Simulations of nanophotonic waveguides and devices using COMSOL Multiphysics

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- ***Simulation of dielectric waveguides and optic fibers using COMSOL***

- ***Simulation of surface plasmon polariton (SPP) waveguides and devices using COMSOL***

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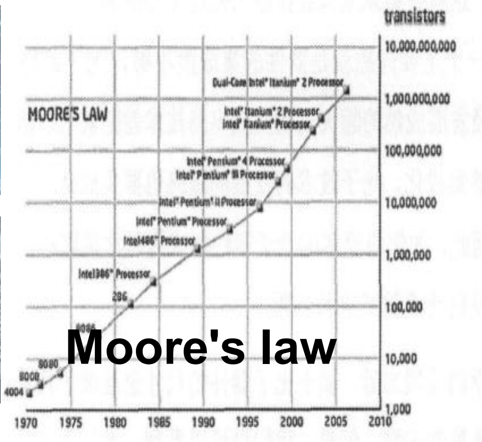
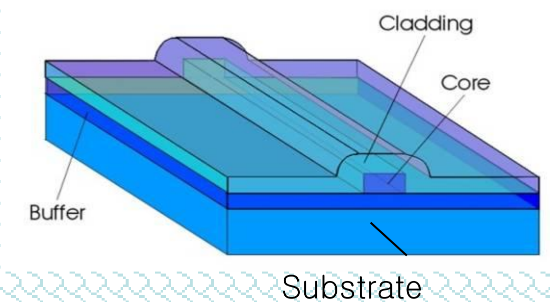
- ***Simulation of surface plasmon polariton (SPP) waveguides and devices using COMSOL***

Motivation - Nanophotonics

Development of Integrated Circuits

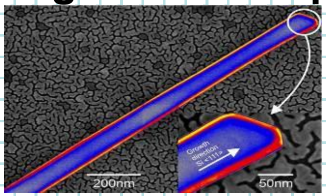


Conventional photonic device

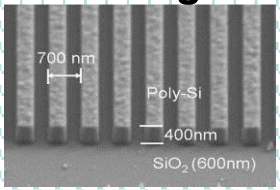


Low-index contrast waveguide

High-contrast planar waveguide

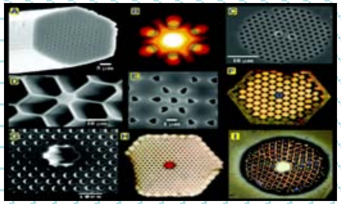


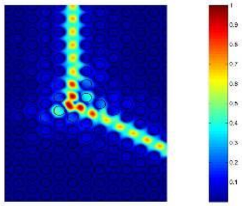
Channel waveguide



Slot waveguide

Photonic crystal fiber and waveguide

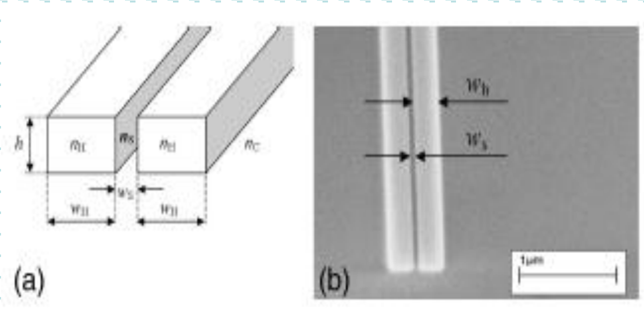




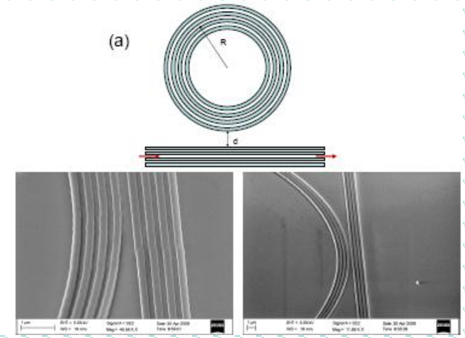
~ Diffraction limit

Dielectric slot waveguides and applications

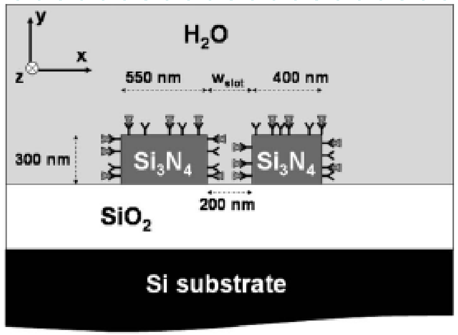
Slot waveguide



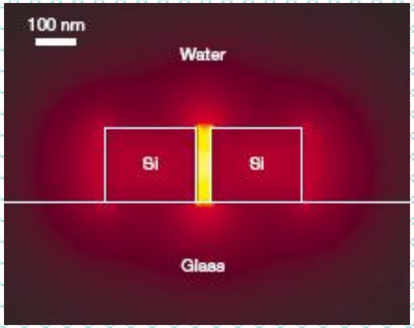
Ring resonator



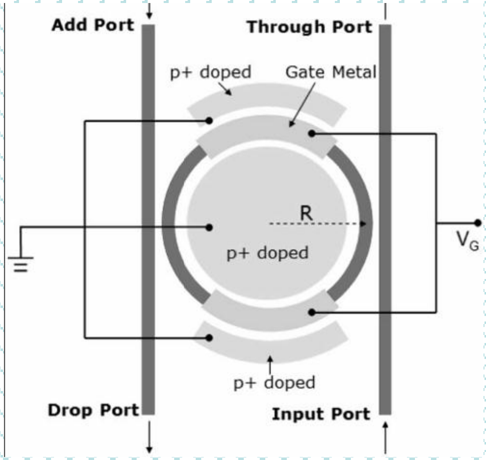
Optical biosensing



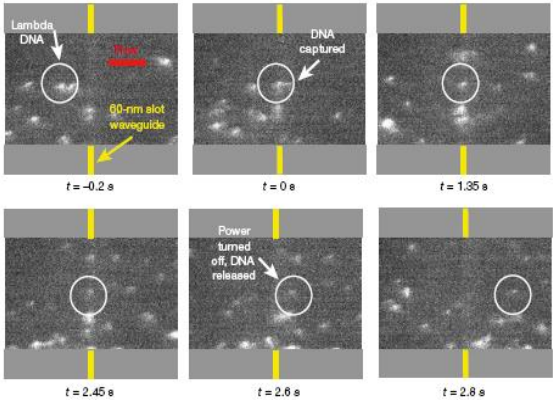
Field distribution



Optical modulator

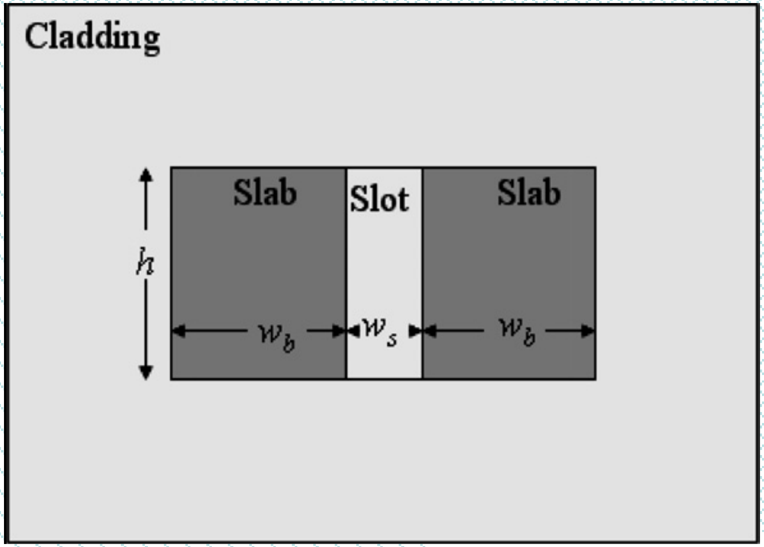


Optical manipulation



*V. R. Almeida et. al, Optics Letters 29, 1209-1211 (2004).

Dispersion analysis of dielectric slot waveguides



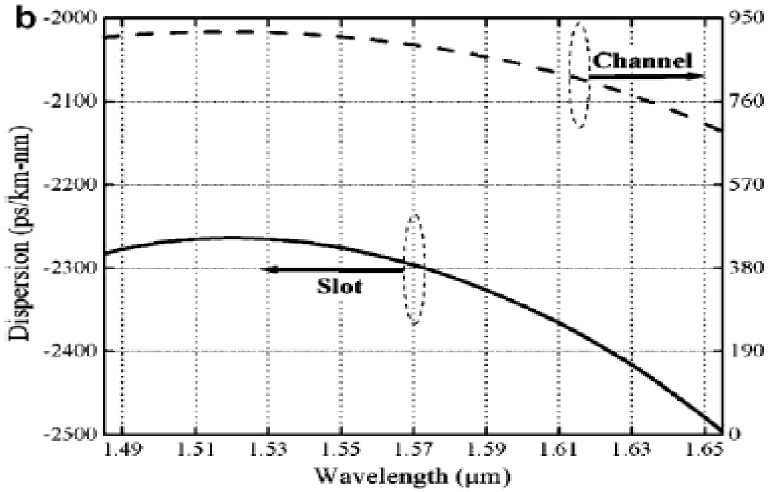
- Group velocity dispersion (GVD) $$D = \frac{\mathrm{d}}{\mathrm{d}\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi}{\lambda^2}\left(2\frac{\mathrm{d}n}{\mathrm{d}\omega} + \omega\frac{\mathrm{d}^2 n}{\mathrm{d}\omega^2}\right)$$
- Sellmeier's equation for silicon and silica refractive indices

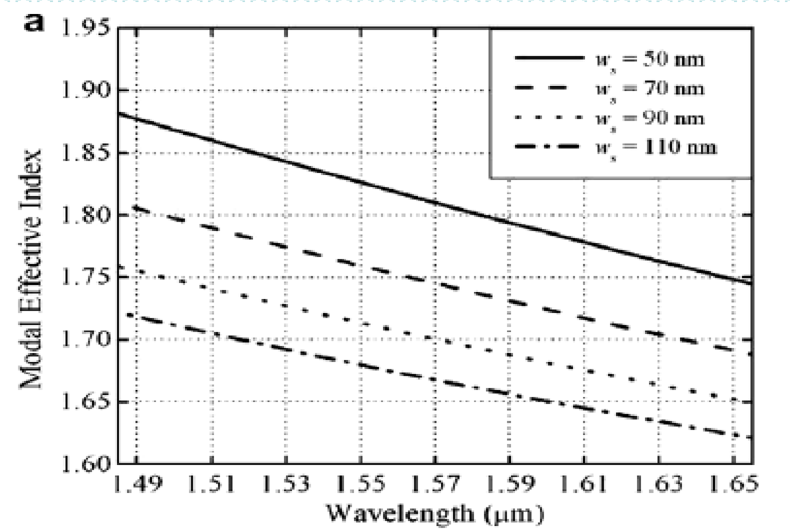
COMSOL settings

- Perpendicular waves of RF module- mode analysis
- Scattering boundary condition

*Z. Zheng, M. Iqbal, Optics Communications 281, 5151-5155 (2008).

Dispersion analysis of dielectric slot waveguides

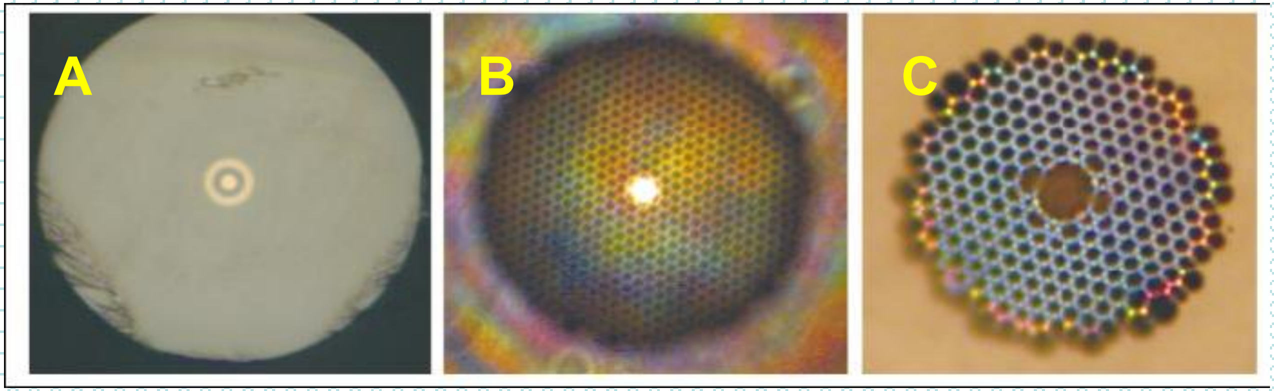




- **Slot waveguide: In the normal dispersion regime near the 1550 nm wavelengths**
  Channel silicon waveguide: In the abnormal dispersion regime
- **GVD (slot) > GVD (channel)**
- **Higher order dispersion behavior depending strongly on the geometric parameters of the slot waveguides (e.g. slot & slab width, material filled in the slot region)**

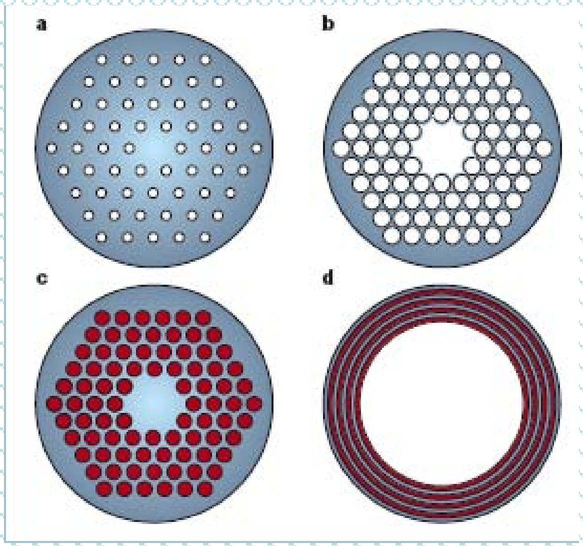
***Z. Zheng, M. Iqbal, Optics Communications 281, 5151-5155 (2008).**

Photonic Crystal Fibers (PCF)



A: Standard optical fiber
(Total external reflection)
B: Index-guiding photonic crystal fiber
(Total internal reflection)
C: Hollow core photonic bandgap fiber
(Photonic bandgap)

Various kinds of PCF



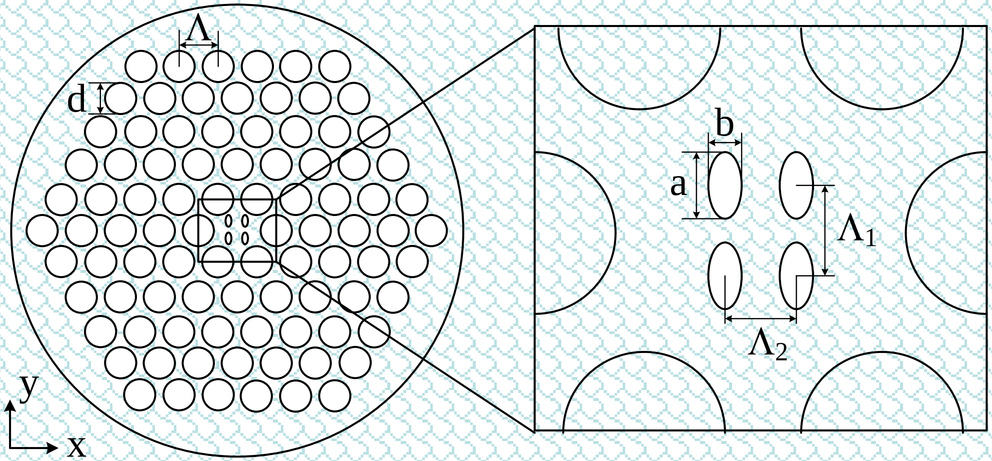
Merits and Potential of PCFs

- Lower transmission loss than conventional fibers
- Substantially higher damage thresholds than conventional fibers
- Promising for various linear and nonlinear optical processes

*J. C. Knight, Nature 424, 847-851 (2003).

Design of ultrahigh birefringent, ultralow loss PCF

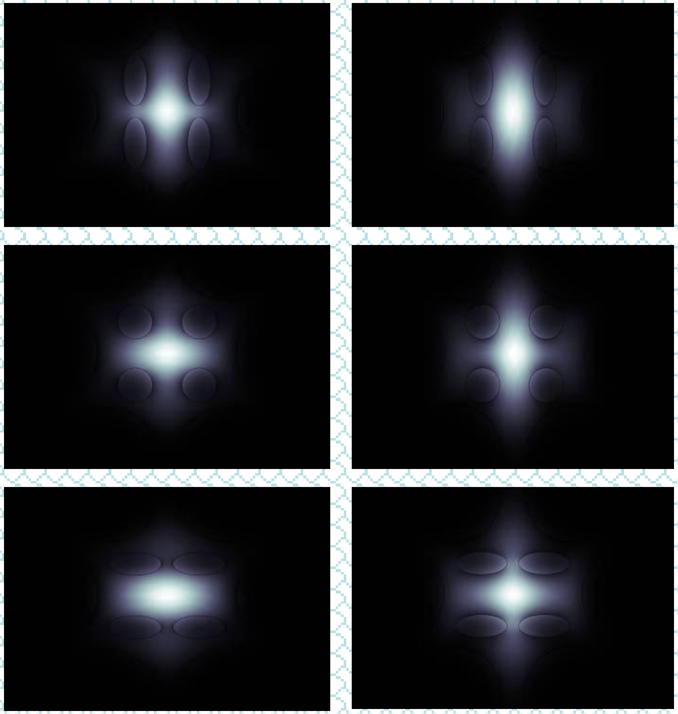
PCF structure



- A core region with a rectangular array of four air holes (to provide the birefringence)
- A conventional circular-air-hole cladding (to reduce the confinement loss).

Intensity distributions

with different elliptic ratio of the air hole



x-polarization y-polarization

COMSOL settings

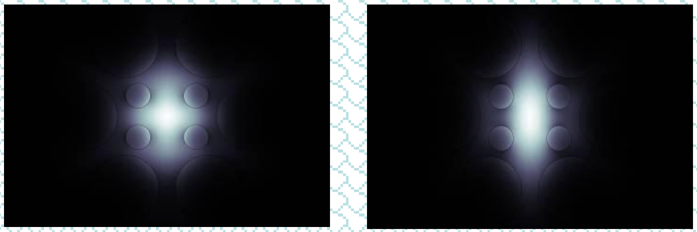
- Perpendicular waves of RF module- mode analysis
- PML boundary condition

*L. An, Z. Zheng. Journal of Lightwave Technology 27, 3175-3180 (2009)

Design of ultrahigh birefringent, ultralow loss PCF

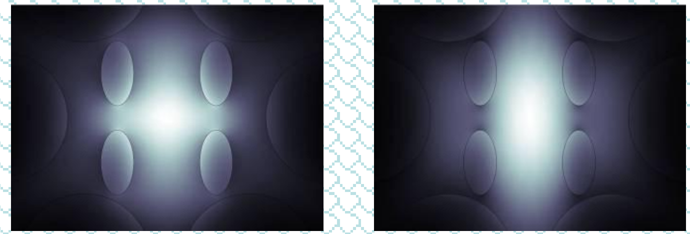
Intensity distribution

PCF with circular air holes



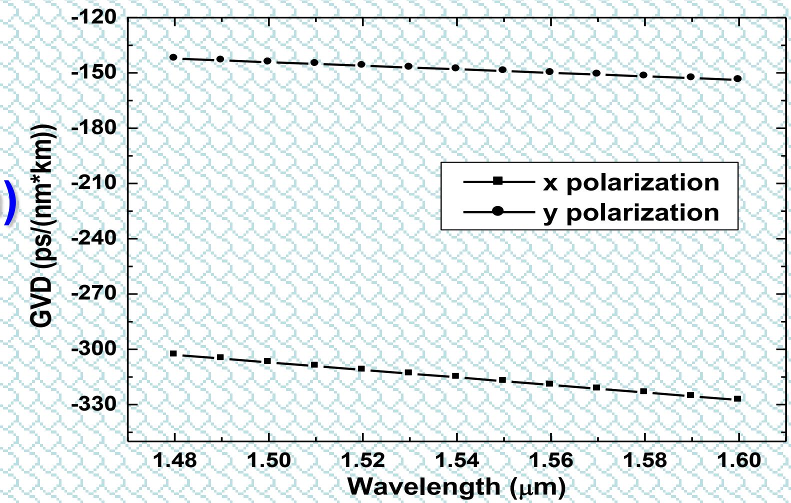
x-polarization　　y-polarization

PCF with elliptical air holes



x-polarization　　y-polarization

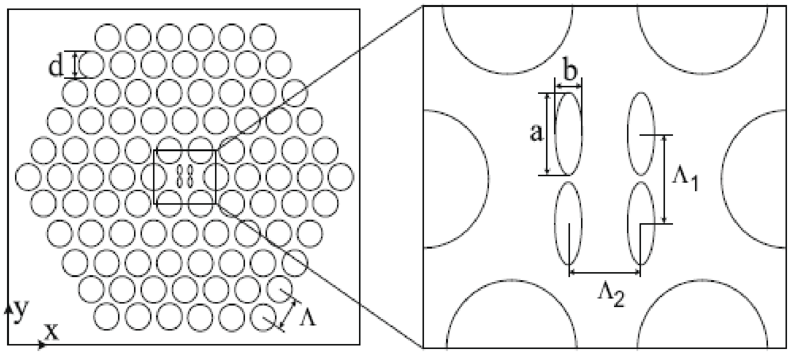
- Ultrahigh single-mode birefringence ($\sim 10^{-2}$)
- Ultralow confinement losses (<0.002 dB/km)
- Relatively flat dispersion
- Easy to fabricate



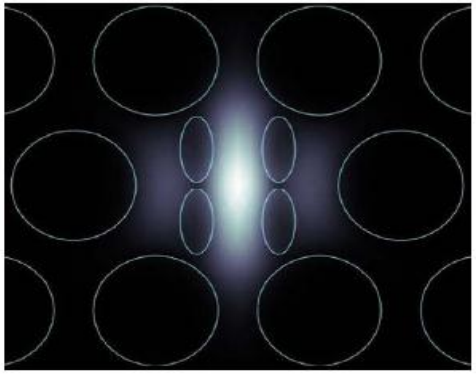
*L. An, Z. Zheng. Journal of Lightwave Technology 27, 3175-3180 (2009)

Design of single-polarization, single-mode PCF

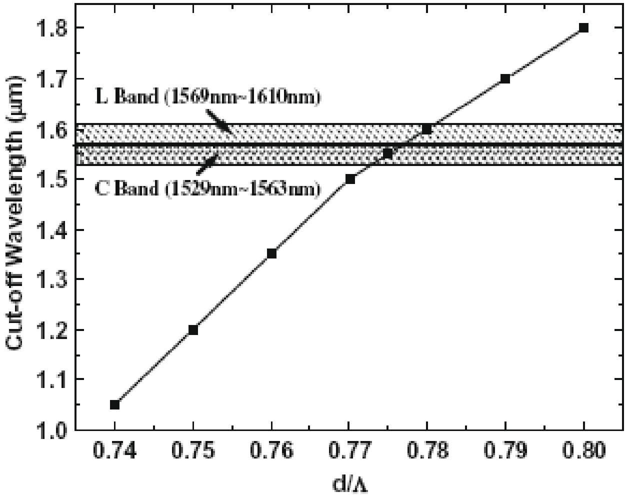
PCF geometry

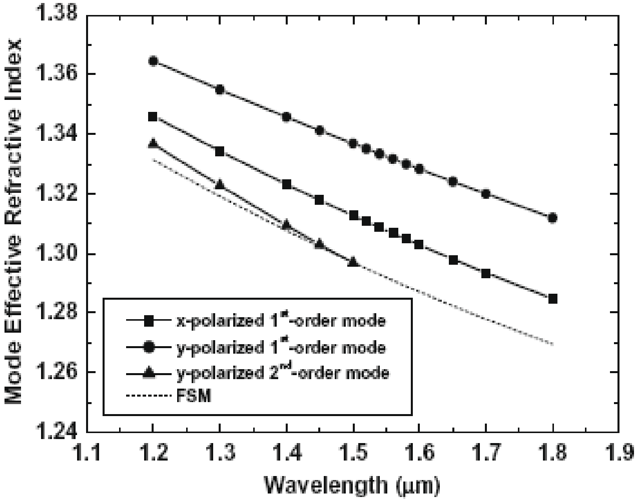


Intensity distribution



y-polarization





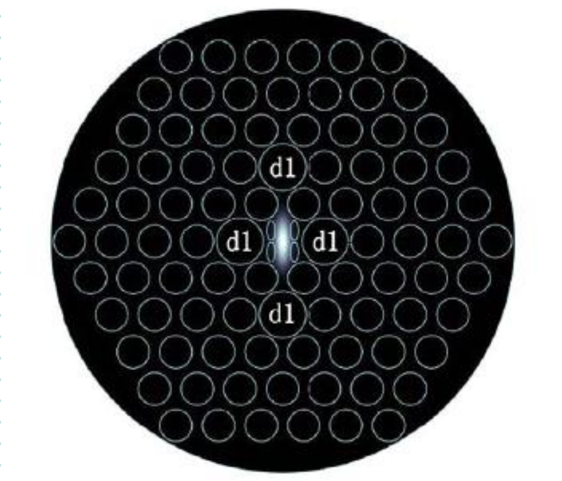
Single-mode and single-polarization propagation can be realized by tuning geometry of the air holes, with low confinement loss and small mode area

*L. An, Z. Zheng, Optics Communications 282, 3266-3269 (2009)

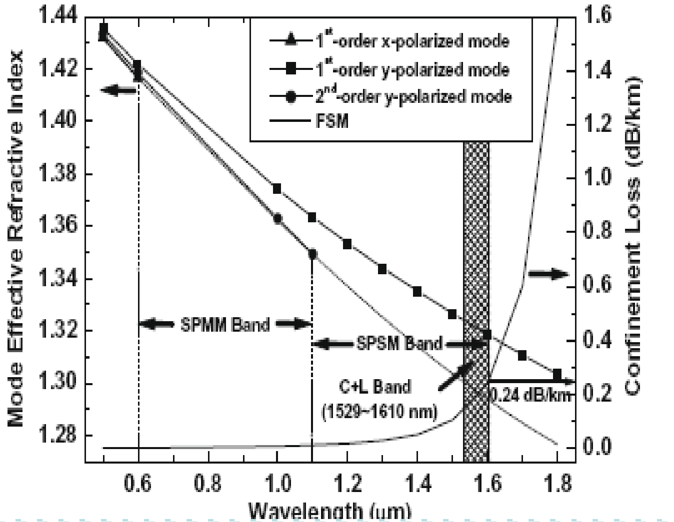
Design of single-polarization, single-mode PCF

Dispersion optimization

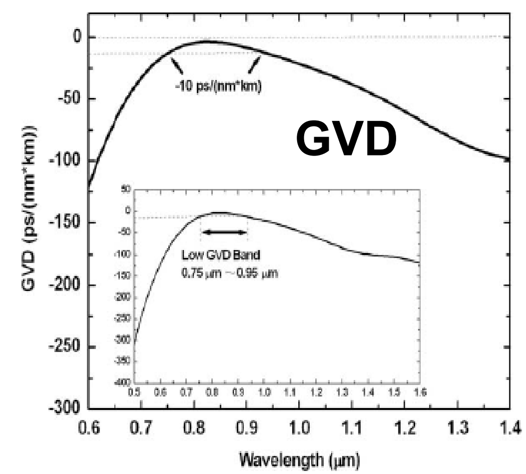
Intensity distribution



Dispersion & confinement loss



GVD



- Near-zero, dispersion-flattened
- Low confinement loss(<0.25 dB/km)
- Small mode area
- Ultra-wide band (0.3–1.84 μm)

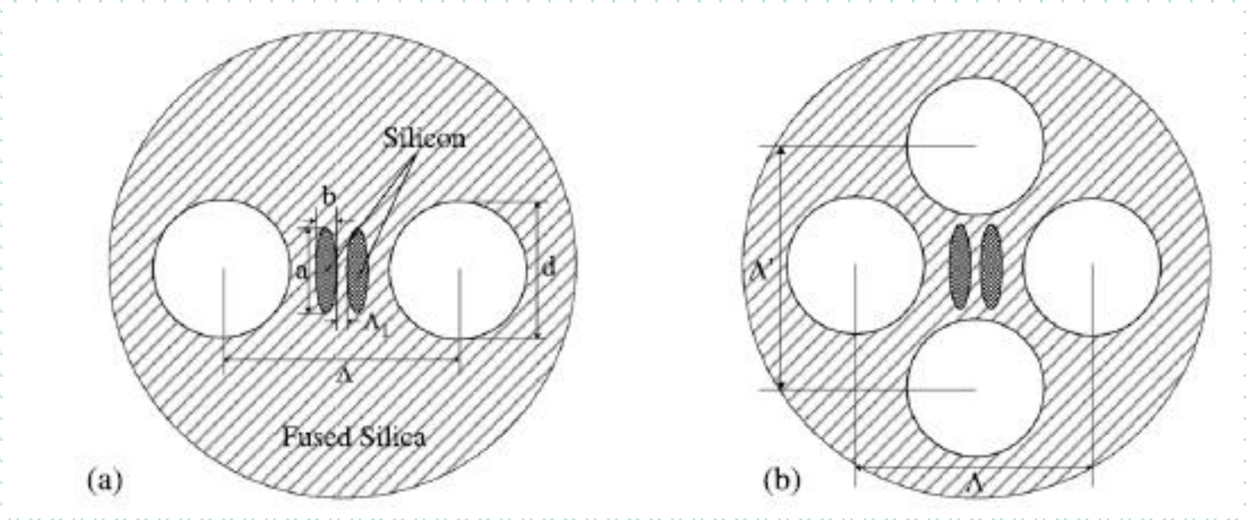
COMSOL settings

- Perpendicular waves of RF module- mode analysis
- PML boundary condition

*L. An, Z. Zheng, Optics Communications 282, 3266-3269 (2009)

Highly nonlinear holey fiber with a high index slot core

Proposed structure



COMSOL settings

- Perpendicular waves of RF module- mode analysis
- PML boundary condition

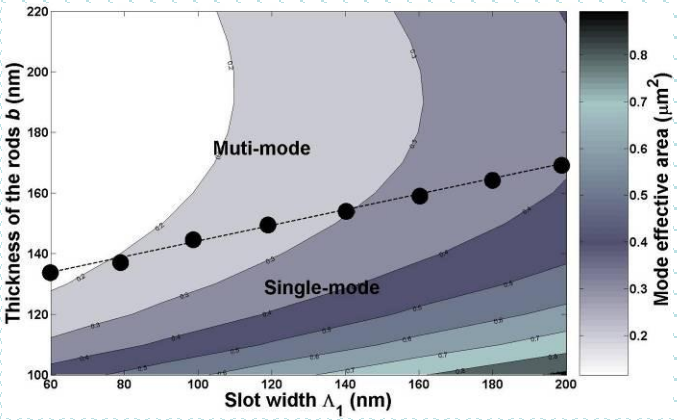
*L. An, Z. Zheng, Journal of Optics, 115502 (2010).

Highly nonlinear holey fiber with a high index slot core

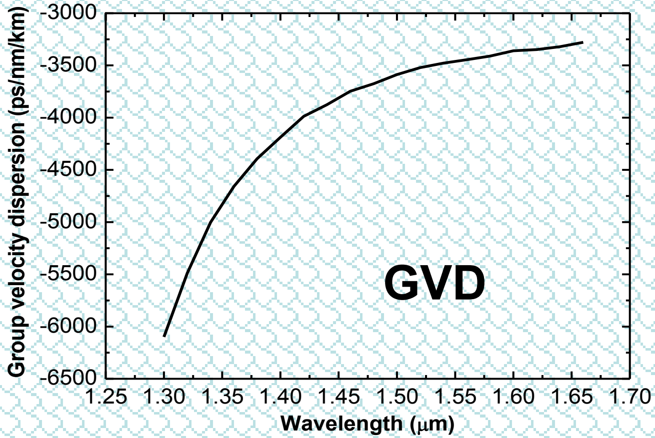
Fiber with a slot core

Intensity distribution

Modal behavior



Group velocity dispersion

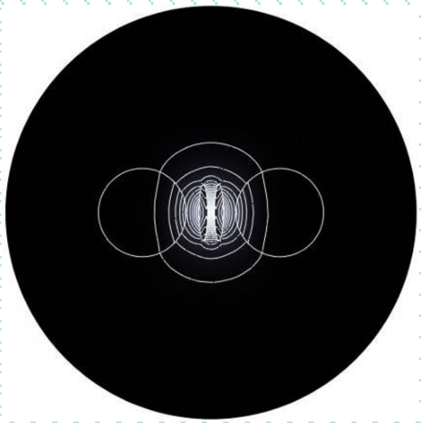


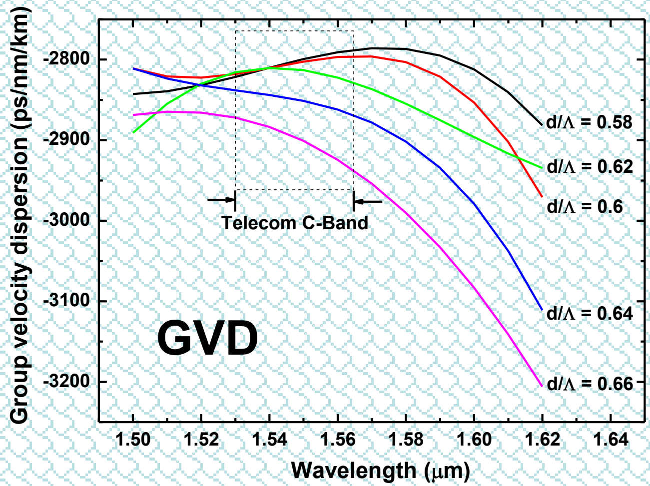
- Quasi-TE mode well confined in the slot region
- Single-mode propagation with ultra-small mode area (< 0.3 μm^2)
- A large negative GVD and large GVD slope

*L. An, Z. Zheng, Journal of Optics, 115502 (2010).

Highly nonlinear holey fiber with a high index slot core

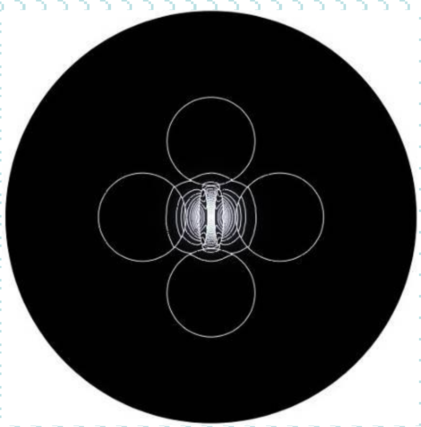
Fiber with a slot core and a two-air-hole cladding

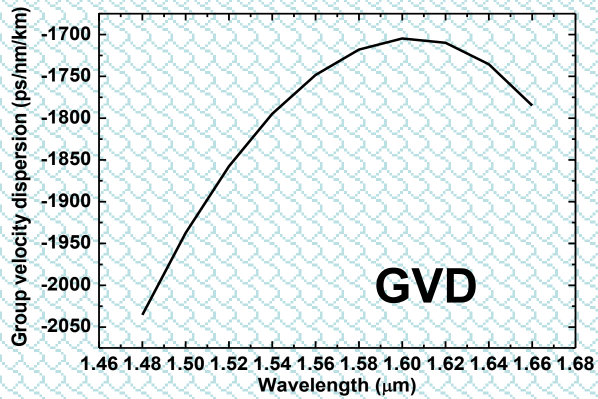




- **Modification of GVD**
  - **Much lower GVD than that without air-hole**
  - **Different dispersion slope at various air-hole parameters**
- **Enhancement of the field confinement**

Fiber with a slot core and a four-air-hole cladding





- **Even lower absolute GVD values**
- **Further enhancement of the field confinement**

*L. An, Z. Zheng, Journal of Optics, 115502 (2010).

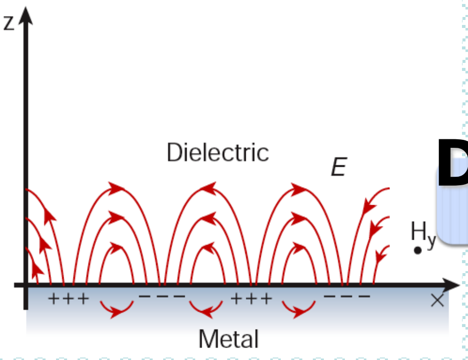
- Simulation of dielectric waveguides and optic fibers using COMSOL

- Simulation of surface plasmon polariton (SPP) waveguides and devices using COMSOL

Introduction-Surface Plasmons

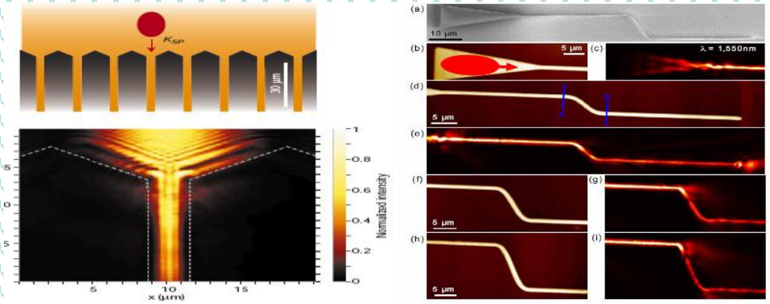
*W. L. Barnes, Nature 424, 824-830 (2003).

Surface plasmons (SPs)

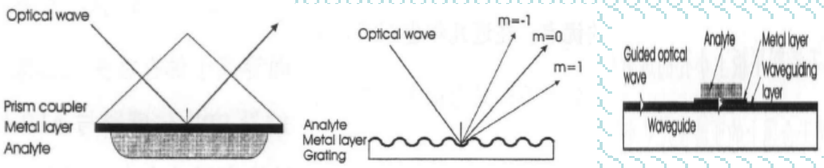


Diffraction limit

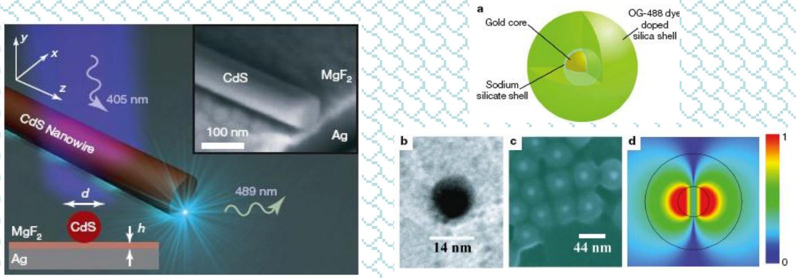
Light guiding



Sensing



Lasing



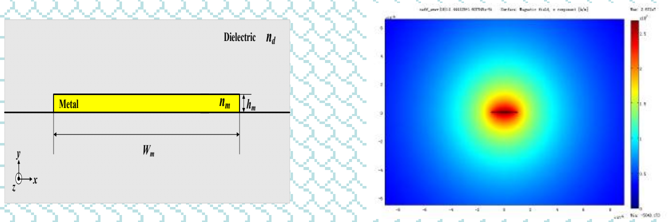
Nanolithography

- Coherent electron oscillations at the metal/dielectric interface
- Field decays exponentially into both neighboring media

Introduction-SPP waveguides

Surface plasmon polariton (SPP) waveguide

Insulator/Metal/Insulator (IMI)



Long-range SPP waveguide

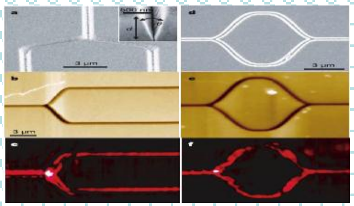
Advantages

Low propagation loss (a few dB/cm)

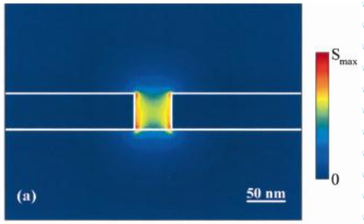
Disadvantages

Weak confinement (mode size~λ)

Metal/Insulator/Metal (MIM)



CPP waveguides



metal slot waveguide

Advantages

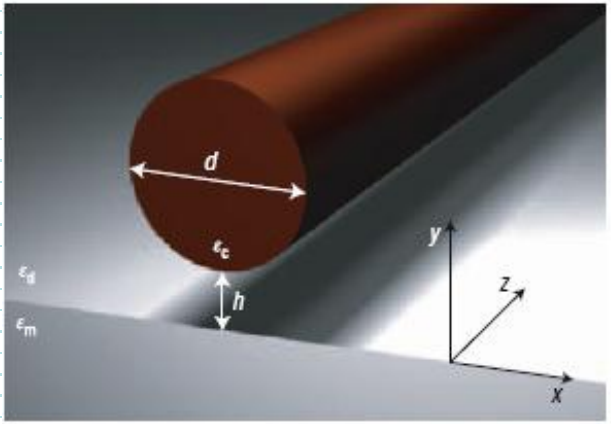
Tight field confinement (subwavelength scale)

Disadvantages

Huge loss (propagation length ~ several μm)

Loss → **Tradeoff** ← **Confinement**

Hybrid plasmonic waveguide



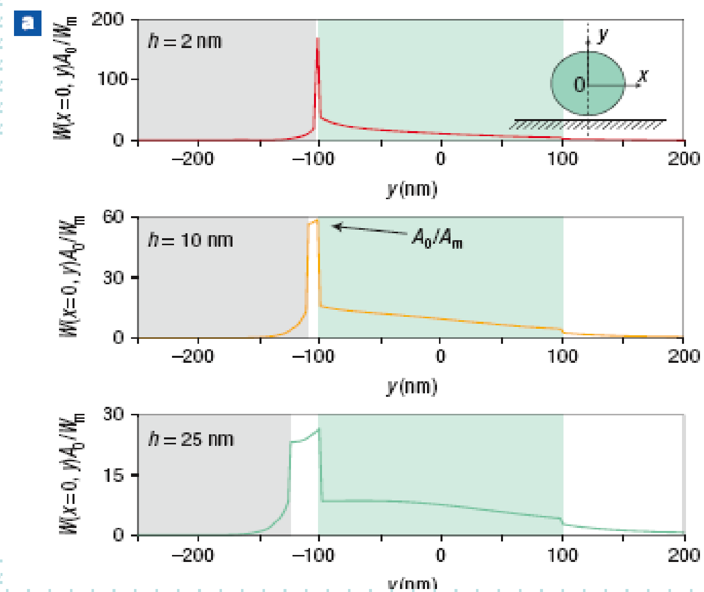
*R. F. Oulton, Nature Photonics, 2008. 2(8): p. 496-500.

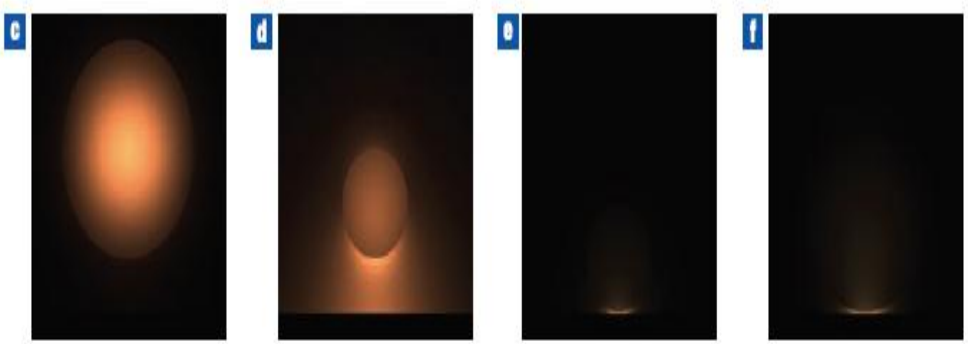
- **Subwavelength mode confinement**

  $\lambda^2/400 \sim \lambda^2/40$

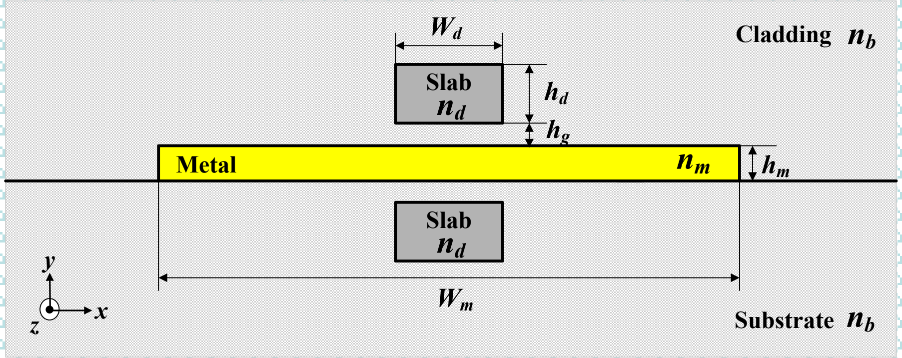
- **Long-range propagation distance**

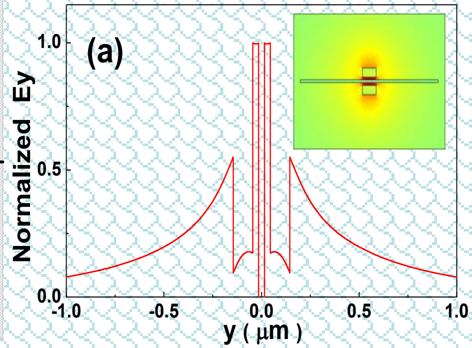
  40 ~ 150 μm

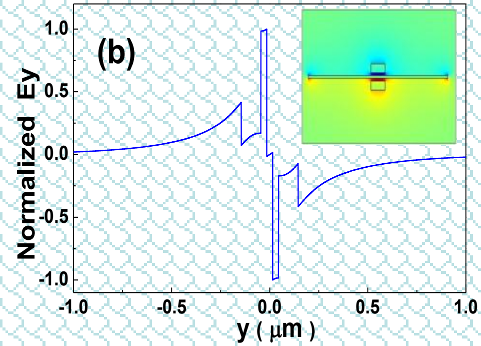


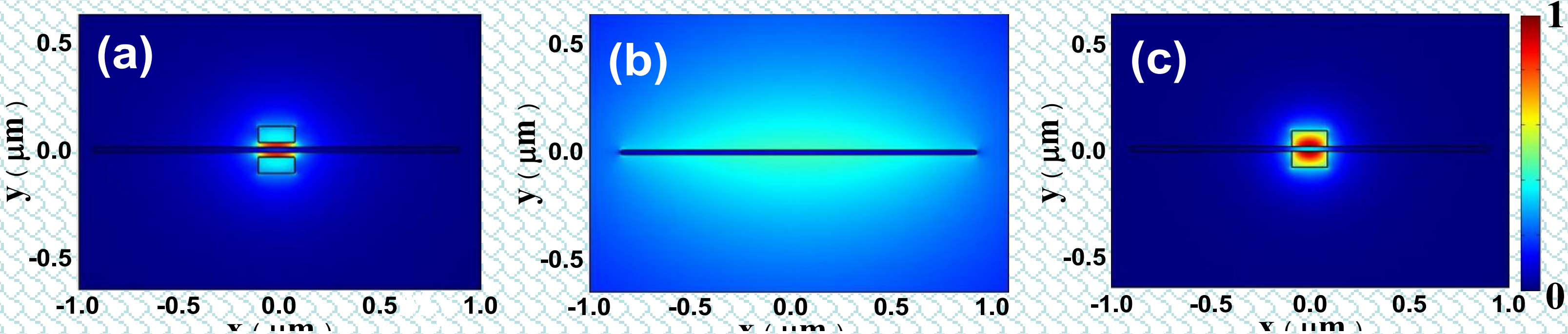


Design of symmetric hybrid plasmonic waveguide





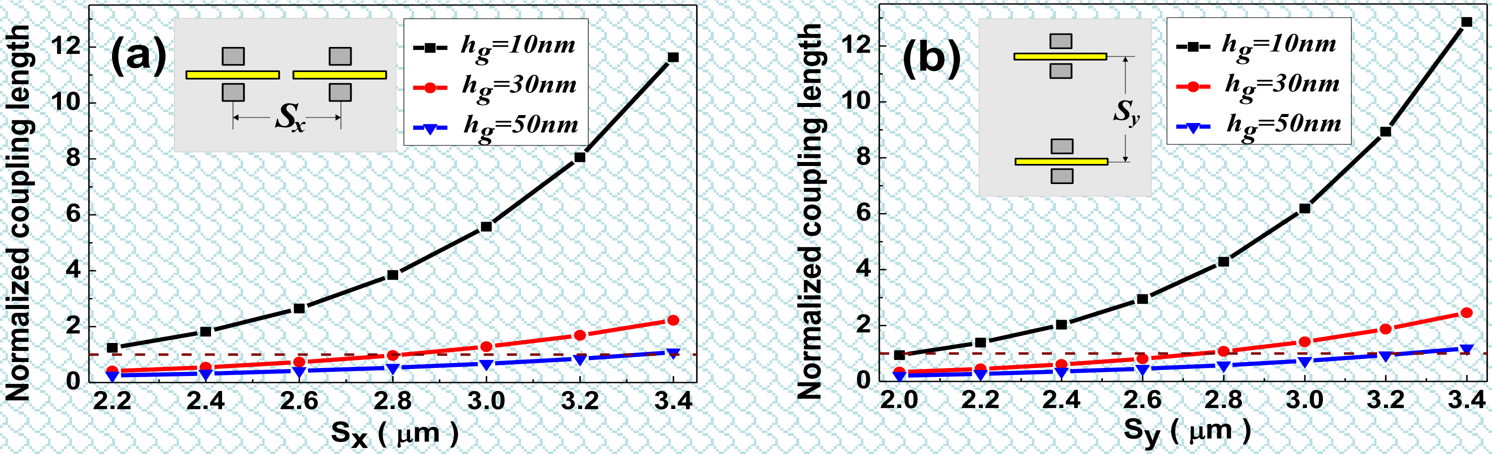




- Subwavelength confinement (1~2 orders of magnitude higher than insulator/metal/insulator waveguides)
- Low loss (propagation length~ hundreds of microns)

*Y. S. Bian, Z. Zheng, Optics Express 17, 21320-21325 (2009).

Design of symmetric hybrid plasmonic waveguide



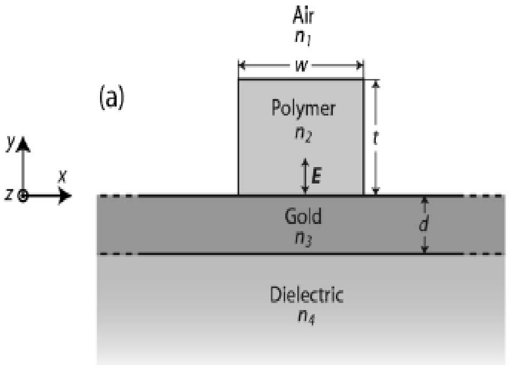
- High-density 3D photonic integration(packing density increased by nearly 60 times over insulator/metal/insulator waveguides)
- Finite dimensions in both directions, enabling multilayer, 3-dimensional (3D) integrated circuits

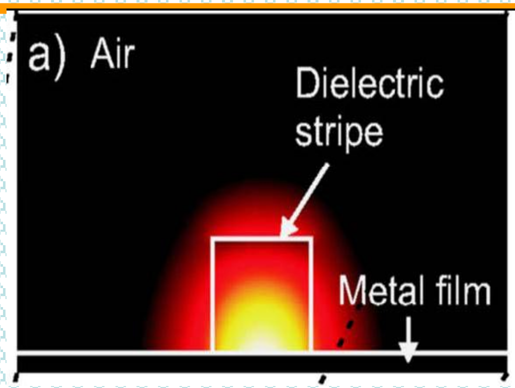
COMSOL settings

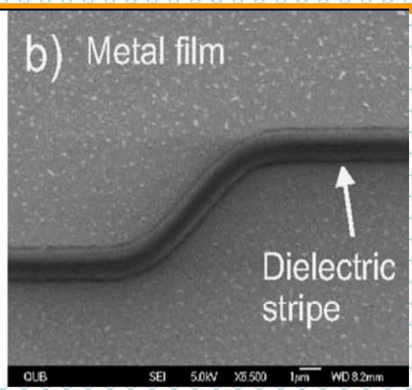
- Perpendicular waves of RF module- mode analysis
- Scattering boundary condition

*Y. S. Bian, Z. Zheng, Optics Express 17, 21320-21325 (2009).

Dielectric-loaded SPP waveguides



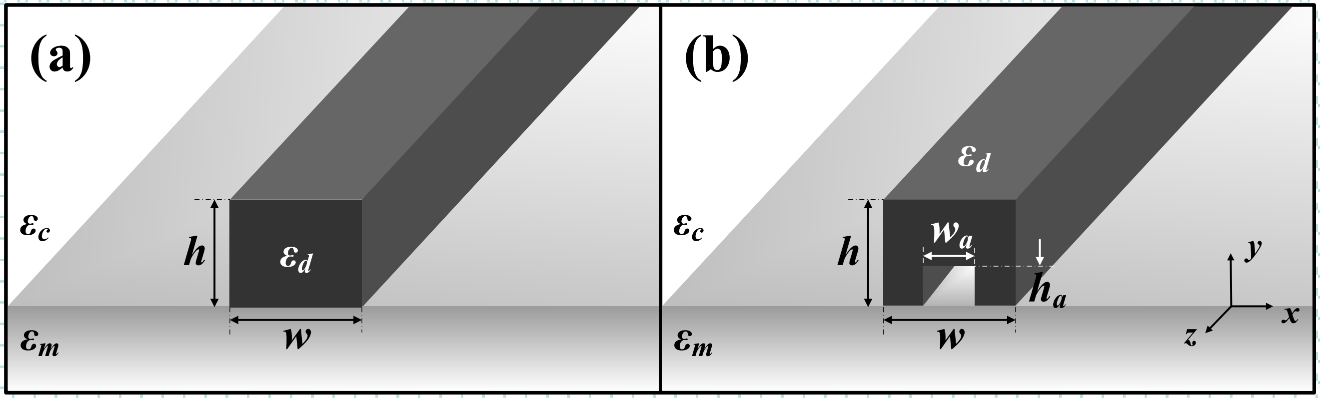




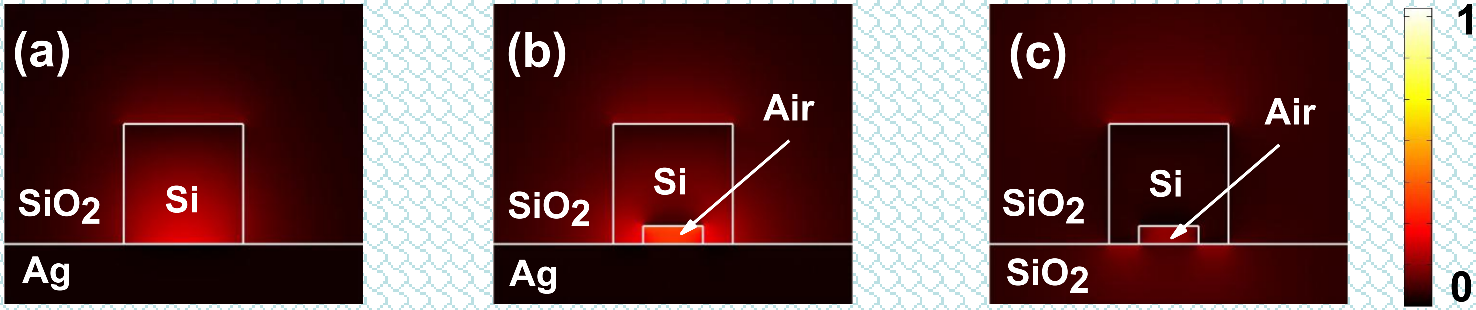
- **Relatively tight confinement of light (subwavelength scale)**
- **Relatively long propagation distance (tens of microns)**

Low-index DLSPP waveguides	**VS**	**High-index DLSPP waveguides**
● Low-index polymer (n~1.5)		● High-index dielectric (n~2 & n~3.5)
● Low loss		● Stronger confinement
● Relatively large geometry size (e.g.600nm×600nm)		● Compact, Si fab process compatible, suitable for integration
● Not suitable for high integration		● Huge loss

Design of DLSPP waveguide with a holey ridge



Geometry



Field distribution

- Strong field enhancement in the nanohole due to the slot effect

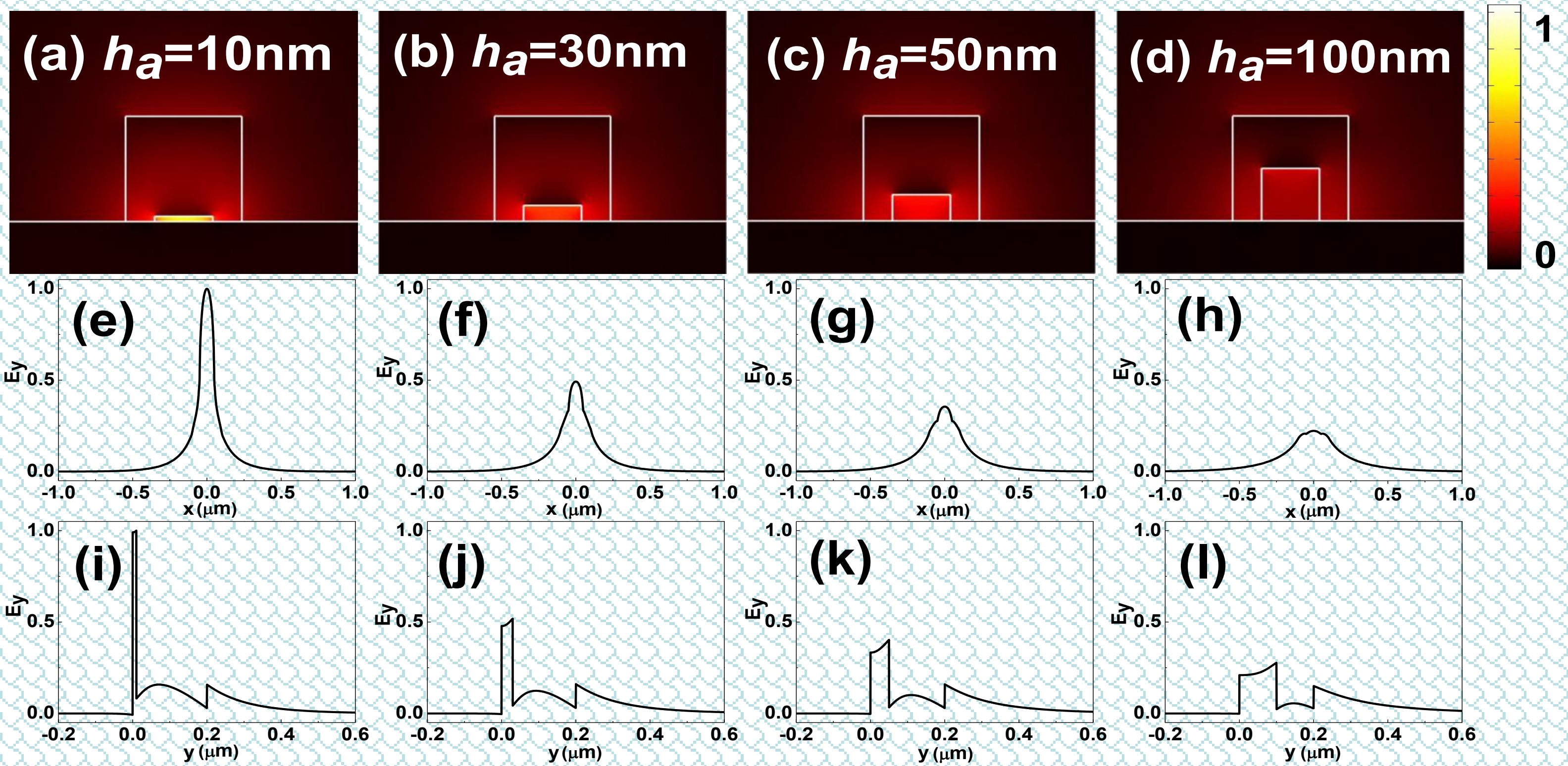
COMSOL settings

- Perpendicular waves of RF module- mode analysis
- Scattering boundary condition

*Y. S. Bian, Z. Zheng, Optics Express, To be published.

Design of dielectric-loaded waveguide with a holey ridge

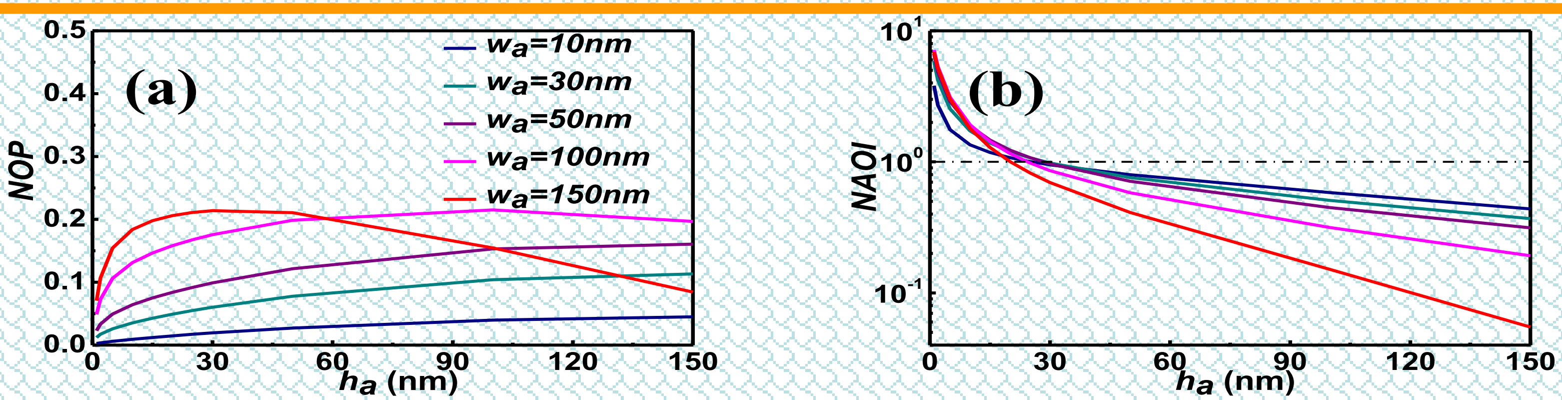
Field distributions at different nanohole widths



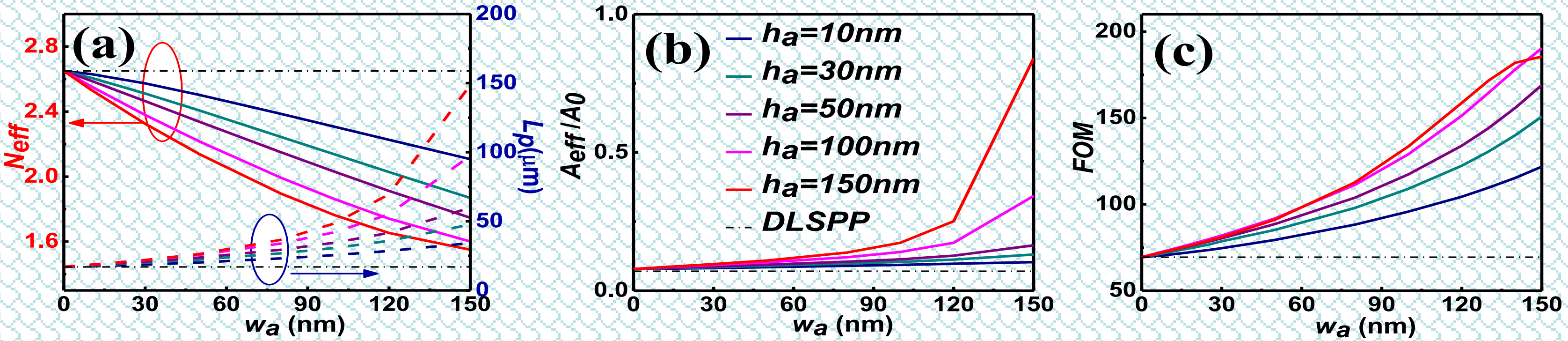
- Even stronger field enhancement with a shallow and wide, low-index nanohole

*Y. S. Bian, Z. Zheng, Optics Express, to be published.

Design of dielectric-loaded waveguide with a holey ridge



- High optical power and strong optical intensity in the nanohole

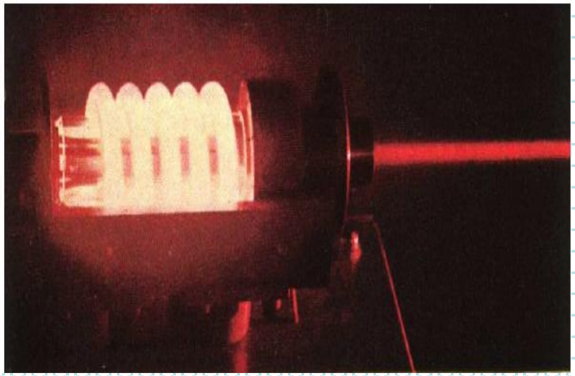


- High optical power and strong optical intensity in the nanohole
- Loss reduction achieved with small sacrifice in the mode area
- Improved figure of merit (FOM) with a shallow and wide air nanohole

*Y. S. Bian, Z. Zheng, Optics Express, To be published.

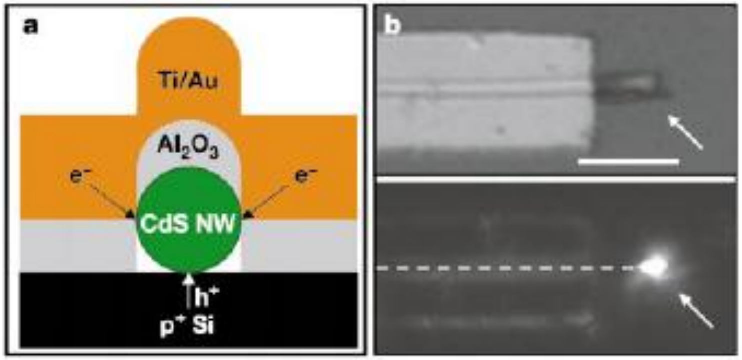
Nanolasers

The first laser (1960)



Nanotechology

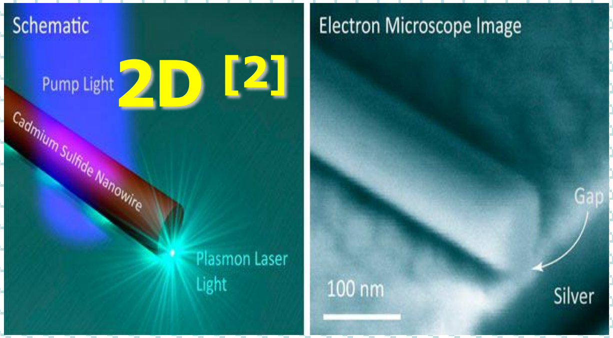
Dielectric nanowire lasers [1]
~ diffraction limit



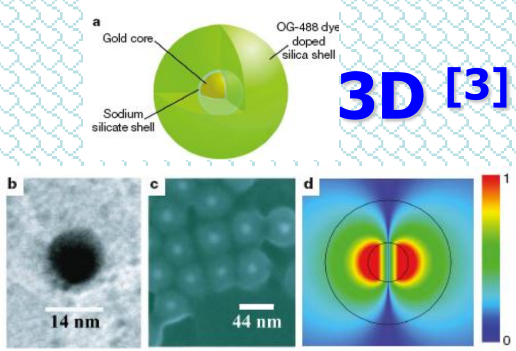
[1] **Nature** 421, 241-245 (2003).

Plasmon nanolasers << diffraction limit

2D [2]



3D [3]

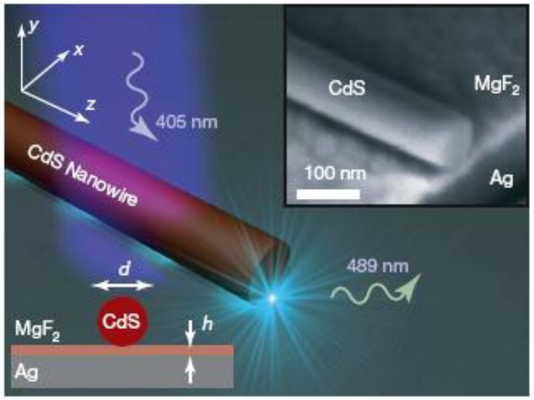


- **Directional emissions similar to the FP lasers**
- **High field confinement in the gain media region**
- **Low-threshold operation**

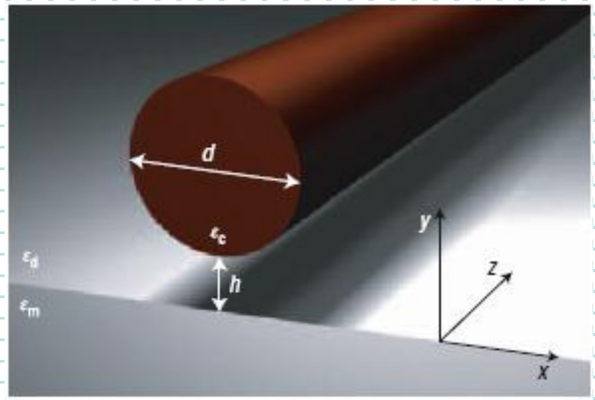
[2] **Nature** 461, 629-632 (2009). [3] **Nature** 460, 1110-1112 (2009).

2D plasmon nanolasers

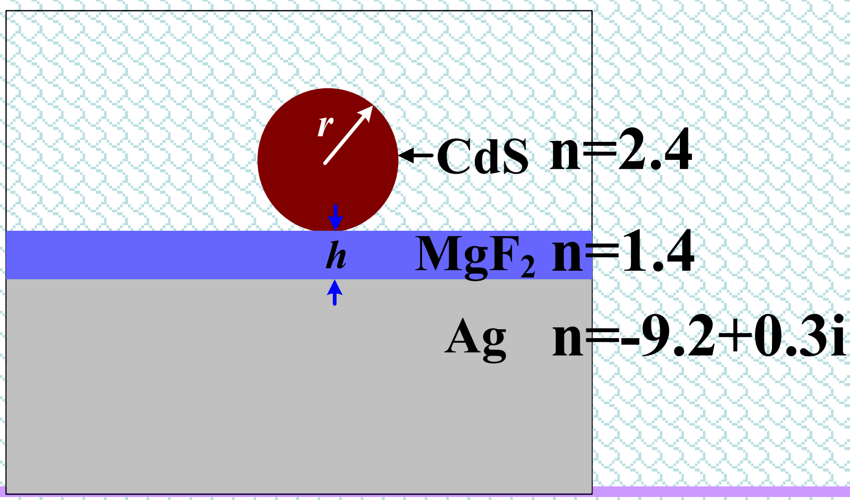
Plasmon nanolaser



Hybrid plasmonic waveguides

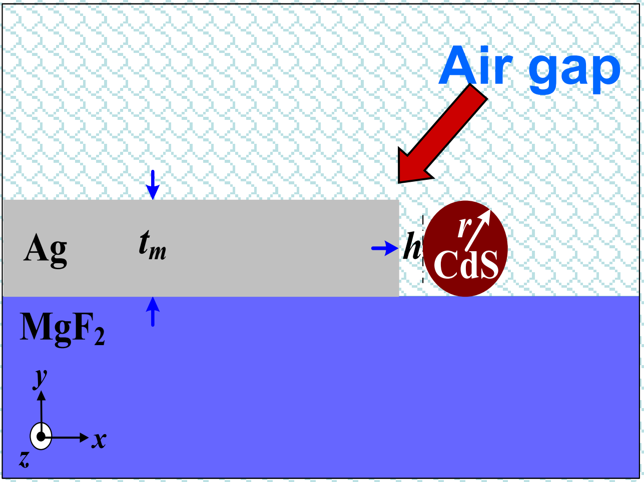


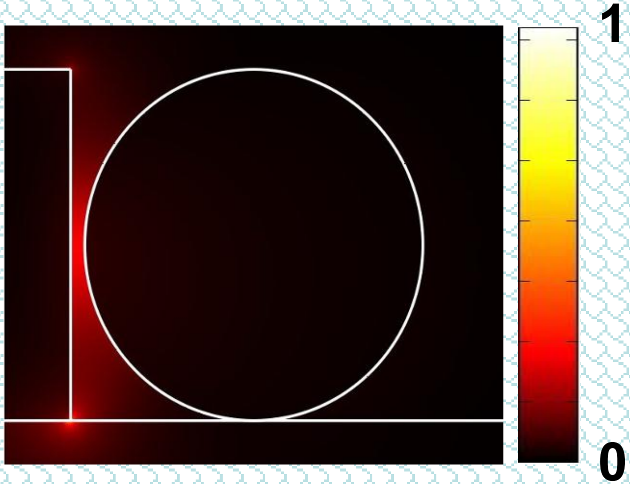
- Low loss propagation
- Subwavelength confinement

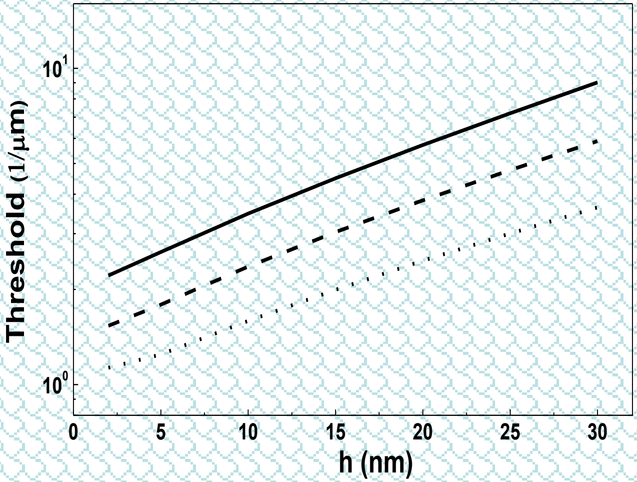


- A lower index buffer (e.g. air) helps to further enhance the field enhancement in that region
- An air gap is impossible to fabricate

Design of coplanar plasmon nanolaser





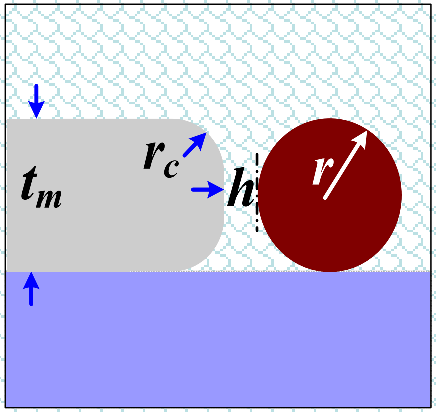


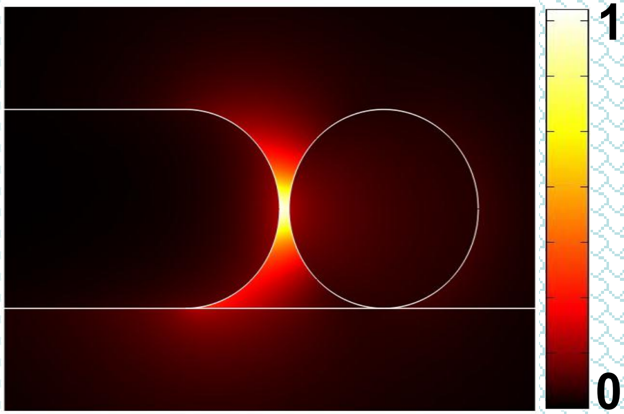
λ=490nm, t_m=2r, *h*:2~30nm

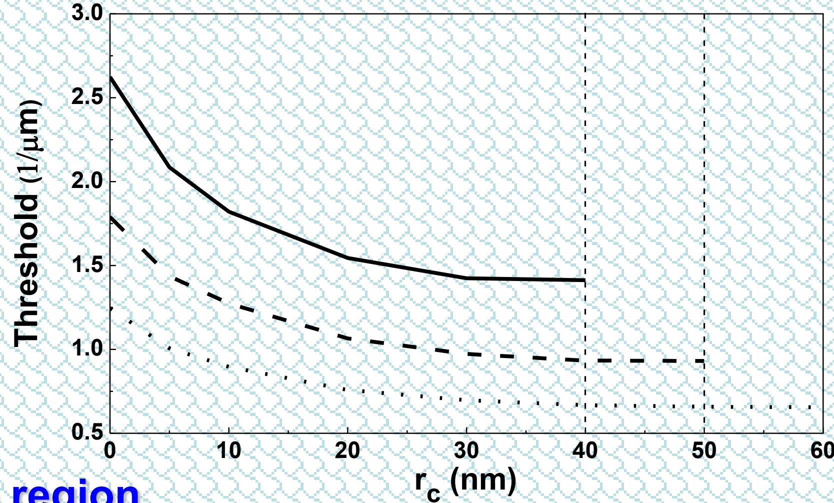
- **Based on an edge-coupled hybrid plasmonic waveguide**
- **Strong field enhancement and low loss caused by the air gap**
- **Easy to fabricate**
- **Edge plasmonic mode**
- **Low pump threshold**

*Y. S. Bian, Z. Zheng, 2010 Frontiers in Optics

Round corner effect for the plasmon laser







- A strong field enhancement occurs in the gap region
- The enhancement is further strengthened in the center of the gap
- The pump threshold shows a monotonical reduction with increased radius
- Compared to the case with sharp corners, the threshold could be lowered by 50% at appropriate corner radius

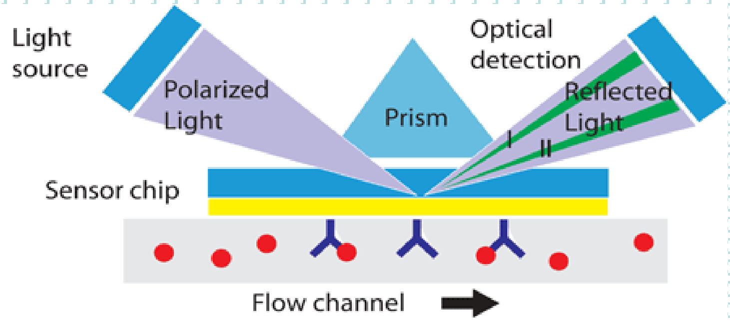
COMSOL settings

- Perpendicular waves of RF module- mode analysis
- Scattering boundary condition

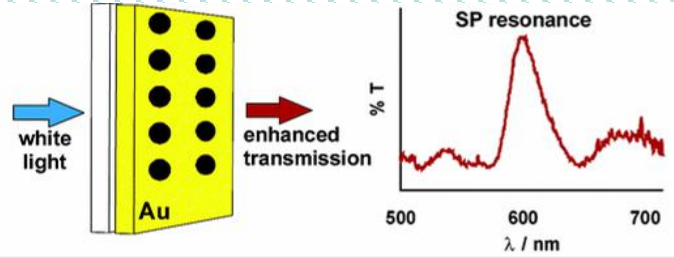
*Y. S. Bian, Z. Zheng, 2010 Frontiers in Optics

Integrated plasmonic sensors w/ nanostructure

Conventional plasmonic sensing device



On-chip SPR sensor based on nanohole array and microfluidic



✓Colinear optical detection
✓Denser integration
✓Smaller footprint
✓Multiplexing biosensing
✓High sensitivity

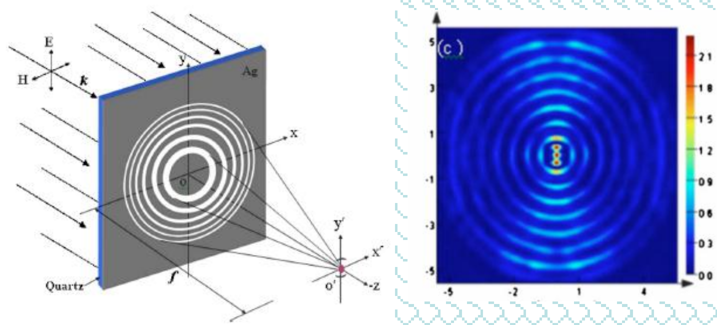
Nature Biotech 26, 417-426 (2008)

Mass transport limitation

Target molecular diffusion rate
<<Binding or reaction rate
→ Target depletion zone

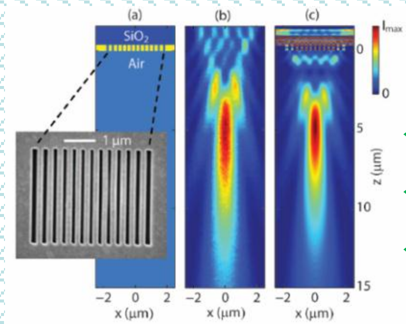
Plasmonic lens

Plasmonic microzone plate lens



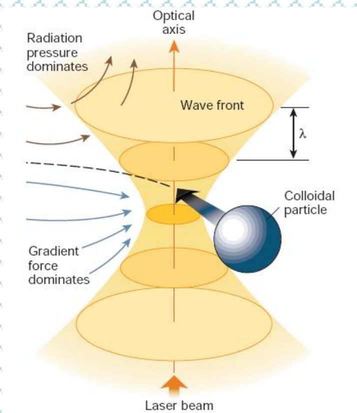
Appl. Phy. Lett. 91, 061124 (2007)

Plasmonic slits array lens



Nano Lett. 9, 235-238 (2009)

- ✓ Subwavelength focusing
- ✓ High field intensity
- ✓ Large field gradient



Focused beam or evanescent field

↓

Optical field gradient

↓

Optical force

↓

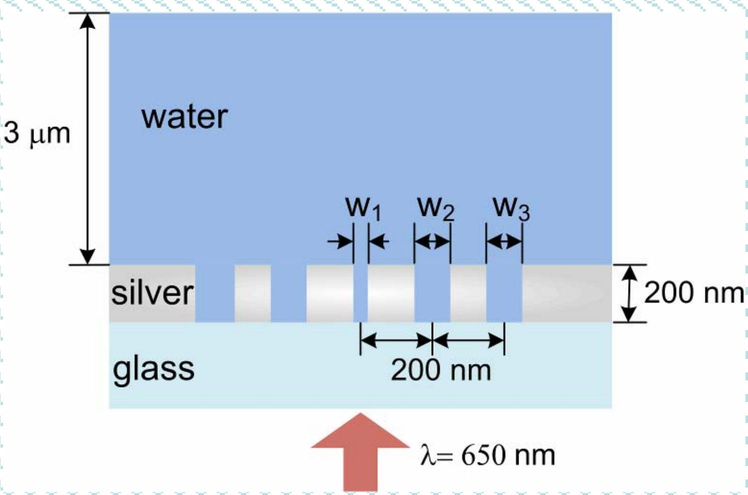
Trapping and manipulating targets

Large optical force

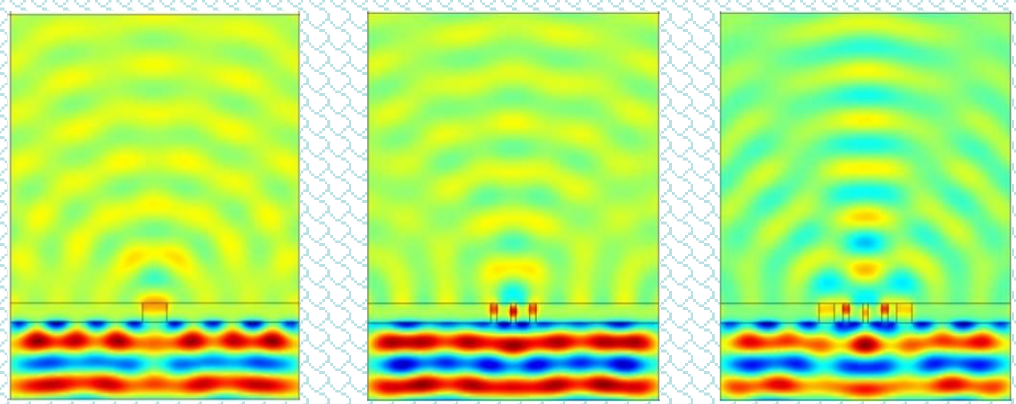
Proposed plasmonic nano-slit array

Focused beam or evanescent field ⇨ Optical field gradient ⇨ Optical force ⇨ Trapping and manipulating targets

Optimized nano-slit structure for trapping in micro-fluidic



H_z of TM mode



Divergent beam →focused beam

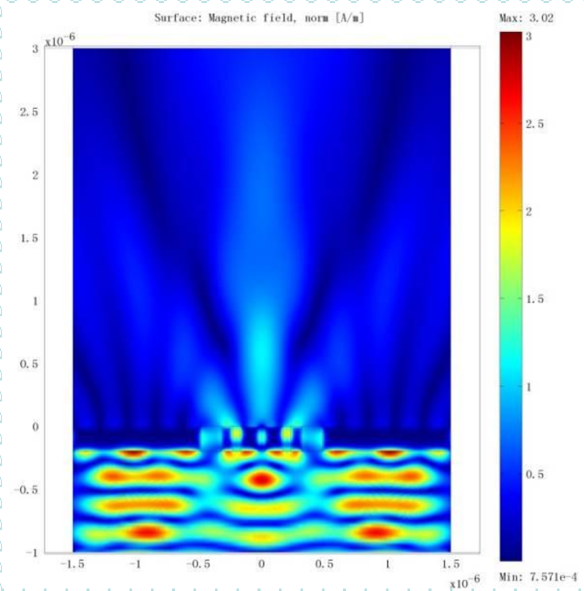
Focal length f ~ 0.6 μm

*X. Zhao, Z. Zheng, 2010 Frontiers in Optics

Optical gradient force of nano-slit lens

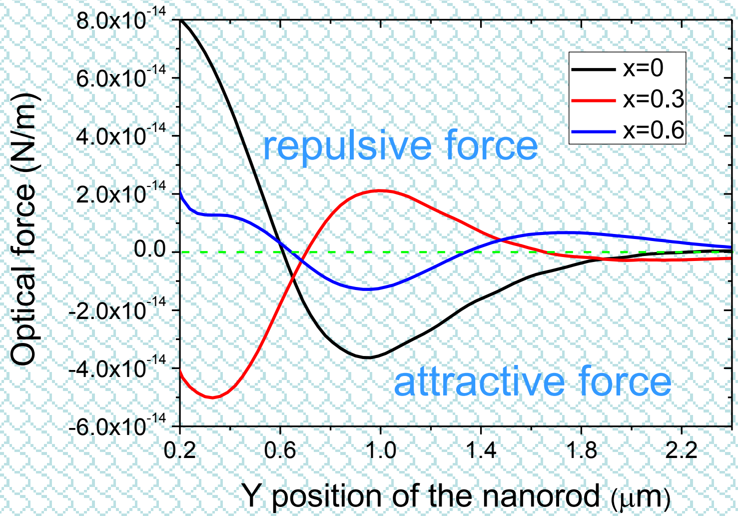
Time average optical force $\langle F_i \rangle_t = \int_A \sum_j \langle T_{ij} \rangle_t n_j dS$

Maxwell stress tensor
$$\langle T_{ij} \rangle_t = \varepsilon_h \varepsilon_0 \langle E_i(r,t) E_j(r,t) \rangle_t + \mu_h \mu_0 \langle H_i(r,t) H_j(r,t) \rangle_t - \frac{1}{2}\delta_{ij}\left[\varepsilon_h \varepsilon_0 \sum_{i'} \langle E_{i'}(r,t) E_{i'}(r,t) \rangle_t + \mu_h \mu_0 \sum_{i'} \langle H_{i'}(r,t) H_{i'}(r,t) \rangle_t \right]$$



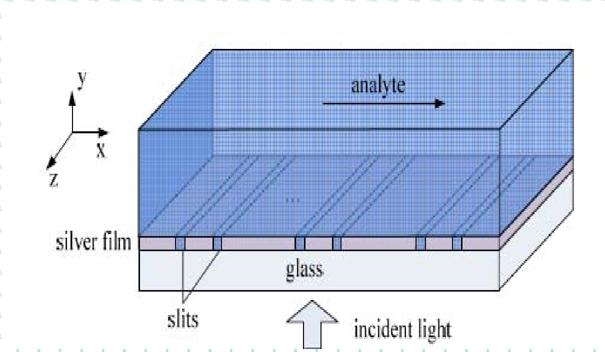
Input power density=1.28mW/mm^2

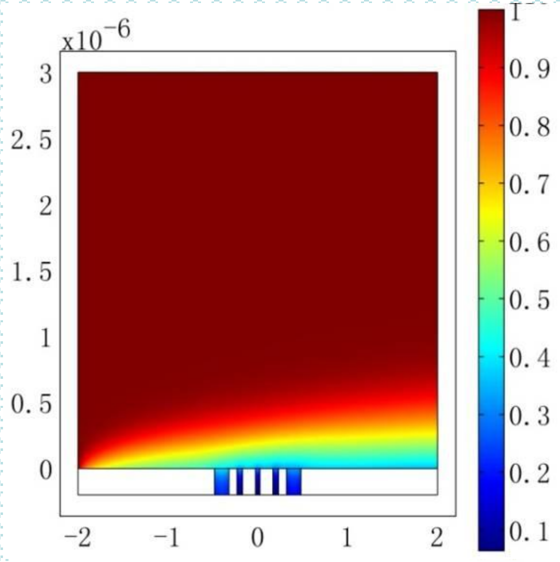
Sensing object: nanorods with a diameter of 50 nm

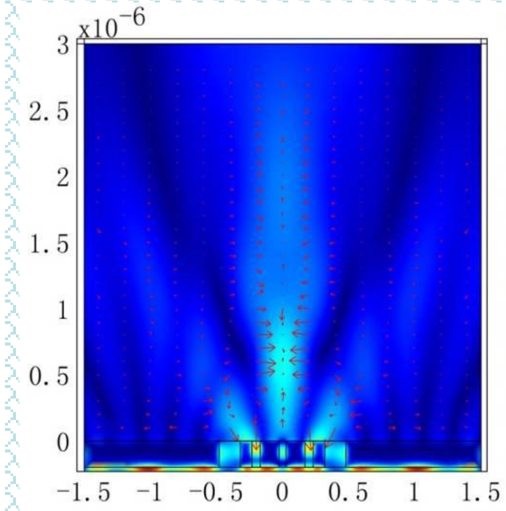


When X=0, Y> f attractive force Y<f repulsive force

Impact and effect of slit in micro-fluidic







- Optical force could increase target concentration near focal point
- More target molecular diffused to the sensing surface

→ Alleviate mass transport limit

Conclusions

- Design and optimization of the nanophotonic devices are critical in realizing advanced photonic integrations in the future.
- Comsol can be used for simulating various types of nanophotonic devices involving different materials and dimensions.
- Increased functionalities of the nanophotonic devices also demand simulators capable of handling complex multiphysics simulations.

Thank you!