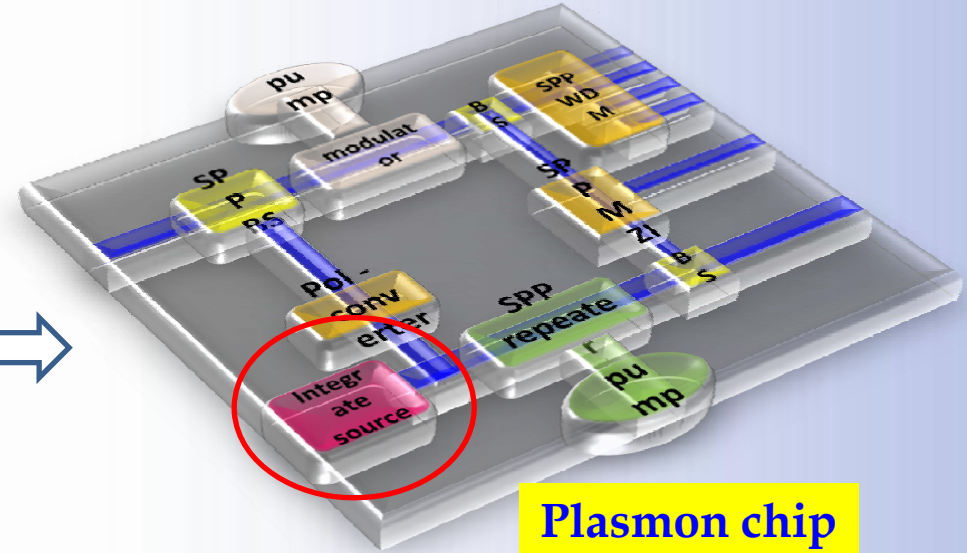
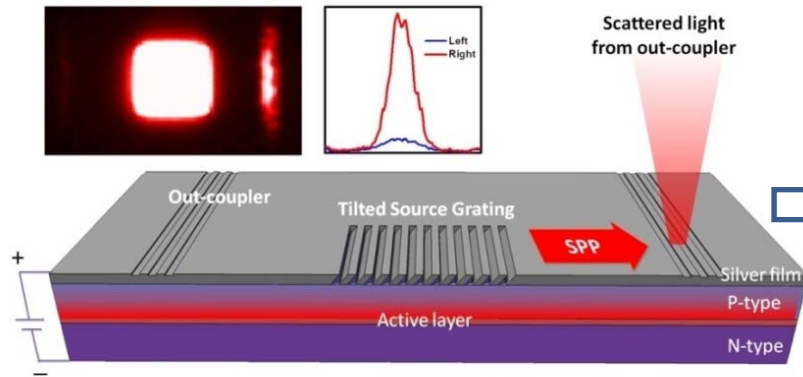
H-Pol



3D LED-display



Summary





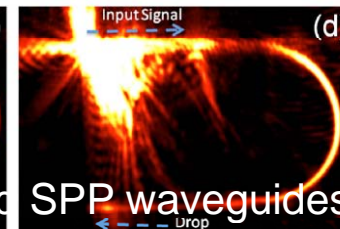
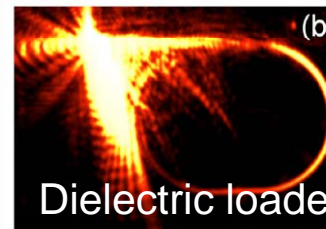
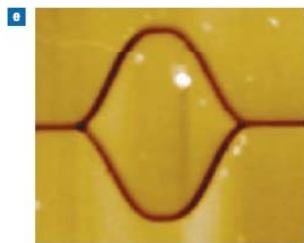
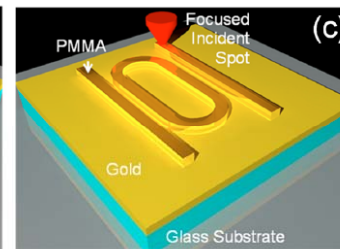
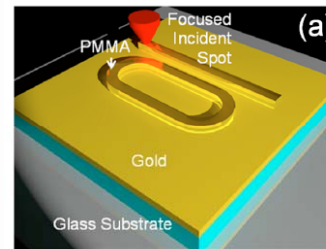
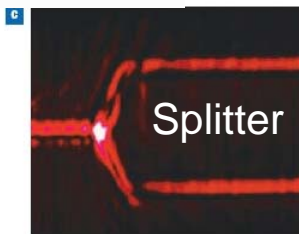
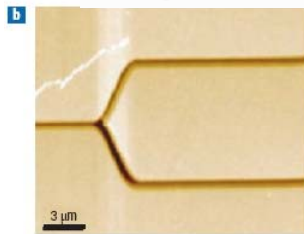
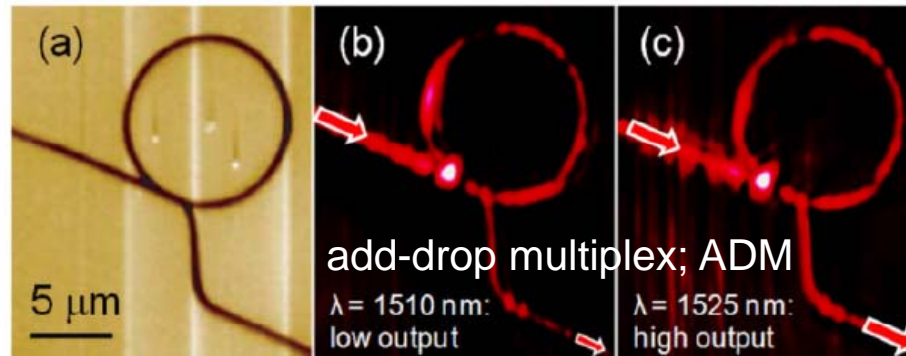
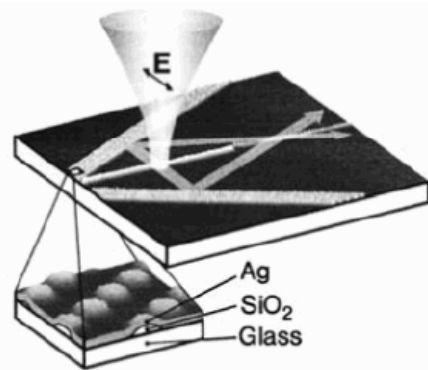
Part III

Nonlinear process in hybrid plasmonic waveguide



Basic motivation

Plasmonics for nanophotonic integration.



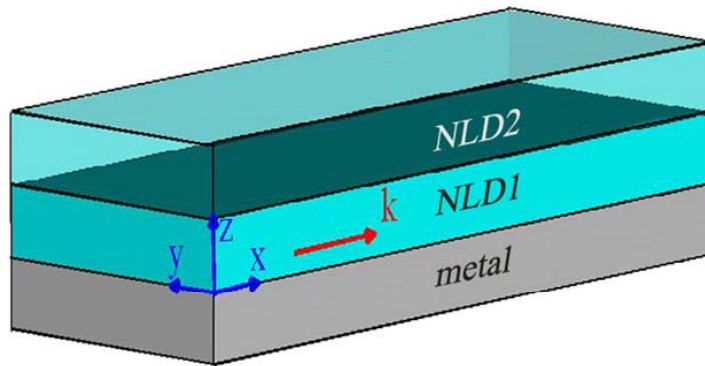


- Most of them are linear and passive, nonlinear plasmonic integration may provide possibilities for dynamic and tunable optical process in the nanoscale!
- **Our consideration:**
Combining metal with nonlinear crystal, taking usage of the nonlinear effect of crystal and profitable EM modes of plasmonics (or hybrid ones).



(I) OPA enhanced SPP propagation

Our design: I/I/M planar waveguide structure



NLD2 → lower index
NLD1 → higher index
Metal → Drude dispersion

TM modes

$$k_1 d = n\pi + \tan^{-1}\left(f_1 \frac{p}{k_1}\right) + \tan^{-1}\left(f_2 \frac{q}{k_1}\right), \quad n = 0, 1, 2, \dots$$

$$k_1 = \sqrt{(k_0^2 \epsilon_{1z} - k^2) \epsilon_{1x} / \epsilon_{1z}}, \quad p = \sqrt{k^2 - k_0^2 \epsilon_m} \quad \text{and} \quad q = \sqrt{(k^2 - k_0^2 \epsilon_{2z}) \epsilon_{2x} / \epsilon_{2z}}$$

The lowest $TM_0 \rightarrow$ SPP

NLD2 → LiNbO3 crystal, ($[n_x, n_y, n_z]$ defined by Sellmeier Equation)

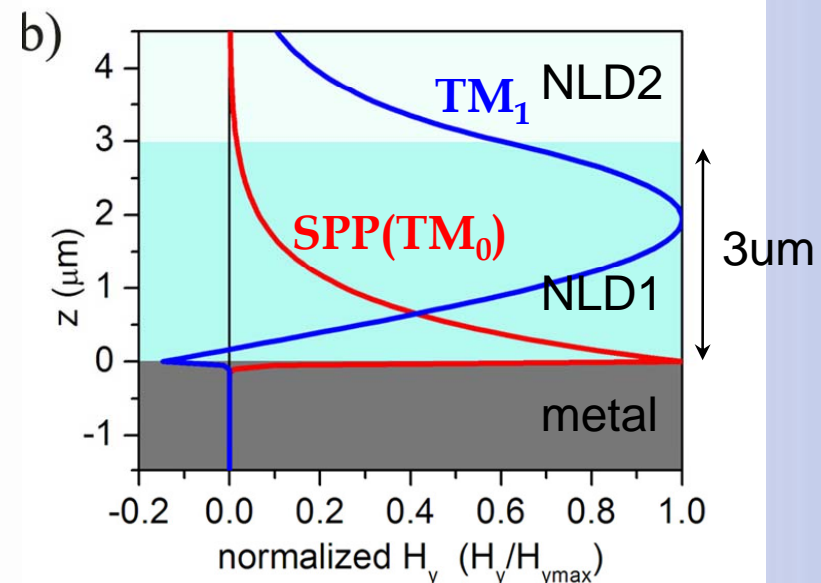
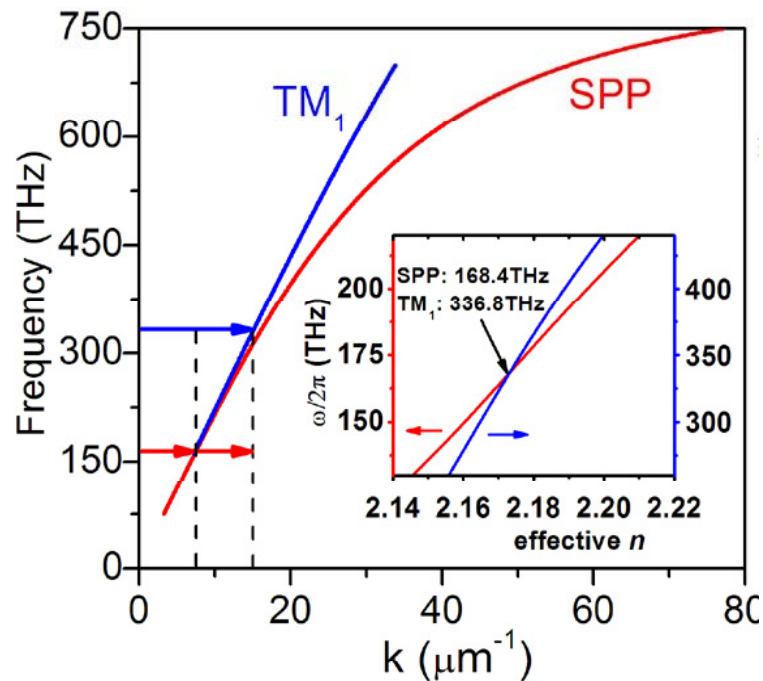
NLD1 → enlarged permittivity ($\epsilon_1 = \epsilon_2 + 0.04$, approximately).

D_{ielectric}



Optical parametric process: phase match

- ✓ It will be fulfilled by carefully designing the dispersion of the SPP and guided modes in such hybrid waveguide.
(need no further treatment, e.g., QPM by periodical poling)



Mode profiles



Optical parametric process (OPA)

$$\frac{\partial A_1}{\partial x} = -\frac{\alpha_1}{2} A_1 + i \frac{\omega \epsilon_0}{4} \kappa_1 A_1^* A_2 e^{i(\beta_2 - 2\beta_1)x},$$
$$\frac{\partial A_2}{\partial x} = -\frac{\alpha_2}{2} A_2 + i \frac{\omega \epsilon_0}{4} \kappa_2 A_1^2 e^{-i(\beta_2 - 2\beta_1)x},$$

Coupled wave equation
 $A_1 \rightarrow \text{SPP}, A_2 \rightarrow \text{TM}_1$

Coupling coefficient $\kappa_1 = \int \chi : \bar{E}_2 \bar{E}_1^* \cdot \bar{E}_1^* dz, \kappa_2 = \int \chi : \bar{E}_1 \bar{E}_1 \cdot \bar{E}_2^* dz$

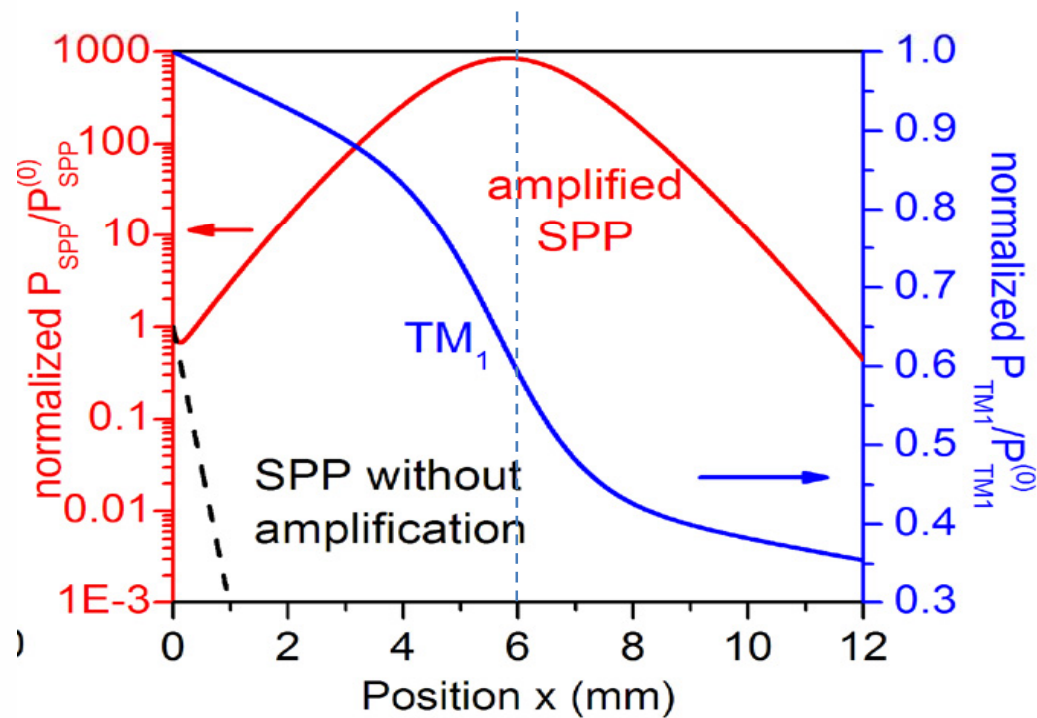
For the nonlinear crystal LiNbO₃, d_{33} is considered with respect to E_z component

$$\kappa_1 = \int d_{33} E_{2,z} (E_{1,z}^*)^2 dz = \kappa^*, \kappa_2 = \int d_{33} E_{2,z}^* (E_{1,z})^2 dz = \kappa,$$

TM₁ is set as the pumping wave at **336.8 THz**
A small **SPP** signal is introduced as the seed (**168.4 THz**)



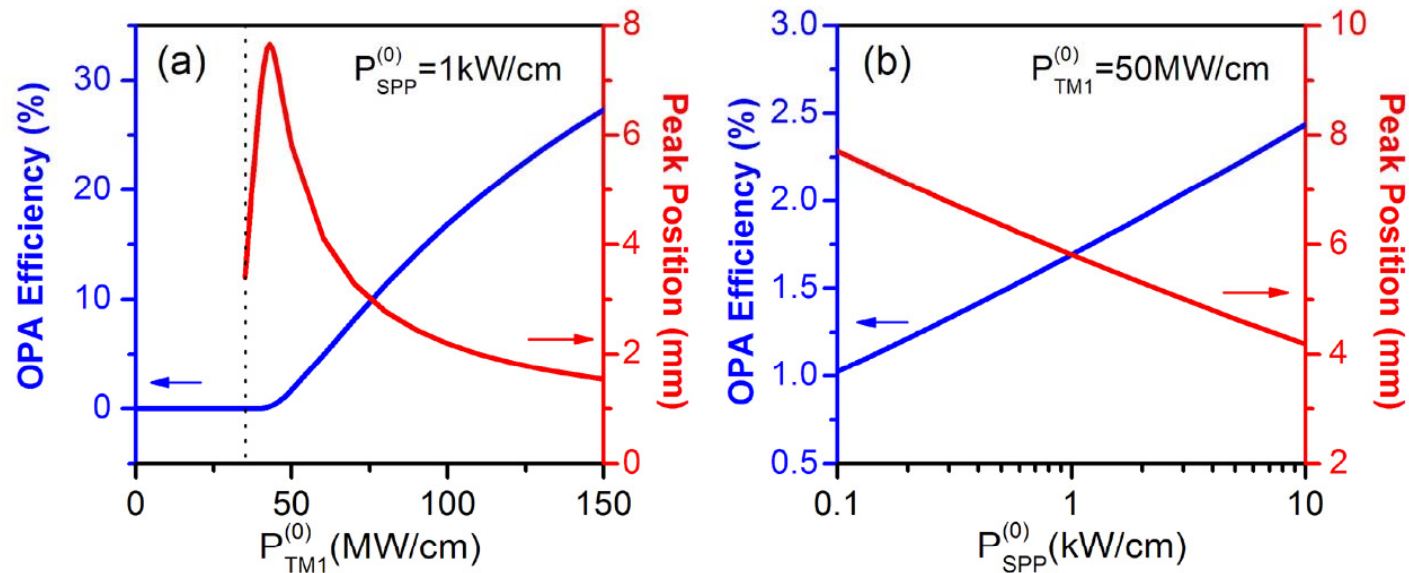
By numerical calculation of the coupled wave equations



From the calculation, with the TM₁ pumping, a definite **SPP OPA** is achieved.



OPA efficiency vs. power of pumping and seed

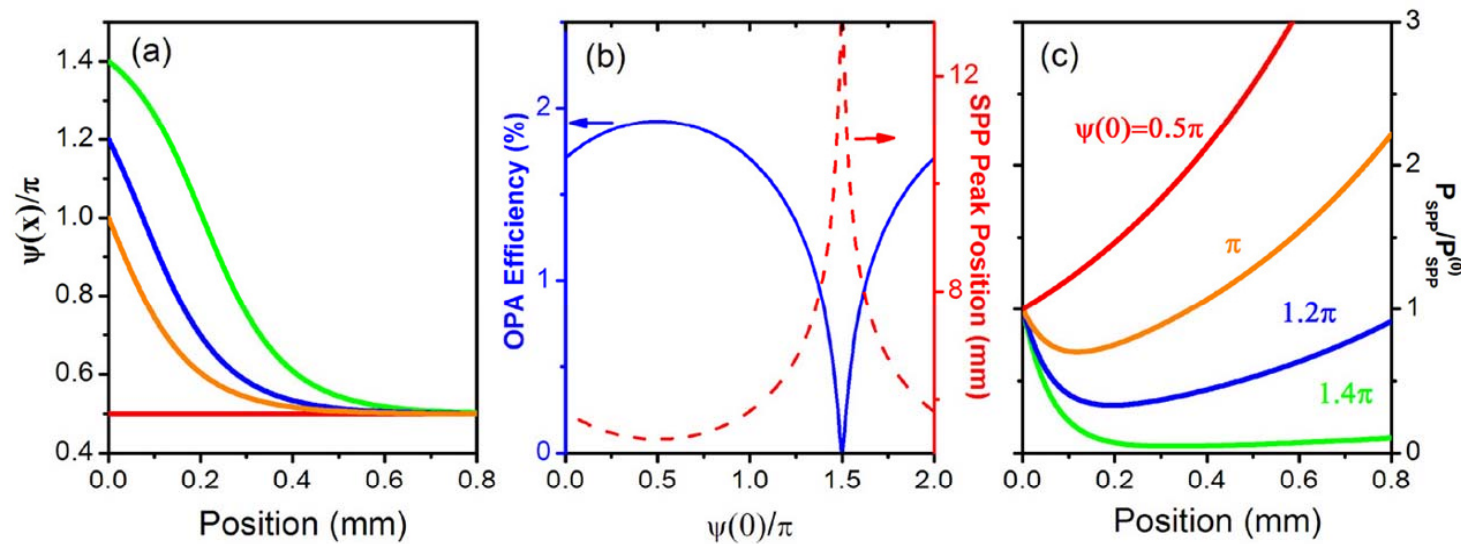


- The stronger power, the higher OPA efficiency;
- Pumping power has a threshold;
- SPP OPA have a maximum that is related with power



Phase evolution and its influence on OPA

- Define $\psi(x) = \Phi + 2\varphi_1(x) - \varphi_2(x)$,



- Difference initial phase difference tends to be a constant 0.5π .
- $\psi(0)=1.5\pi$ will lead to a zero OPA efficiency, it is a suppression but not an amplification for the SPP seed signal.
- $\psi(0)=0.5\pi$ corresponds to a rapidest amplification.



These results are calculated from the following equations

$$\frac{d|A_1|}{dx} = \frac{1}{2}|A_1|[-\alpha_1 + \frac{1}{2}\omega\varepsilon_0|\kappa||A_2|\sin\psi(x)],$$

$$\frac{d\varphi_1}{dx} = \frac{1}{4}\omega\varepsilon_0|\kappa||A_2|\cos\psi(x),$$

$$\frac{d|A_2|}{dx} = \frac{1}{2}|A_2|[-\alpha_2 - \frac{1}{2}\omega\varepsilon_0|\kappa|\frac{|A_1|^2}{|A_2|}\sin\psi(x)],$$

$$\frac{d\varphi_2}{dx} = \frac{1}{4}\omega\varepsilon_0|\kappa|\frac{|A_1|^2}{|A_2|}\cos\psi(x).$$

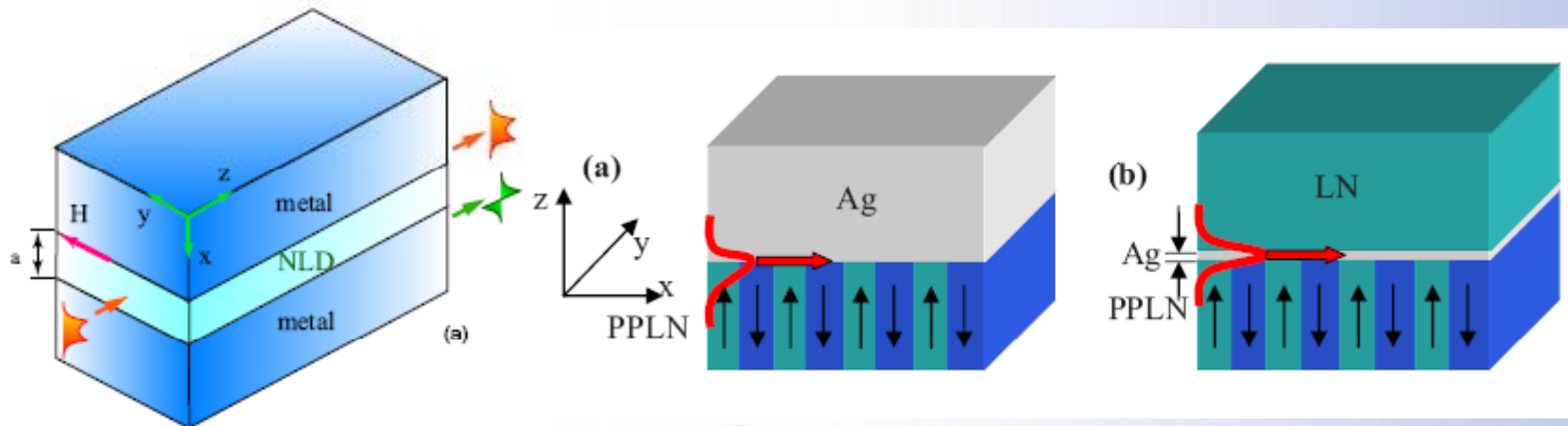
- The phase difference gives rise to the competition between the loss and gain generated from the pumping wave.

The phase influence provides us implications for flexible modulations on the SPP propagation, not only a pure amplification.



(2) Efficient SHG in deep subwavelength scale

- A major problem blocks the development of nonlinear plasmonic waveguide and integration is **large loss**.
- Most studies are in planar plasmonic waveguides, because further **in-planar confinement** will increase the loss drastically.



Kivshar group, OE (2008)

Shen group, PRB (2010)

SHG Efficiency
 $\sim 10^{-3}$ (%)

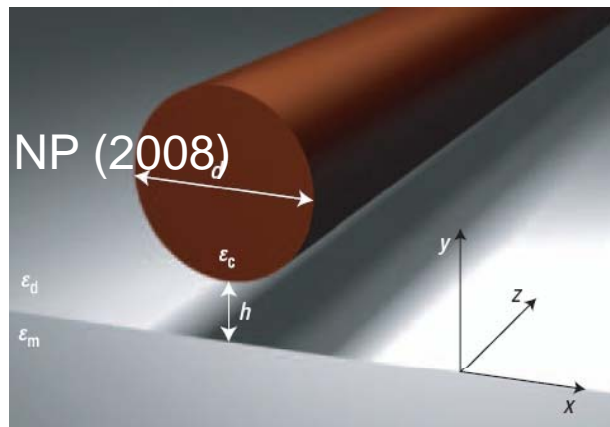


For practical sub- λ nonlinear integration

Two tasks:

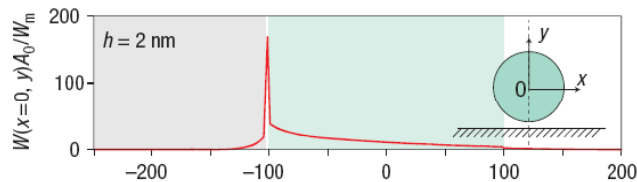
- 1) improve the nonlinear efficiency;
- 2) 2D confinement of EM wave.

◆ A smart structure proposed by X. Zhang group!

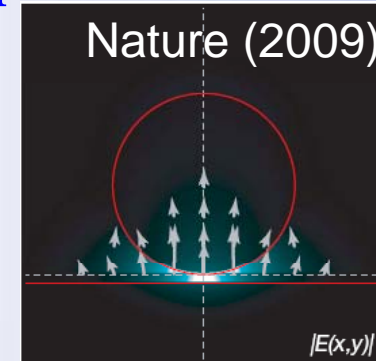
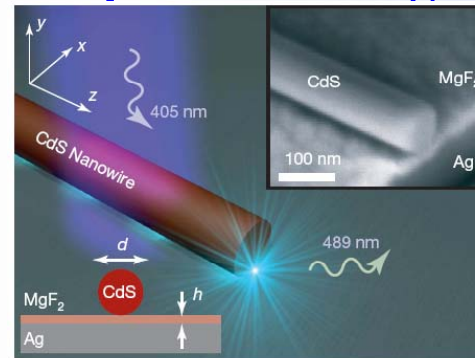


Hybrid plasmonic mode

Deep subwavelength confinement of EM field together with lower loss



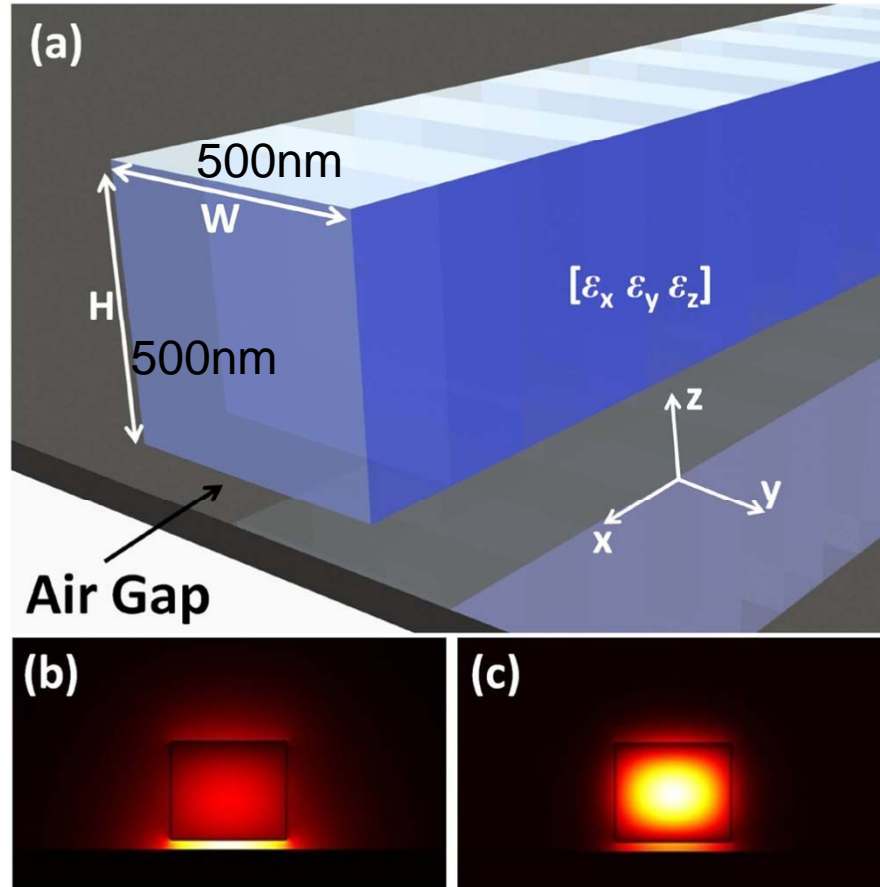
Deep subwavelength plasmon laser



provide illuminations!



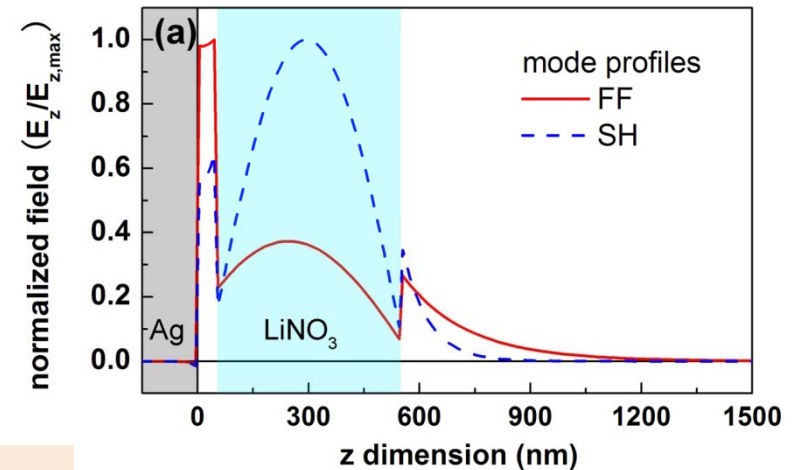
Our design



PPLN on the top of silver film with an air gap

PPLN is used for the phase matching

Mode profiles



SPP-like hybrid mode for FF

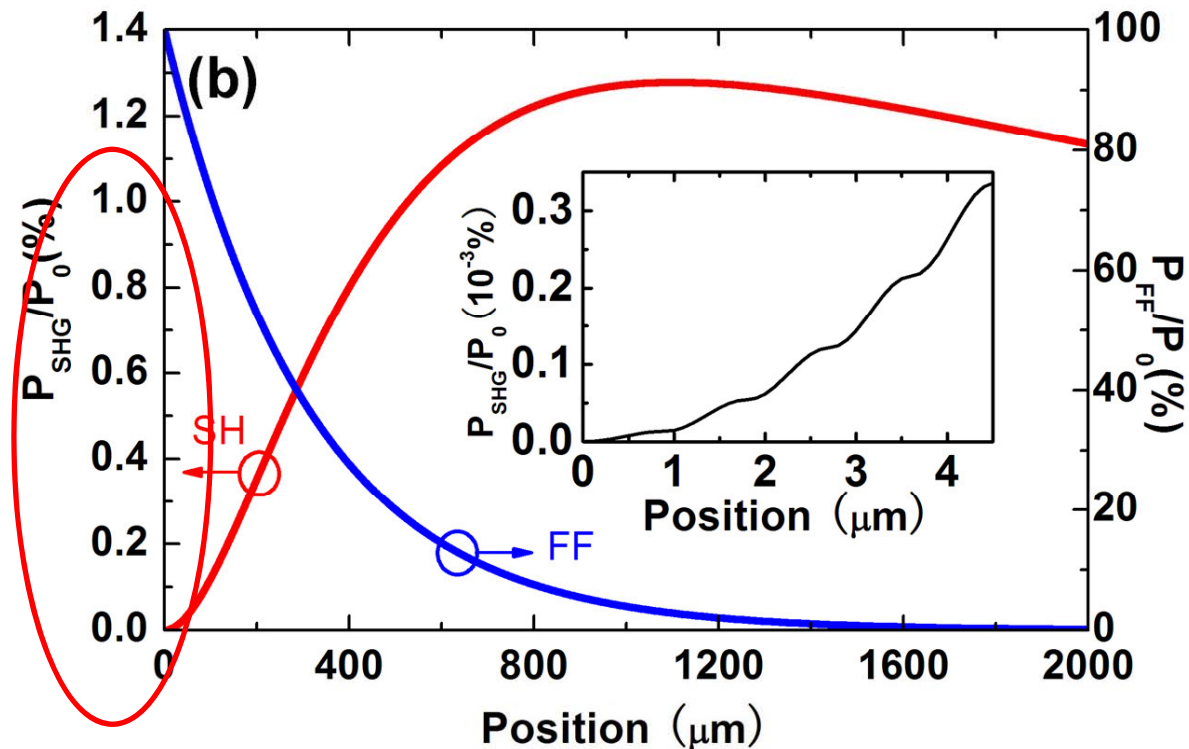
Waveguide-like hybrid mode for SH

D_{ielectric} S_{uperlattice} L_{aboratory}

Mode overlaps



By solving the coupled wave equations with the simulated field distribution, we get the SHG process. Here, $\lambda(\text{FF})=1.55\mu\text{m}$, $\lambda(\text{SH})=775\text{nm}$, incident power= $400\text{MW}/\text{cm}^2$.

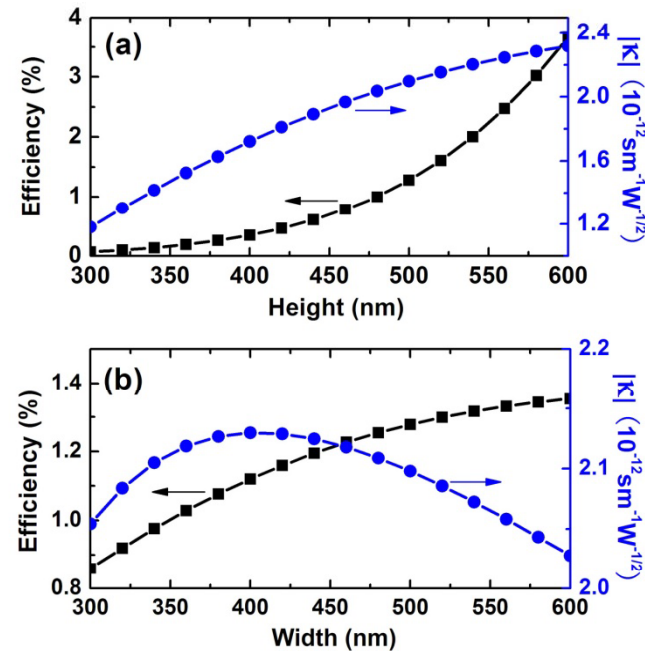
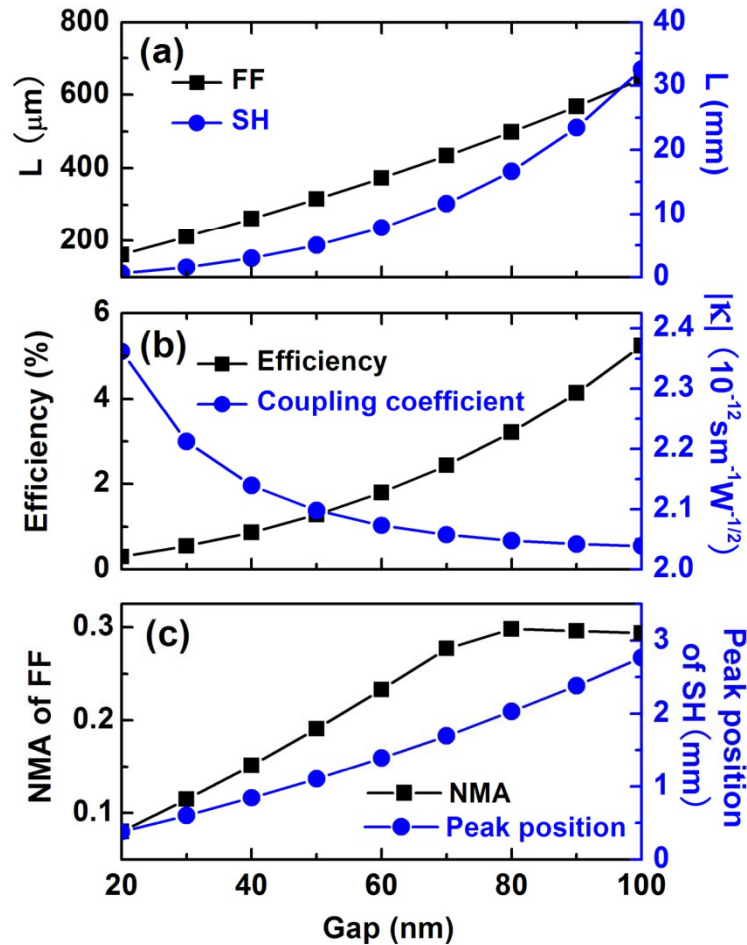


Greatly improved SH efficiency

Normalized mode area (A/A_{diff}) ~ 0.2



Influence of detailed structural parameter



Larger gap, bigger PPLN, will increase the efficiency, but less field-confinement and lower down conversion rate!

Opt. Lett. 36, 3371 (2011)



Summary

- More optimizations of efficient nonlinear parametric process are possible by careful structure design and mode selections.
- Flexible modulations on the SPPs are manifested by nonlinear process (e.g., intensity and phase).
- Further experimental explorations in nonlinear plasmonics are hopeful!



Related publications

- L. Wang, et al, *Scientific Reports* **2**, 2603 (2013).
- L. Li, et al, *Phys. Rev. Lett.* **110**, 046807 (2013).
- L. Li, et al, *Opt. Lett.* **37**, 5091 (2012).
- L. Wang, et al, *Opt. Express* **20**, 8710 (2012).
- L. Li, et al, *Phys. Rev. Lett.* **107**, 126804 (2011).
- L. Li, et al, *Nano Lett.* **11**, 4357 (2011).
- F. F. Lu, et al, *Opt. Lett.* **36**, 3371 (2011).
- F. F. Lu, et al, *Opt. Express* **19**, 2858 (2011).
- T. Li, et al, *Appl. Phys. Lett.* **97**, 261113 (2010).
- T. Li, et al, *Appl. Phys. Lett.* **93**, 021110 (2008)



Nanjing University

Acknowledgement

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Thank you for your attention!

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