

# 表面等离激元的共振模式和波前调控研究

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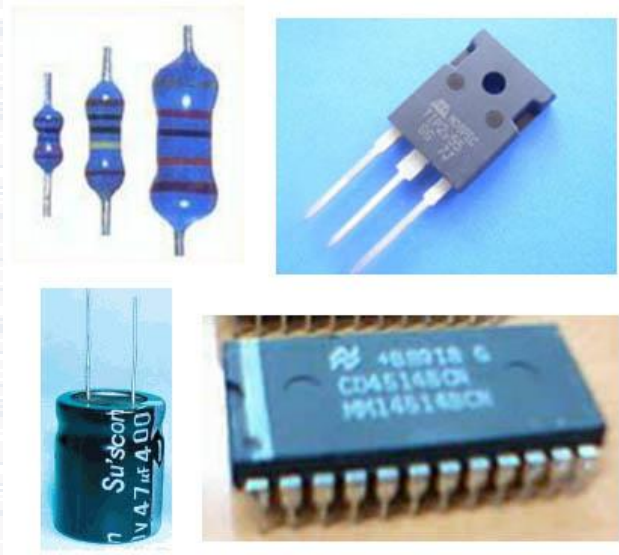
# 内容

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- 一. 表面等离激元基础
- 二. 表面等离激元纳米腔模式
- 三. 光学天线中的场增强和模式
- 四. 表面等离激元的波前调控
- 五. 总结

# 一、表面等离激元基础

## 1. 电子学器件和光学器件的比较

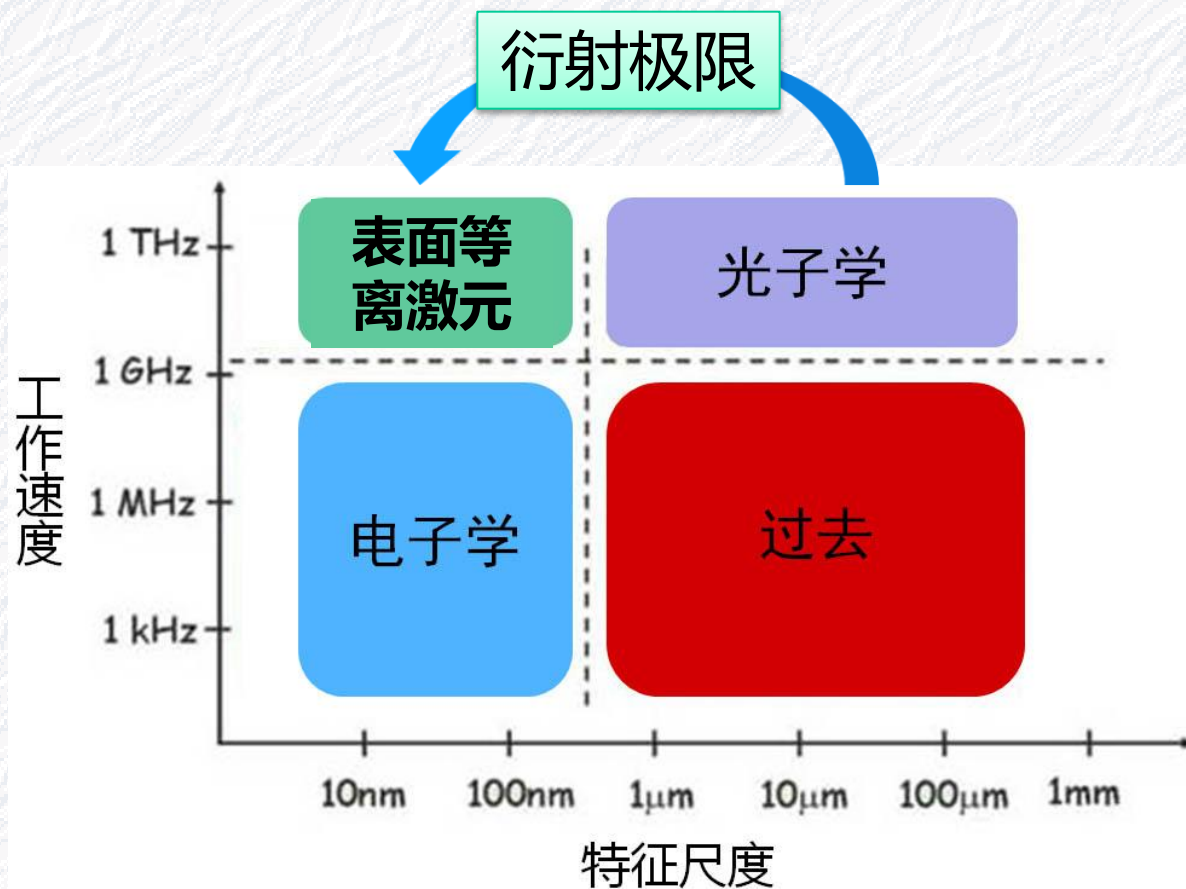


电子学器件



光学器件

## □ 器件的速度-尺度关系



③ 表面等离子激元和光子的相互耦合

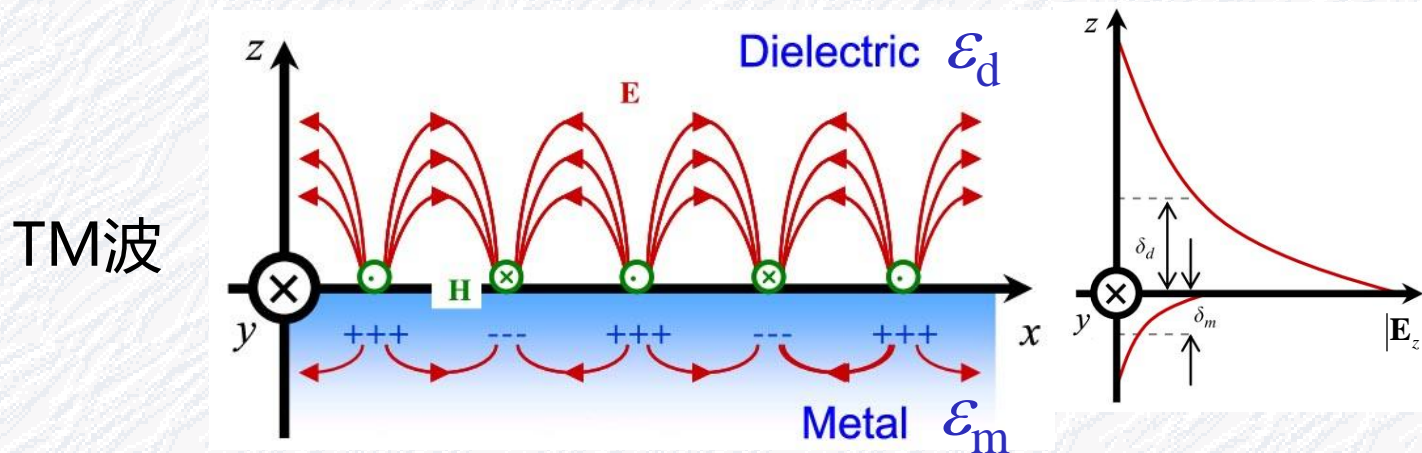
➔ 纳米尺度光调控

➔ 新原理、新方法

## 2. 什么是表面等离子激元

表面等离子激元【Surface plasmon polariton (SPP) or surface plasmon (SP)】：

金属-介质界面上的电磁场模式： $\epsilon_d \epsilon_m' < 0$      $\epsilon_d + \epsilon_m' < 0$

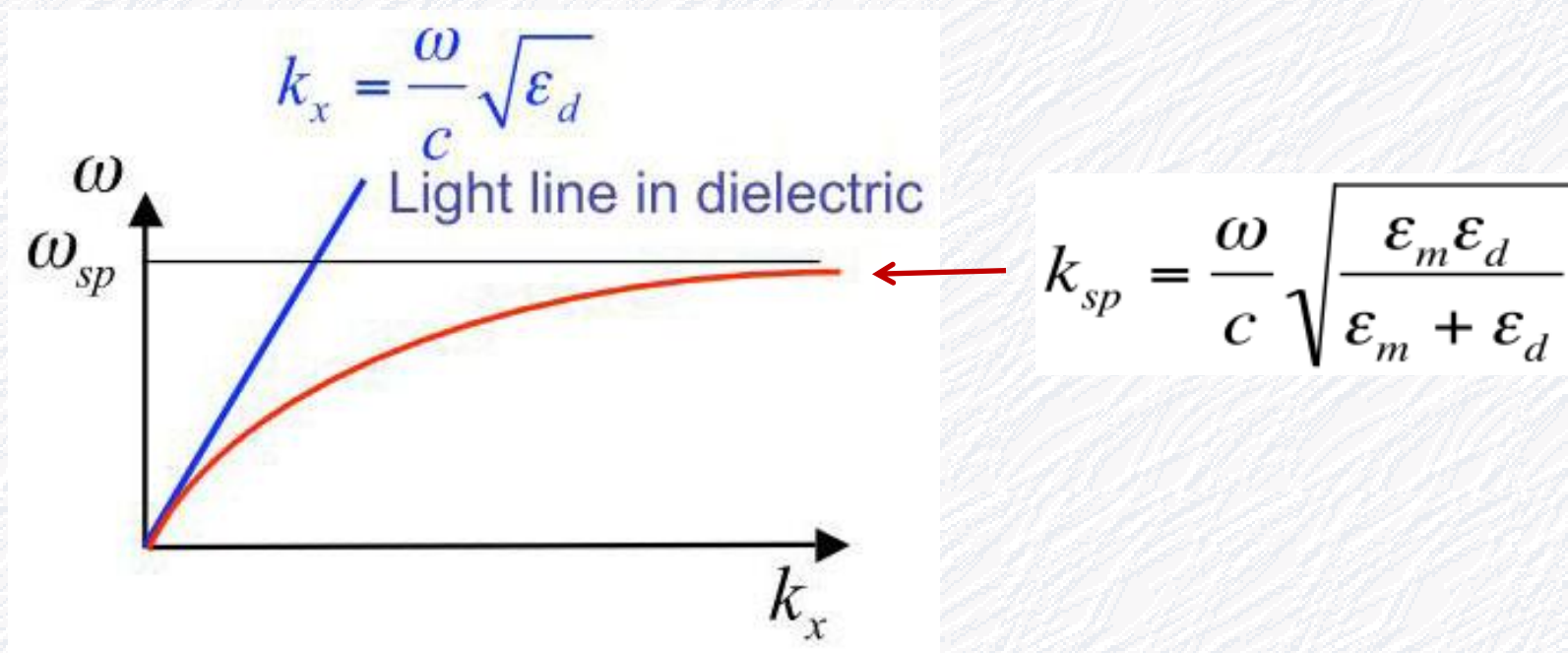


电场的面内分量（平行分量）： $\mathbf{E}_{\parallel} = \mathbf{E}_x + \mathbf{E}_y$

电场的面外分量（垂直分量）： $\mathbf{E}_{\perp} = \mathbf{E}_z$

介质中： $|\mathbf{E}_{\perp}| > |\mathbf{E}_{\parallel}|$ ；金属中： $|\mathbf{E}_{\parallel}| > |\mathbf{E}_{\perp}|$

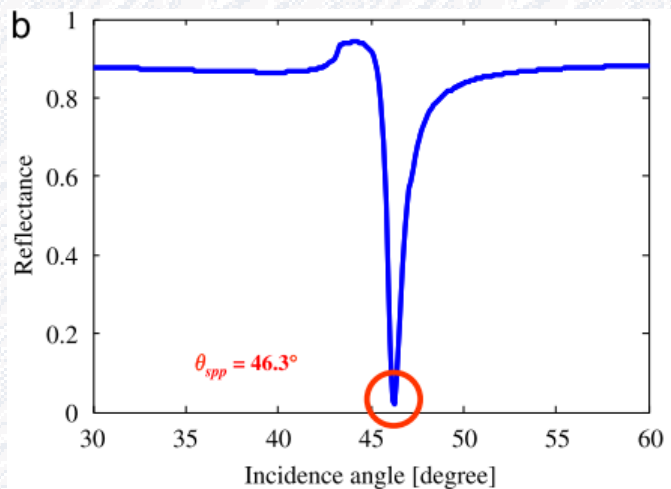
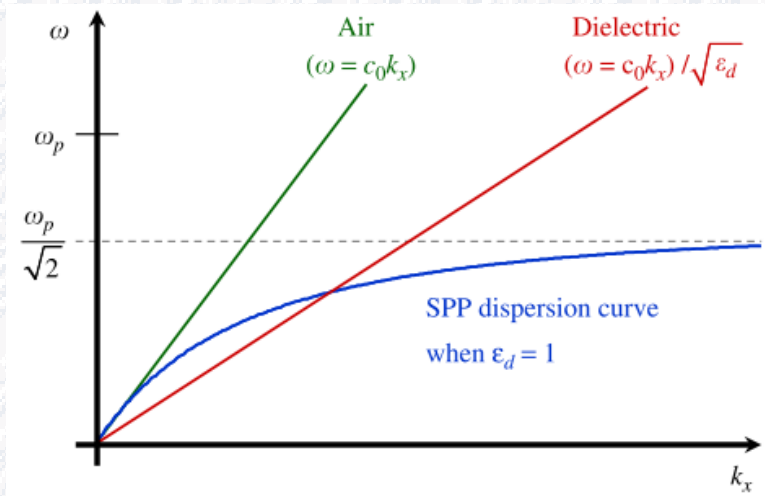
# SPP的色散关系



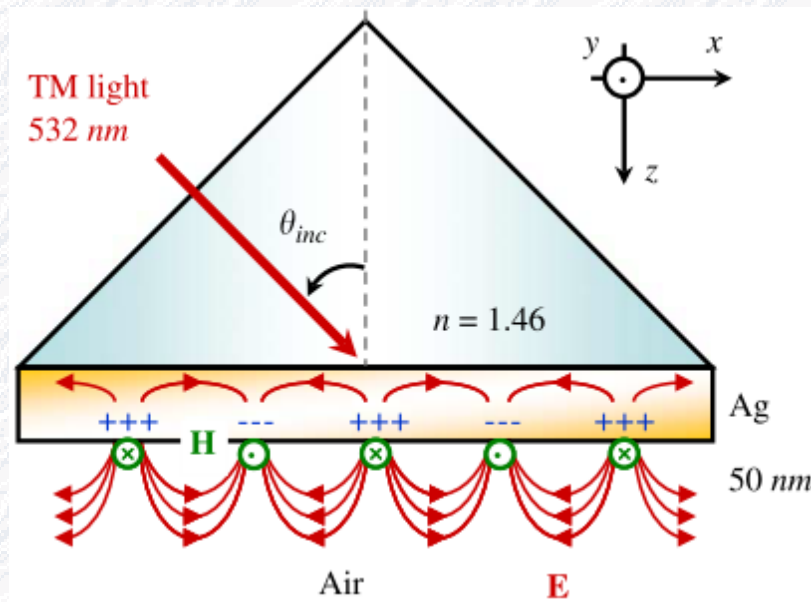
SPP和光耦合的关键：波矢匹配（动量守恒）

# 3. SPP的激发方法

最早的激发方法：电子束激发

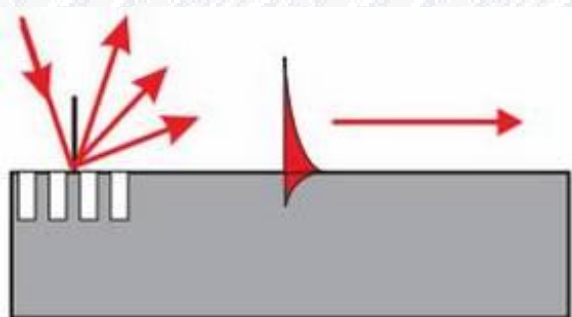


常用的SPP光激发方法

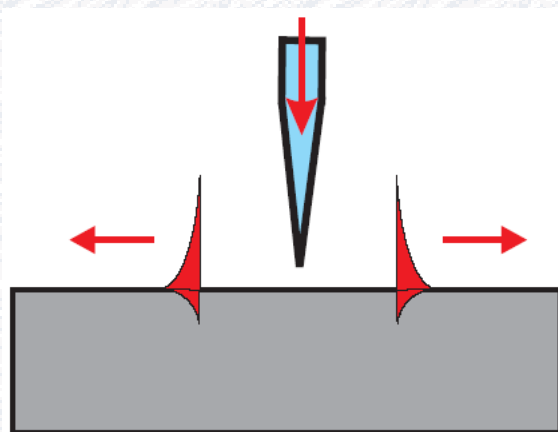


Kretschmann-Raether结构

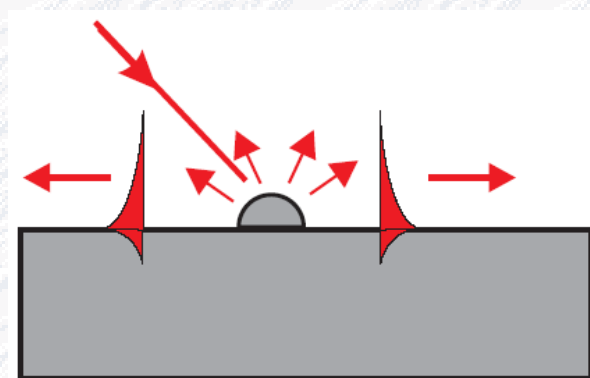




光栅激发



近场探针激发



粗糙表面的激发



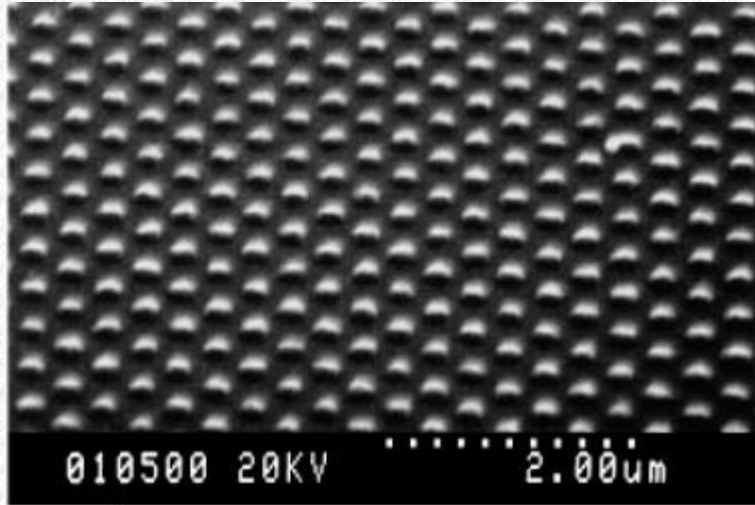
双缝SPP马赫-曾德尔干涉仪

Xiaofei Wu et al., Opt. Lett. 34, 392 (2009).

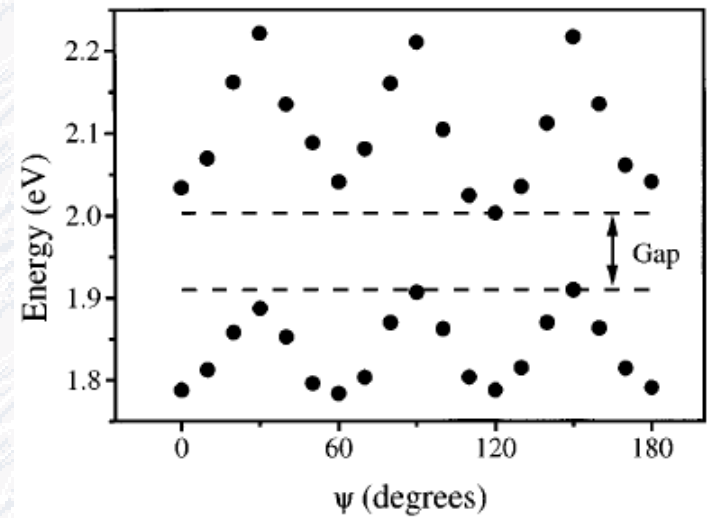
## 4. SPP的特点

- 二维平面上的波
- 与光之间可以互相转换
- 色散关系可以通过结构调控
- 局域场增强
- 光学波段的磁相应
- 金属波导

## □ 二维平面上的波



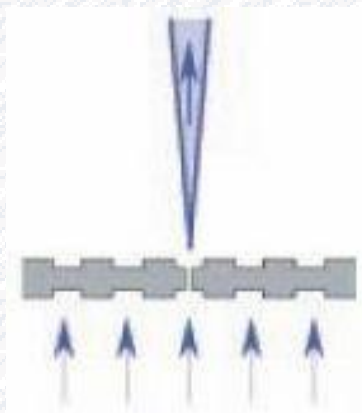
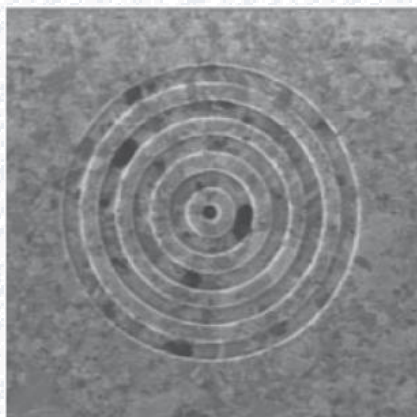
表面模式的完全光子带  
隙结构



能带结构

Kitson et al., Phys. Rev. Lett. 77, 2670 (1996)

## □ SPP与光之间互相转换

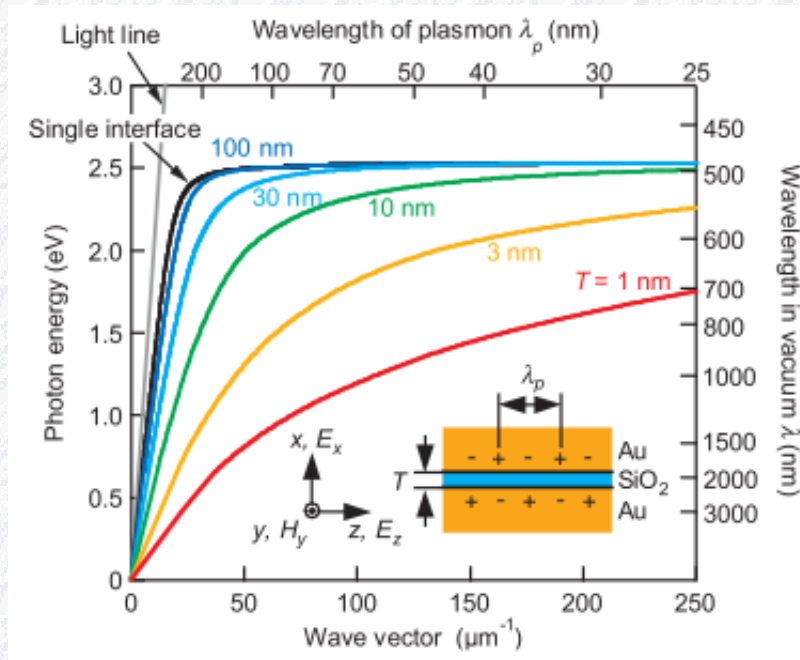


意义：通过SPP与光  
之间互相转换获得操  
控光的新方法

牛眼型结构超透射

Ebbesen et al., Science 297, 820 (2002)

## 色散关系可以通过结构调控



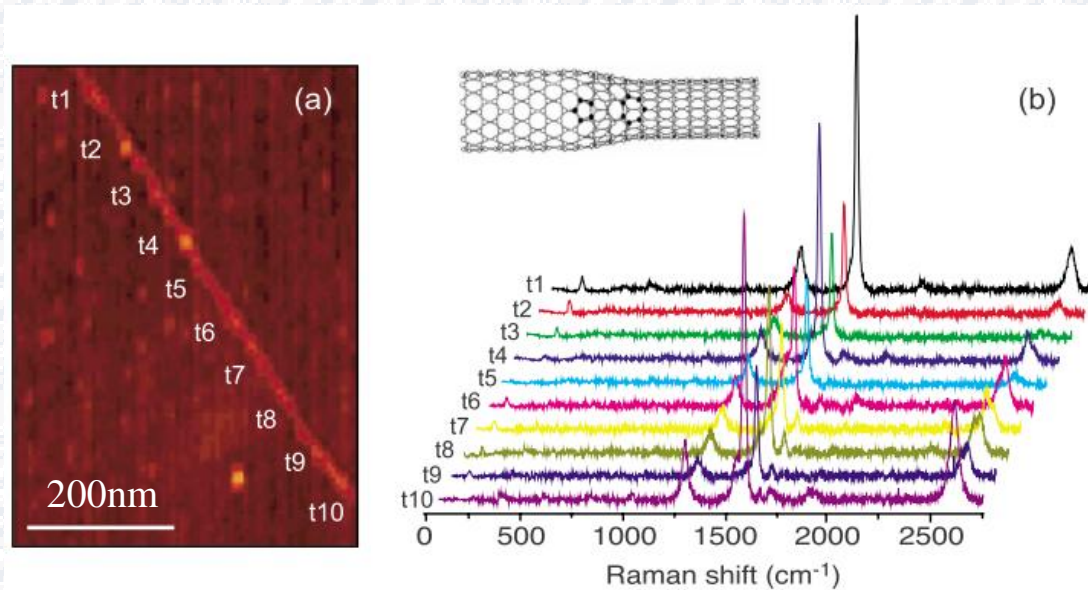
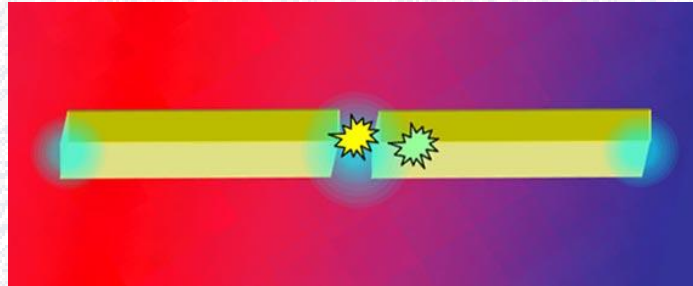
沿z方向传播的TM模式  
MIM波导色散关系

实验结果:  
 $T = 3\text{nm}$ ,  $\lambda_0 = 651\text{nm}$   
获得  $\lambda_{\text{SPP}} = 51\text{nm}$

Miyazaki et al., Phys. Rev. Lett.  
96, 097401 (2006)

利用结构调控色散关系可以获得超短波长

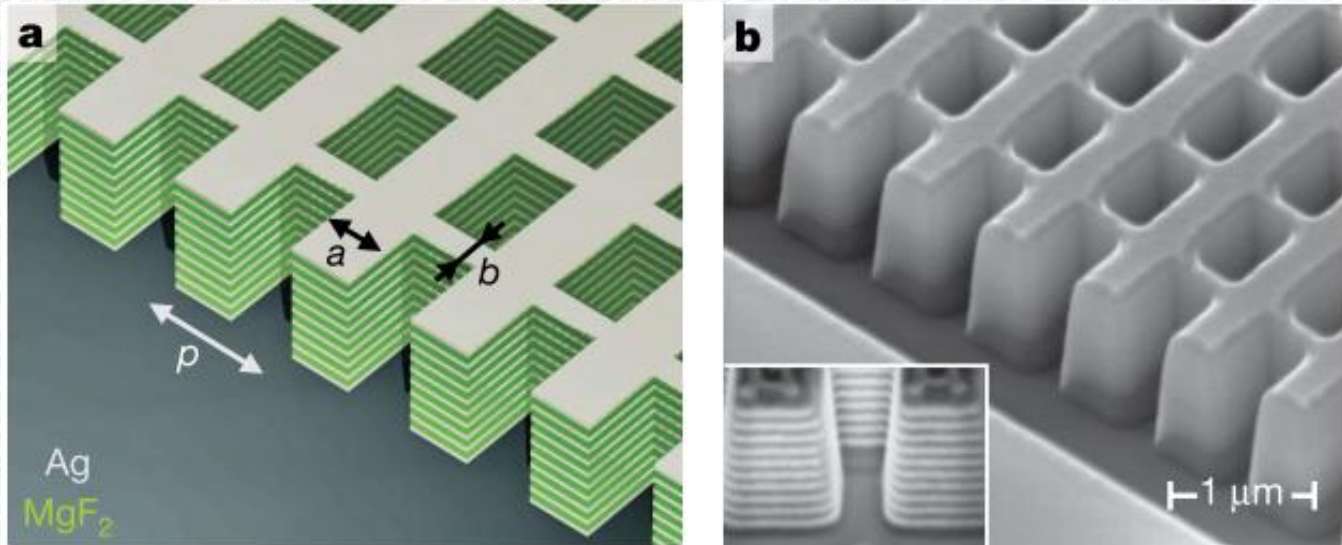
## □ 局域场增强



Tip-enhanced Raman spectroscopy of a single-walled carbon nanotube

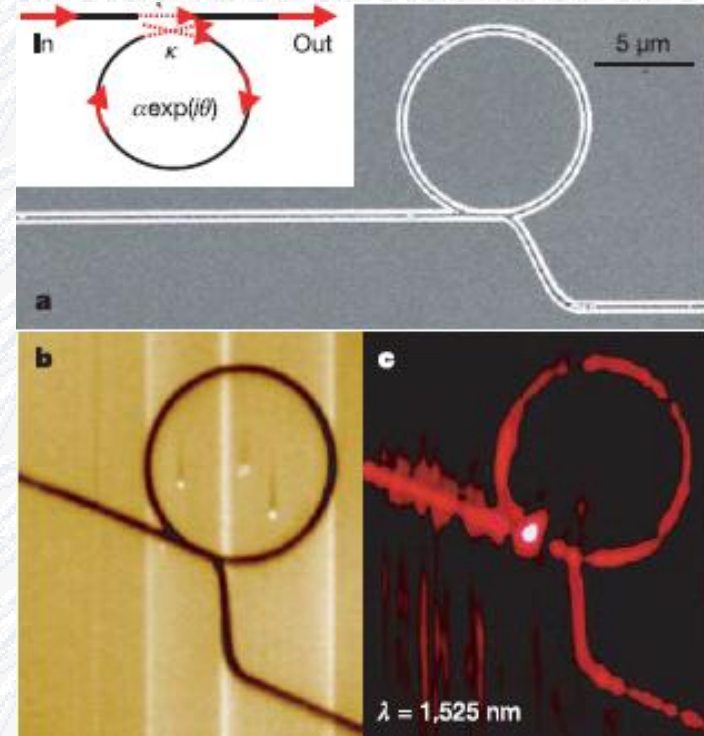
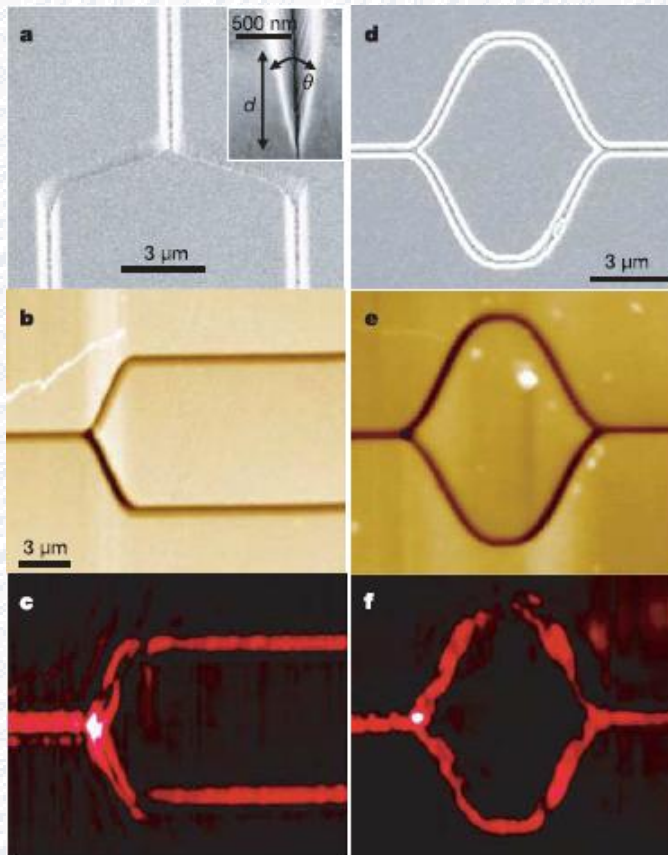
Anderson et al., Nano Lett. 7, 577–582 (2007)

## □ 光学波段的磁响应



Valentine et al., Nature 455, 376-379 (2008)

# □ 金属波导 —— 光、电信号共同的载体



Nature 440, 508 (2006)

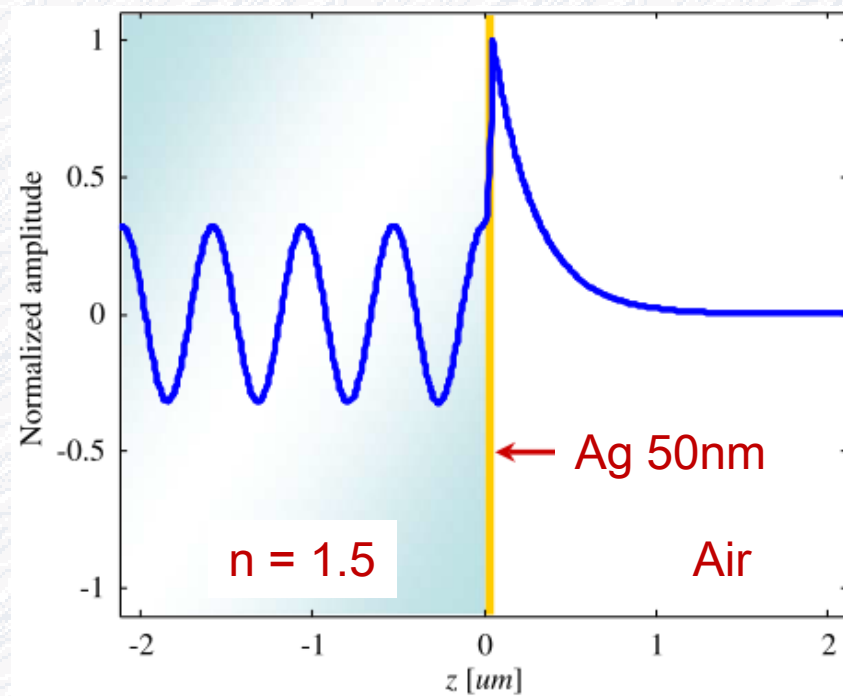
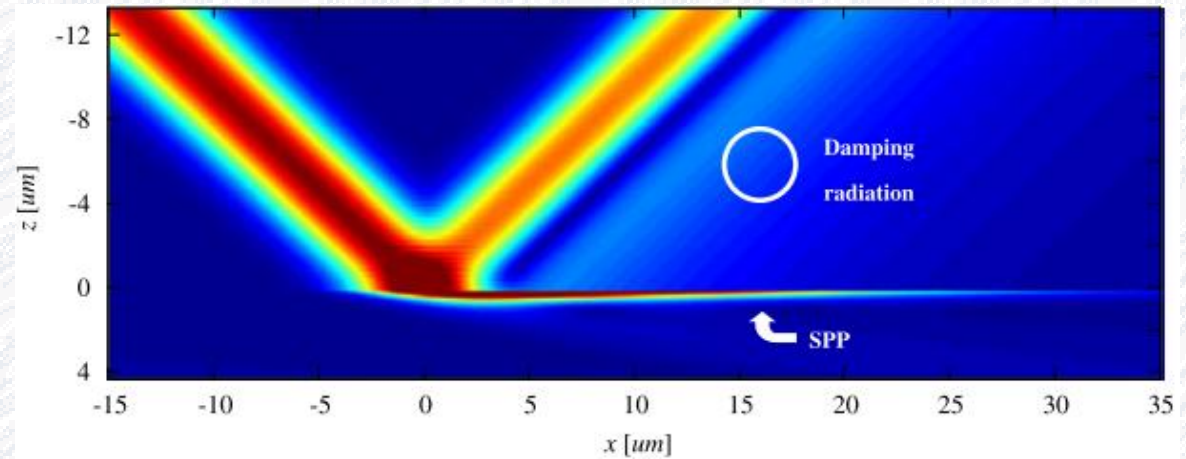
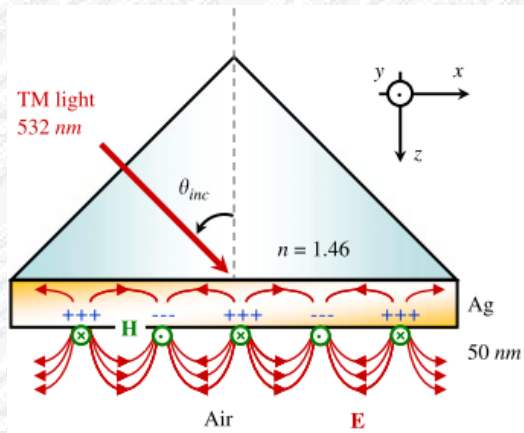


## 5、表面等离激元的探测方法

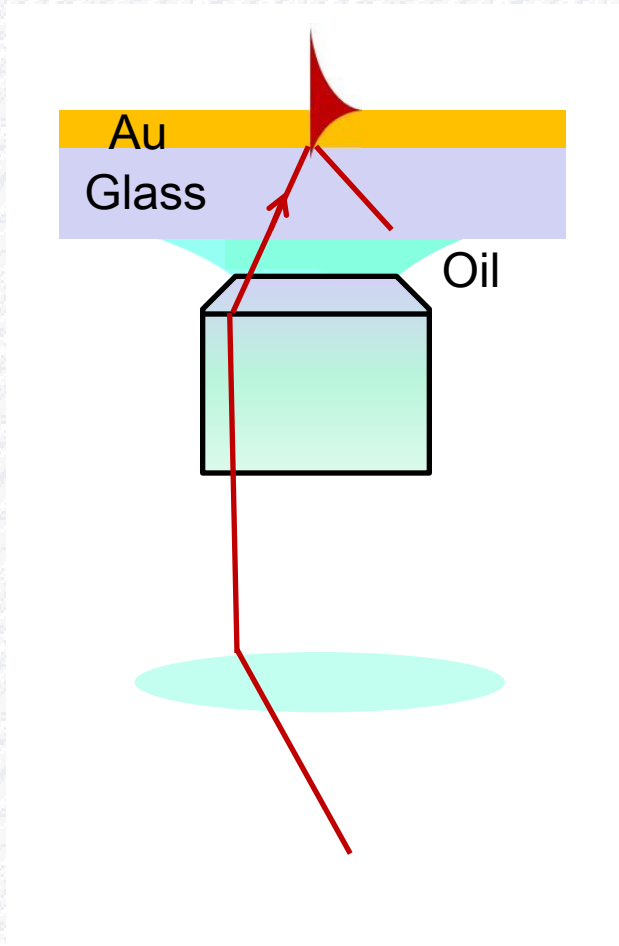
- (1) 泄露辐射显微镜
- (2) 扫描近场光学显微镜
- (3) 荧光成像
- (4) 阴极荧光显微镜

原理：将SPP转化为自由空间传播的光

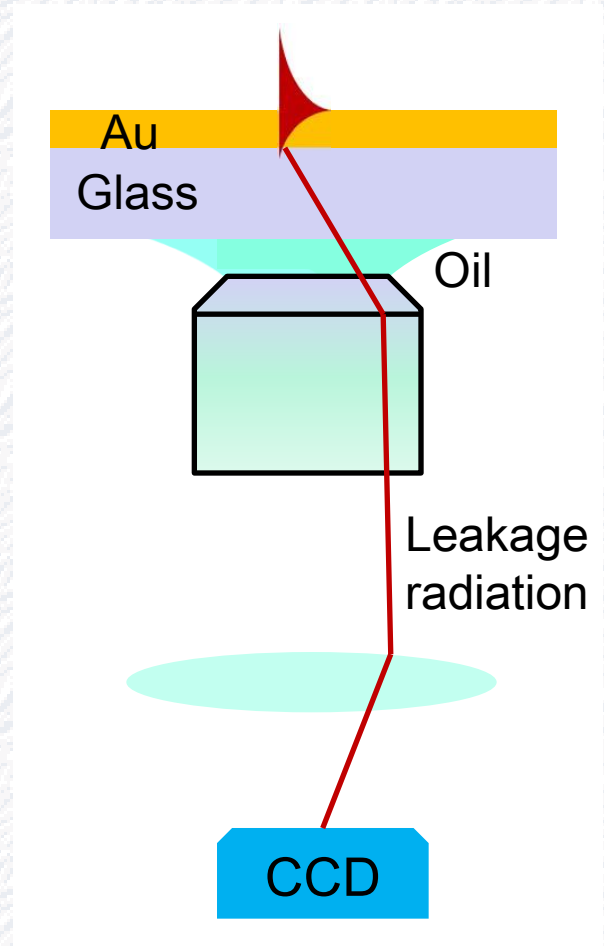
# (1) 泄露辐射显微镜



SPP的泄露模式

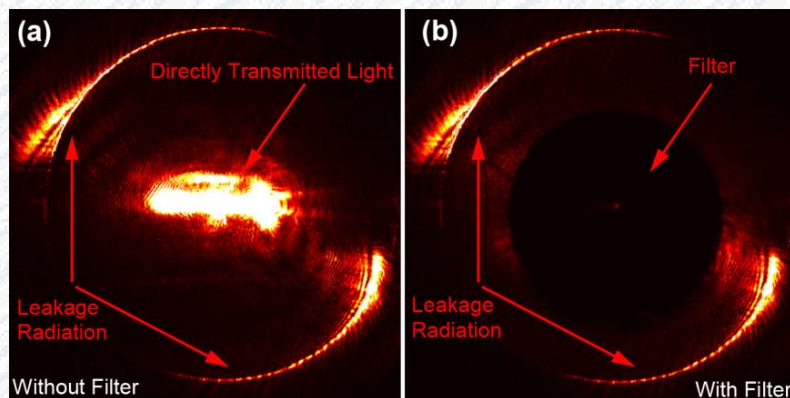
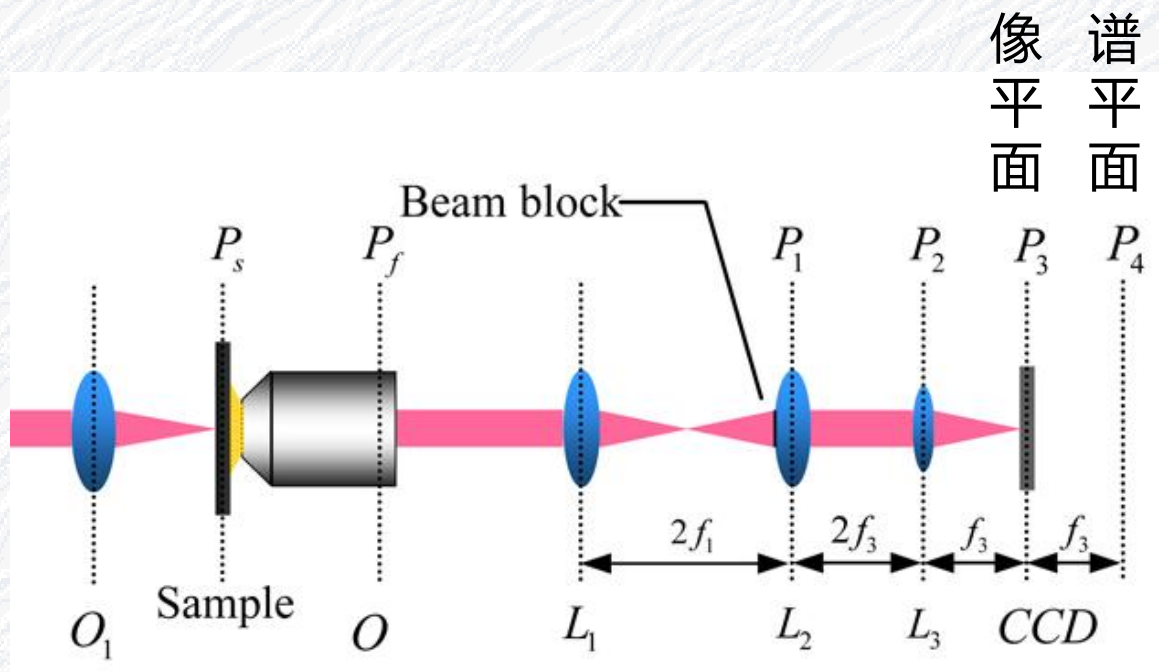


油浸物镜激发SPP

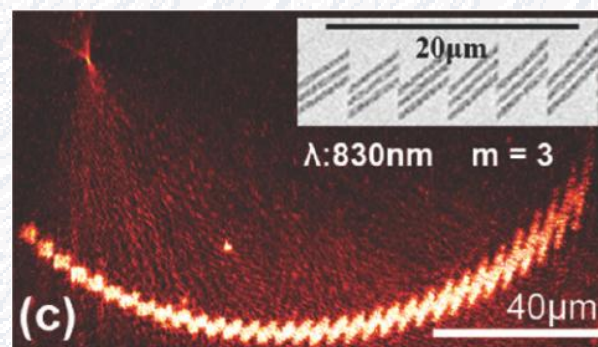


泄露辐射显微镜

# 泄露辐射显微镜实验装置



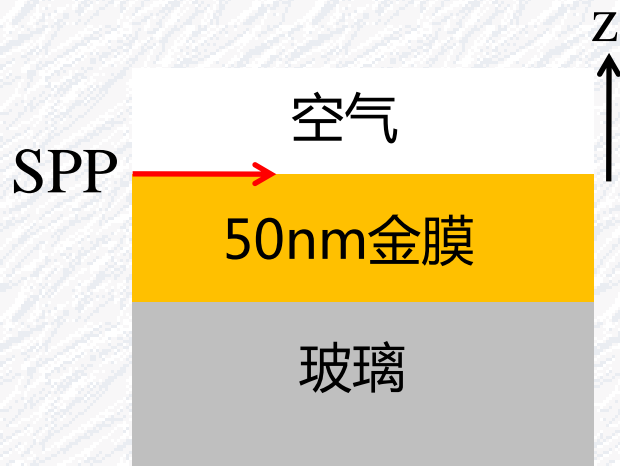
滤波前和滤波后的谱



SPP像

## □ 泄漏辐射显微镜信号与SPP分量的关系

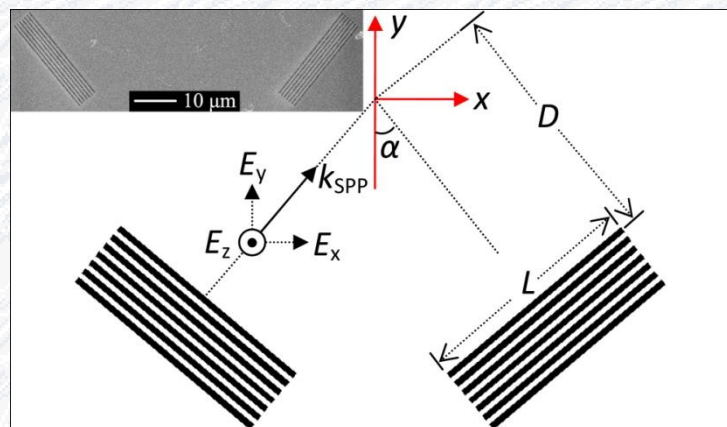
通常人们笼统地认为：泄漏辐射显微镜信号正比于SPP强度。



面内分量： $\mathbf{E}_{\parallel} = \mathbf{E}_x + \mathbf{E}_y$

面外分量： $\mathbf{E}_{\perp} = \mathbf{E}_z$

$|\mathbf{E}_{\perp}|^2$ 和 $|\mathbf{E}_{\parallel}|^2$ 的分布可能不一样！



实验样品示意图

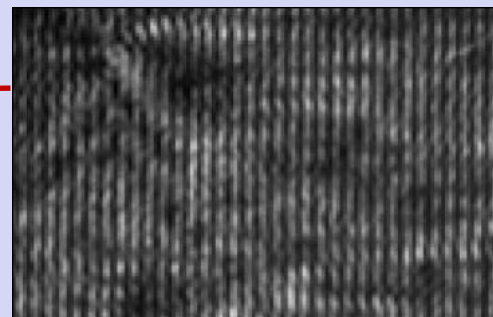
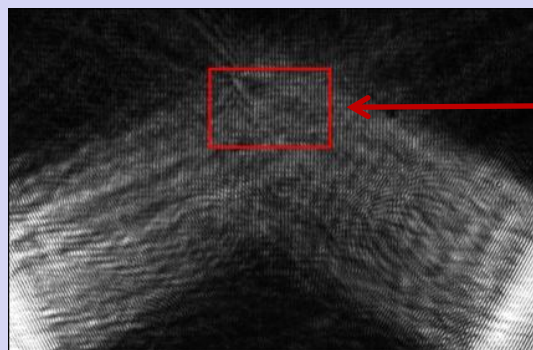
入射光：x偏振平面波

两个光栅激发的SPP各分量关系：

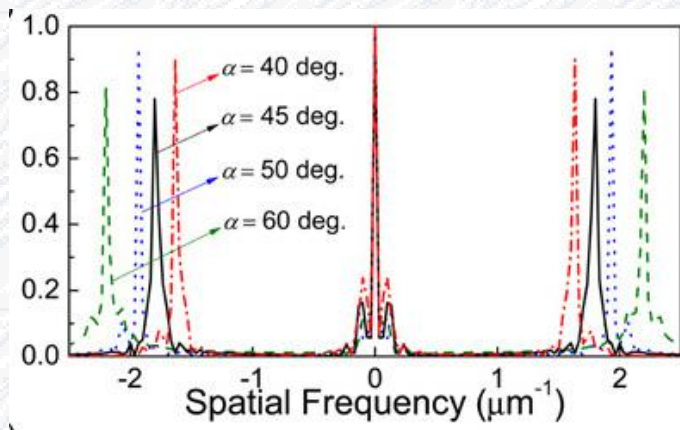
$E_x$ 同相； $E_y$ 和 $E_z$ 反相

目的： $|E_x + E_y|^2$ 和 $|E_z|^2$ 分布不同 $\rightarrow$

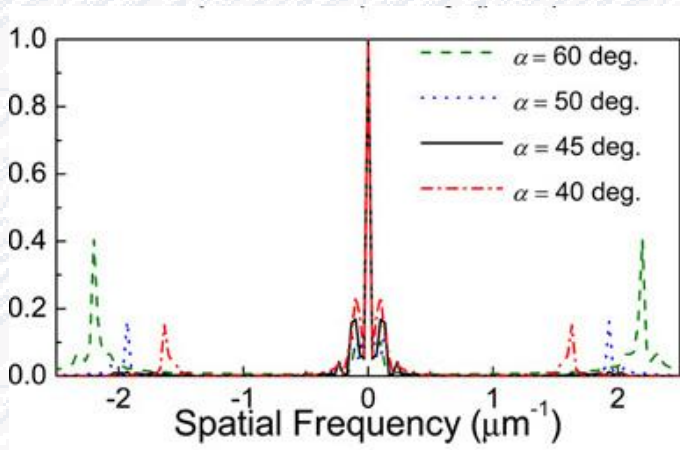
调制度不同



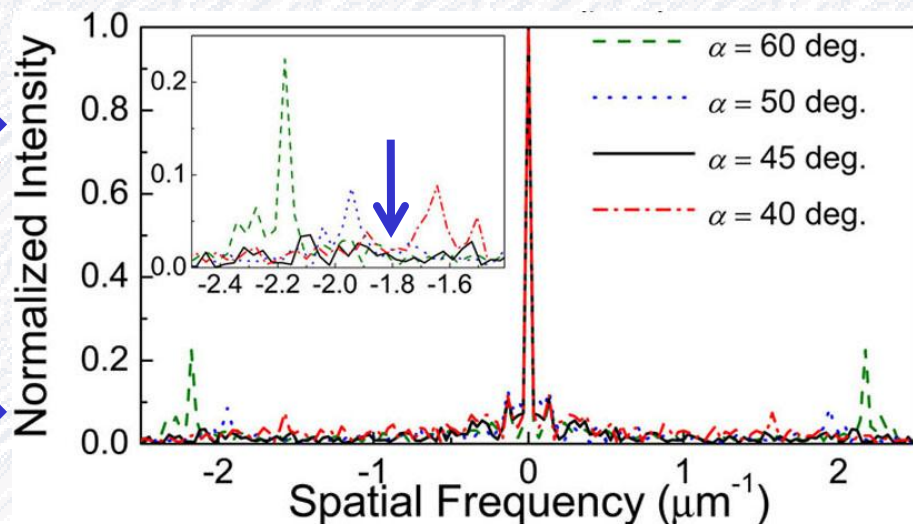
$\alpha = 60^\circ$  实验结果



$|E_{\perp}|^2$  傅里叶变换

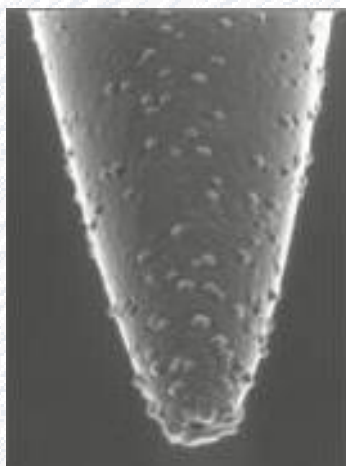
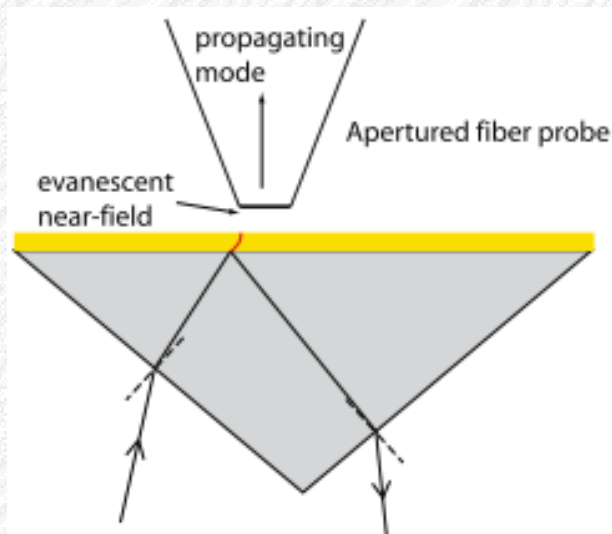
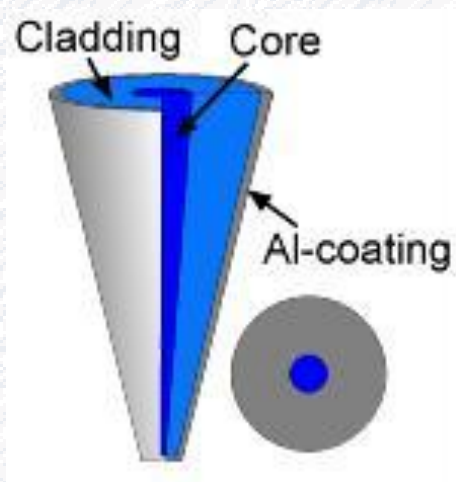


$|E_{\parallel}|^2$  傅里叶变换

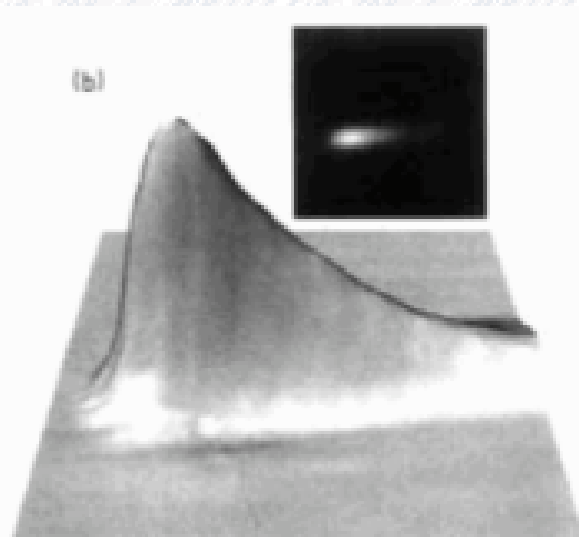


我们的结论：泄漏辐射显微镜信号  
正比于SPP电场平行分量的强度

## (2) 扫描近场光学显微镜



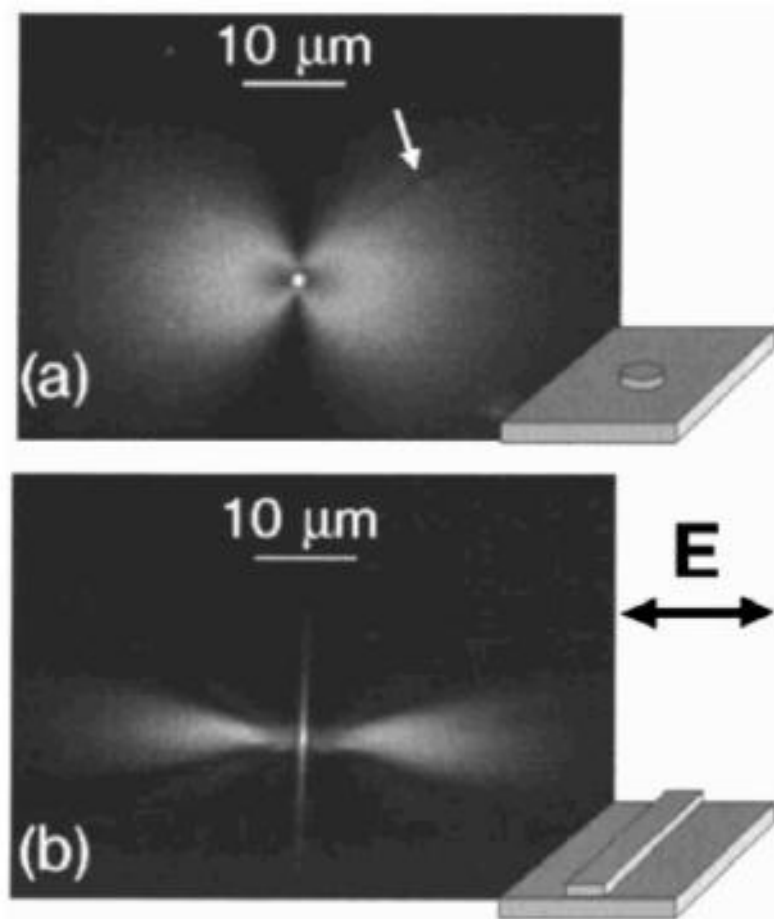
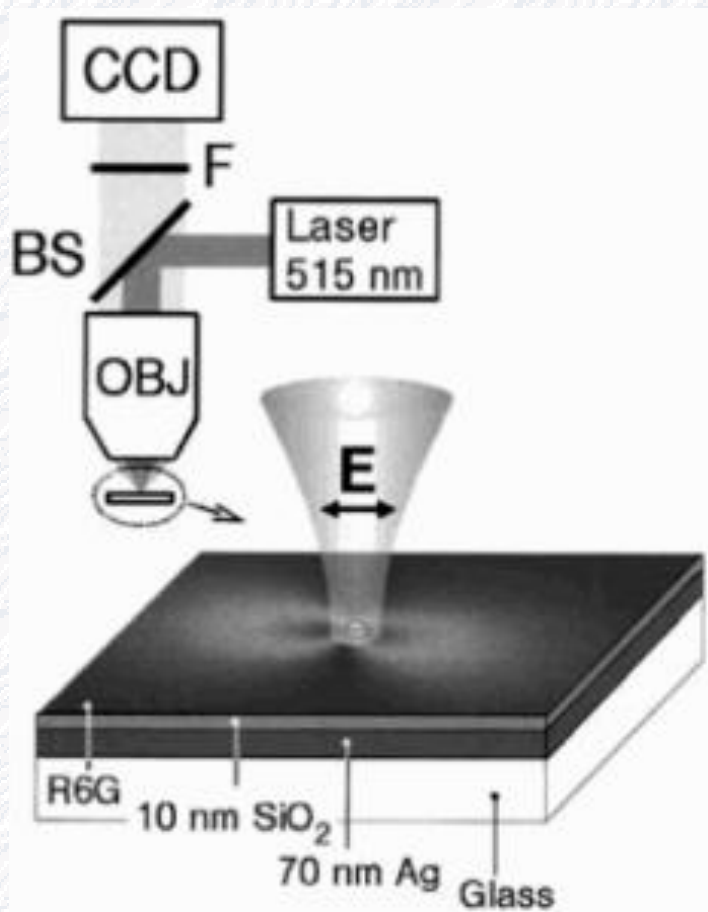
有孔探针



$\lambda = 633 \text{ nm}$ ,  
53 nm thick  
silver film  
(scan range  
 $40 \times 40 \mu\text{m}$ ).

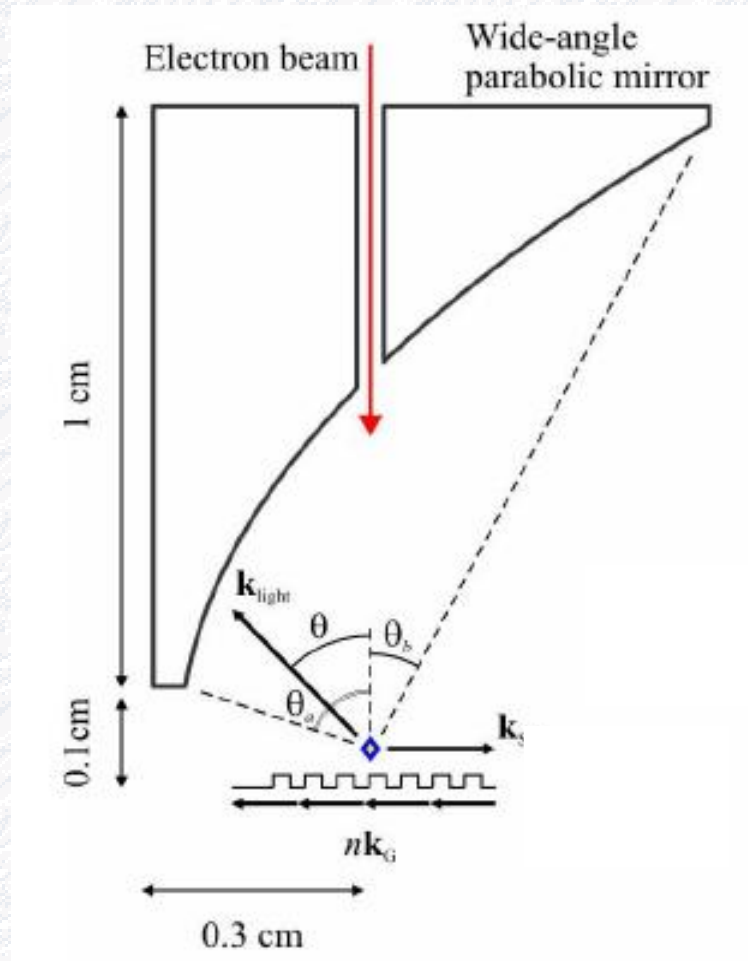


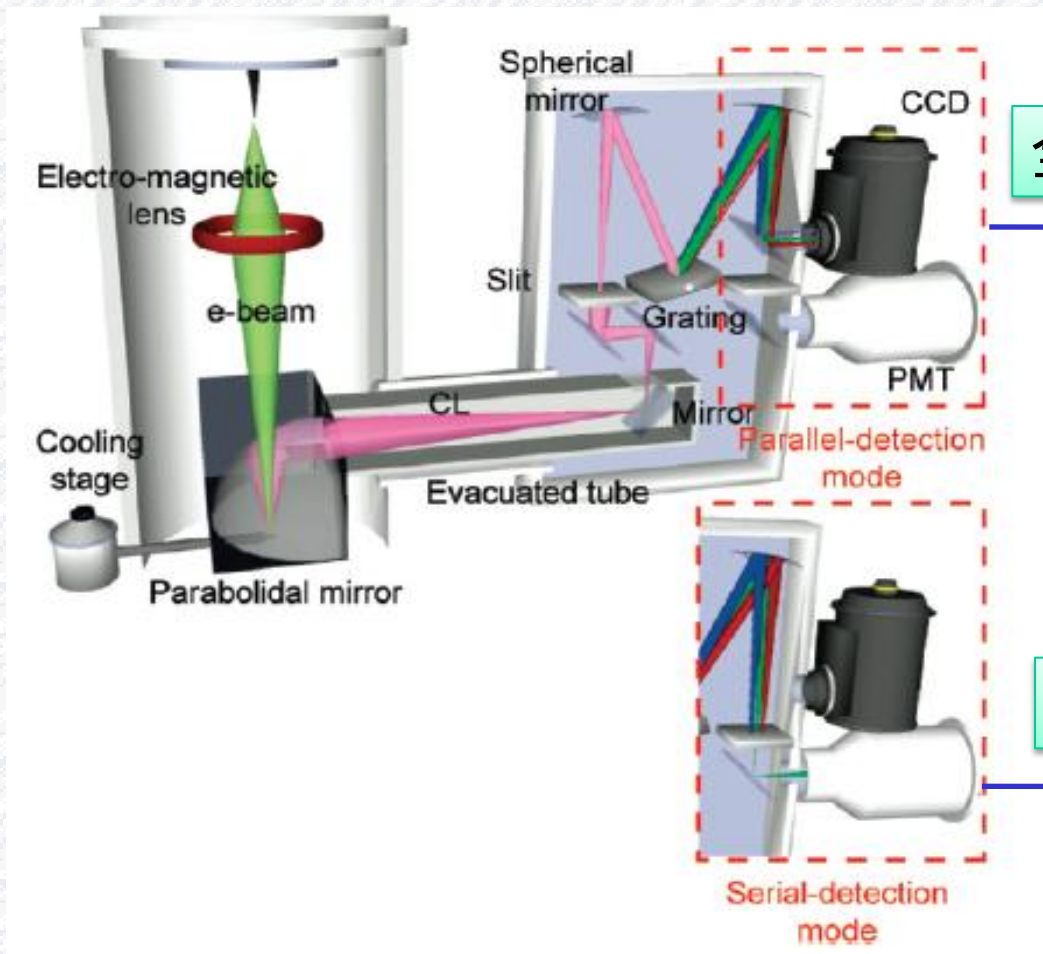
### (3) 荧光成像



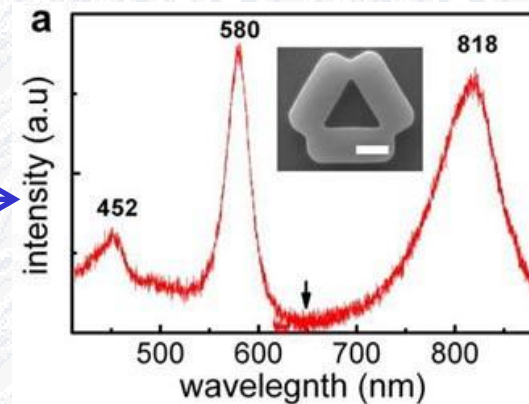
实验装置

## (4) 阴极荧光显微镜



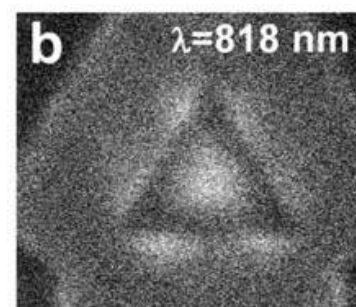


全谱



CL谱

单色

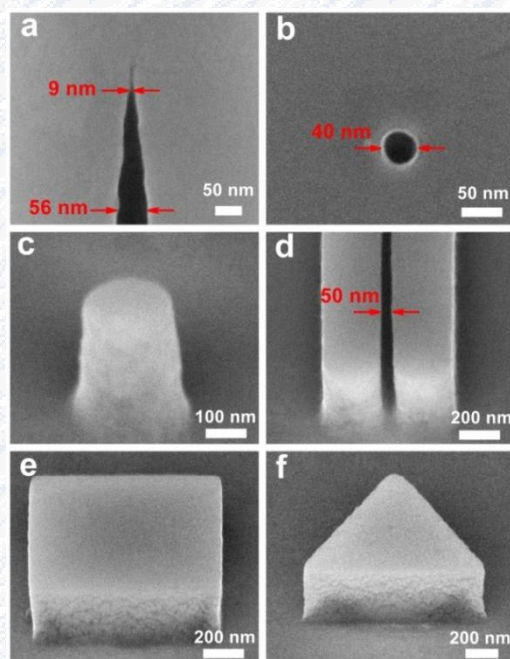
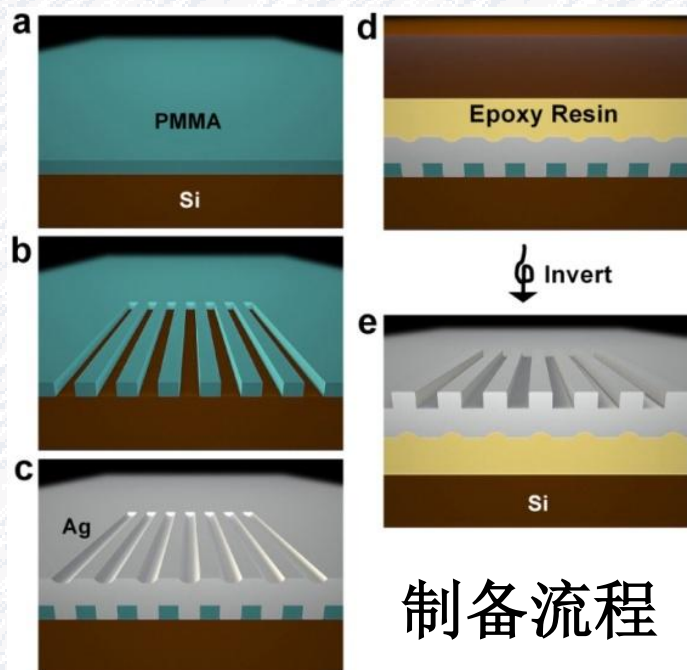


模式

Cathodoluminescence (CL)  
谱实验示意图

## 6、金属纳米结构的制备 —— PMMA模板法

方法：将Si和PMMA的表面复制到金属结构上



表面粗糙度

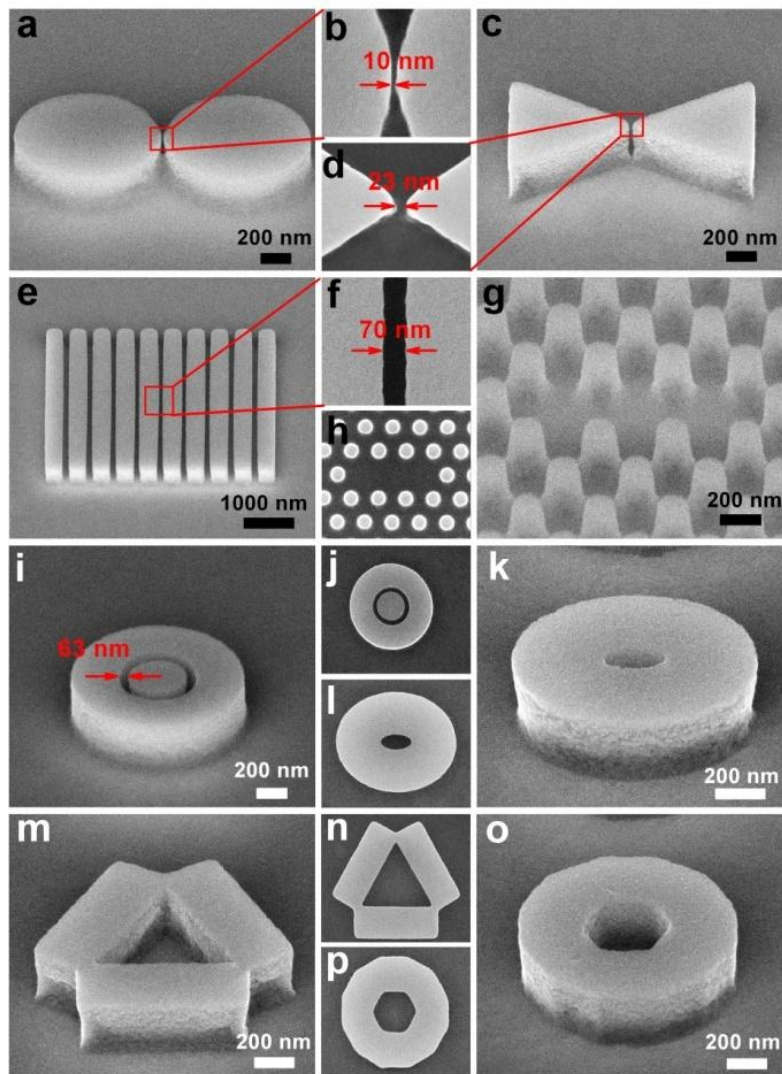
0.55~  
0.88nm

最小特征尺度

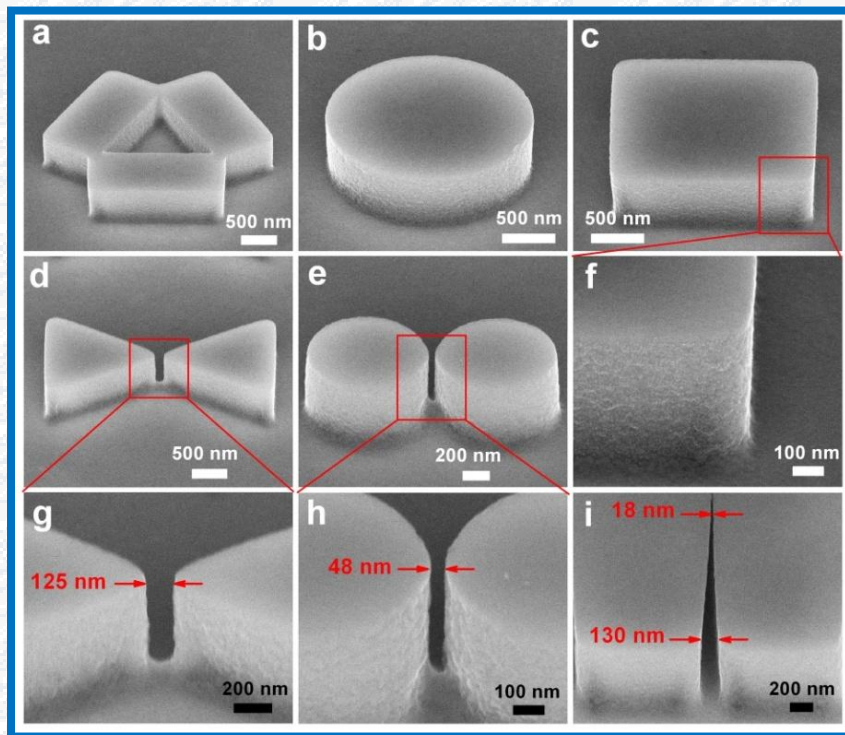
9nm

深宽比

>20



$h = 300 \text{ nm}$



$h = 700 \text{ nm}$

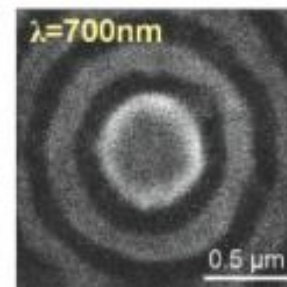
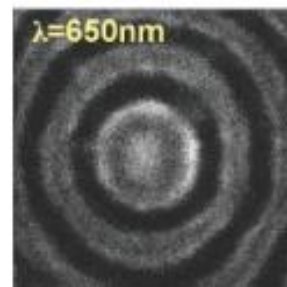
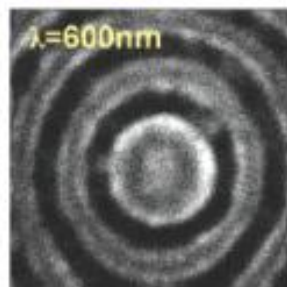
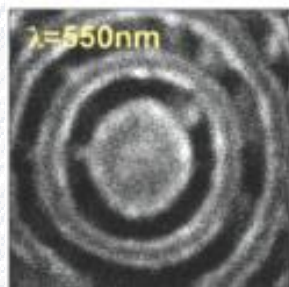
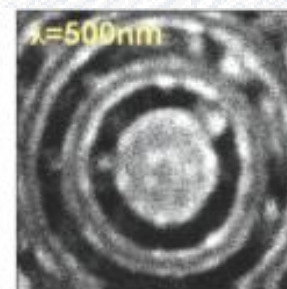
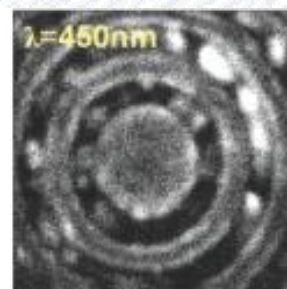
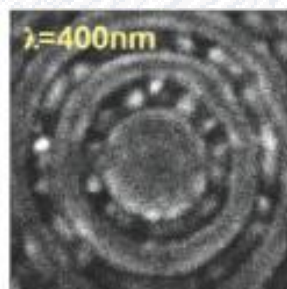
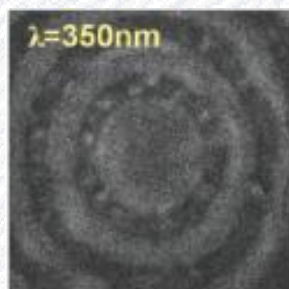
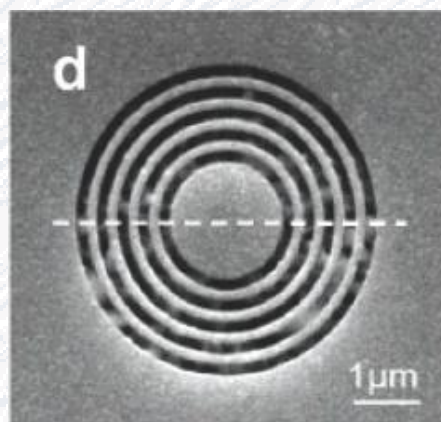
Xinli Zhu et al., **Advanced Materials**,  
Published online.

## 二、表面等离激元纳米腔模式

### □ 圆形SPP纳米腔

$D = 620\text{nm}$

$M_{0,1}$



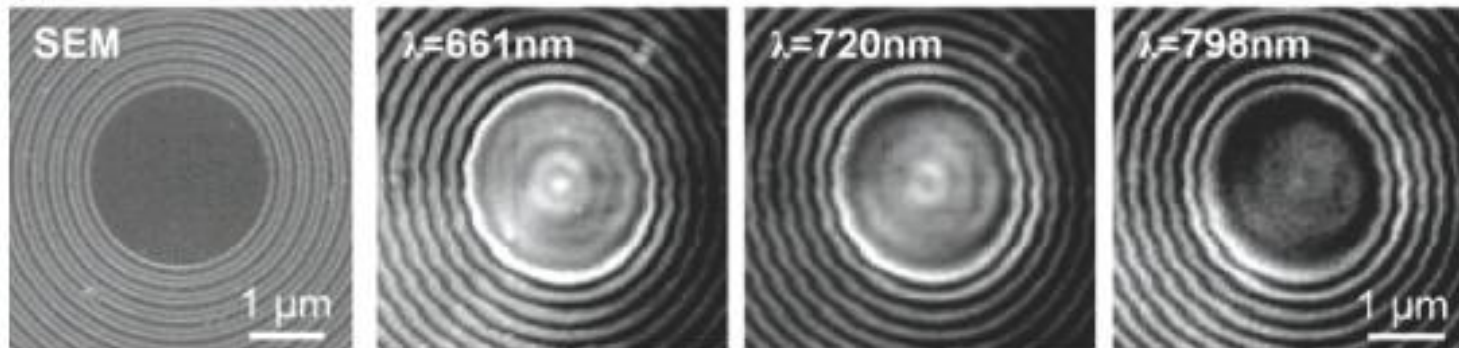
$M_{1,0}$

$M_{0,0}$

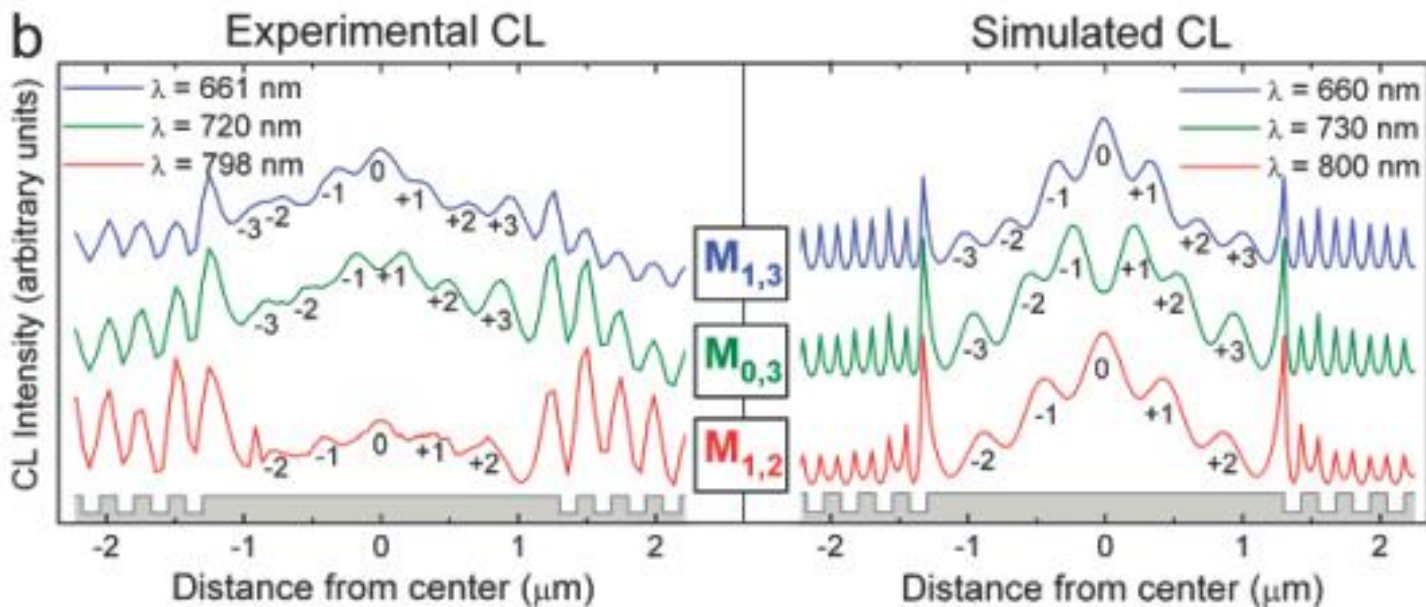
Hofmann et al., Nano Lett. 7, 3612 (2007)

$$D = 2.6 \mu\text{m}$$

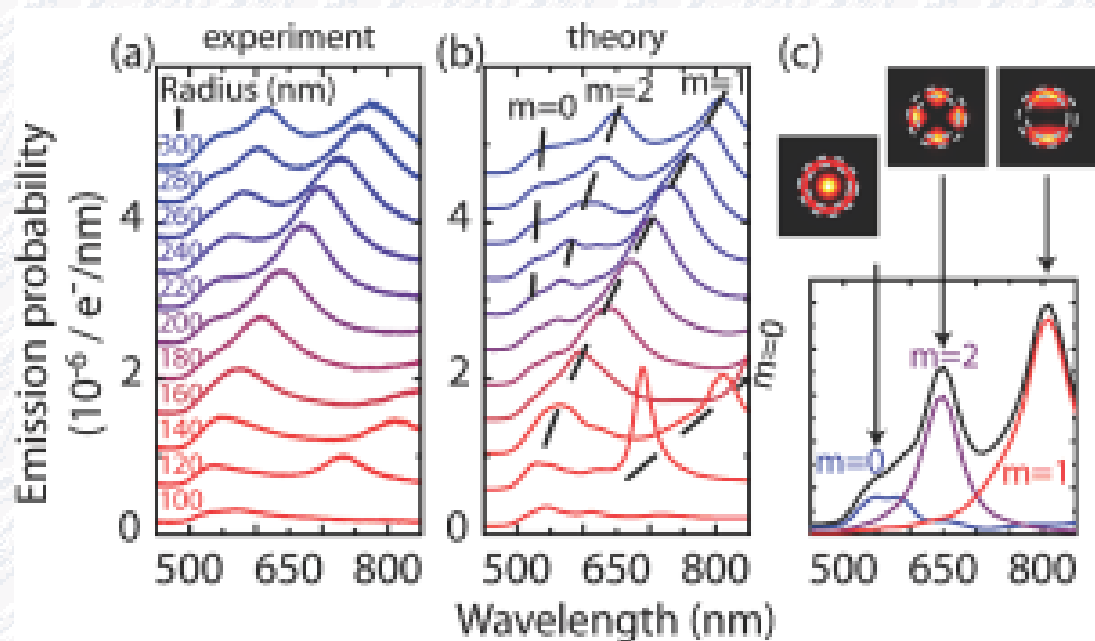
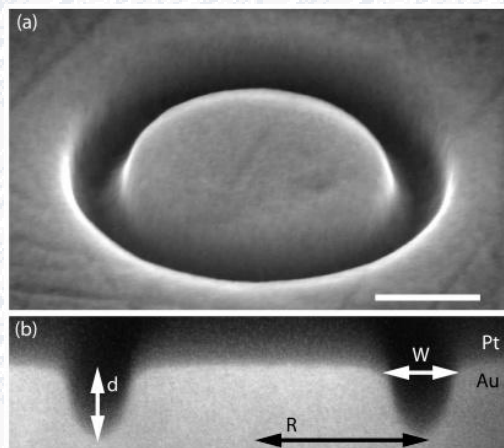
a



b



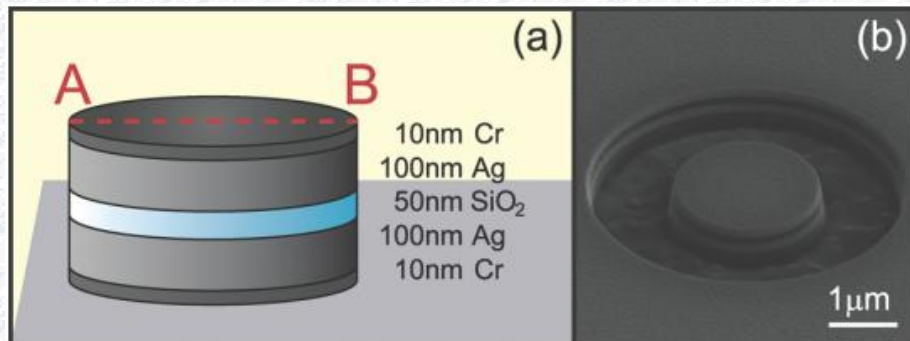
# □ 回音壁形SPP纳米腔



Vesseur et al., Nano Lett. 9, 3147 (2009)

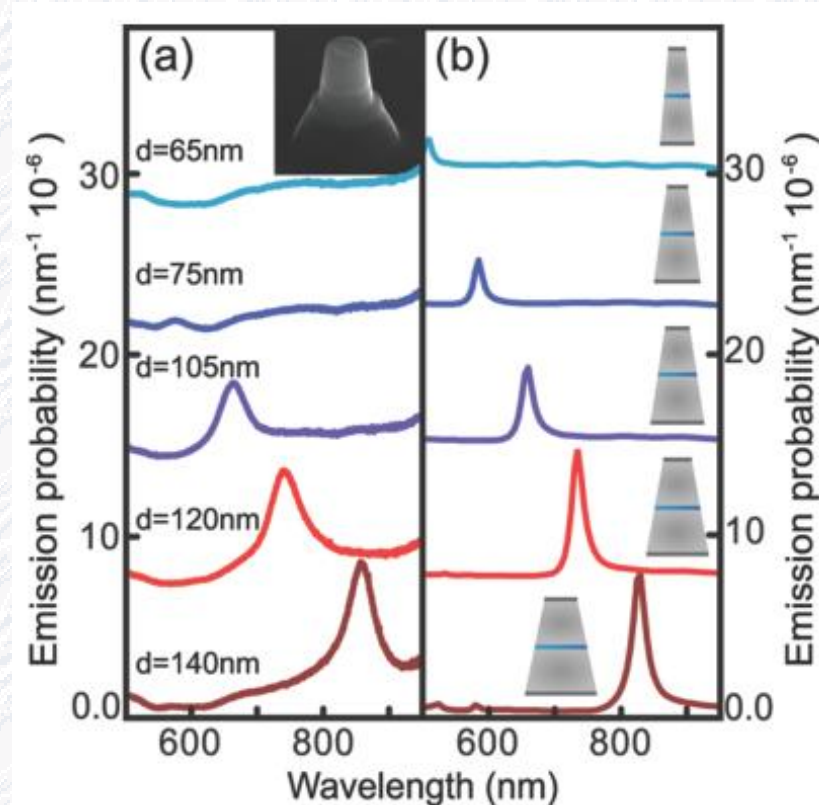


## □ MIM结构SPP纳米腔



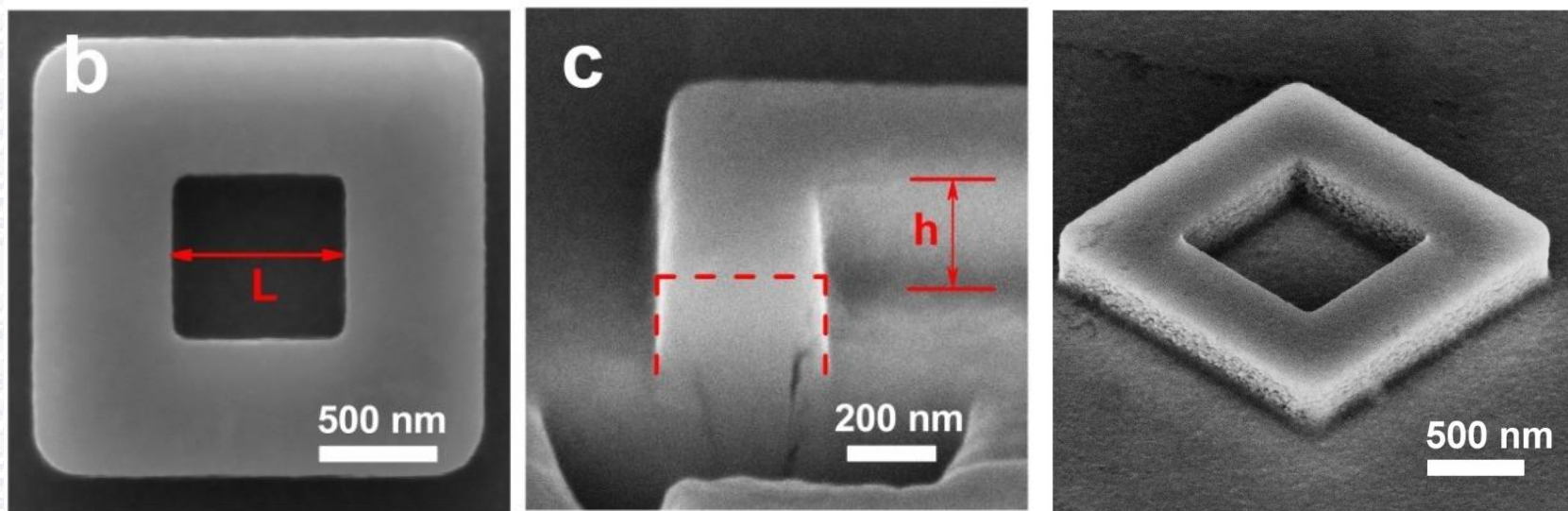
### MIM结构SPP纳米圆盘共振腔

$D = 105 \text{ nm}$  时：模体积 =  $0.00033\lambda_0^3$ ，是光子晶体构成的腔的最小模体积的1/100。

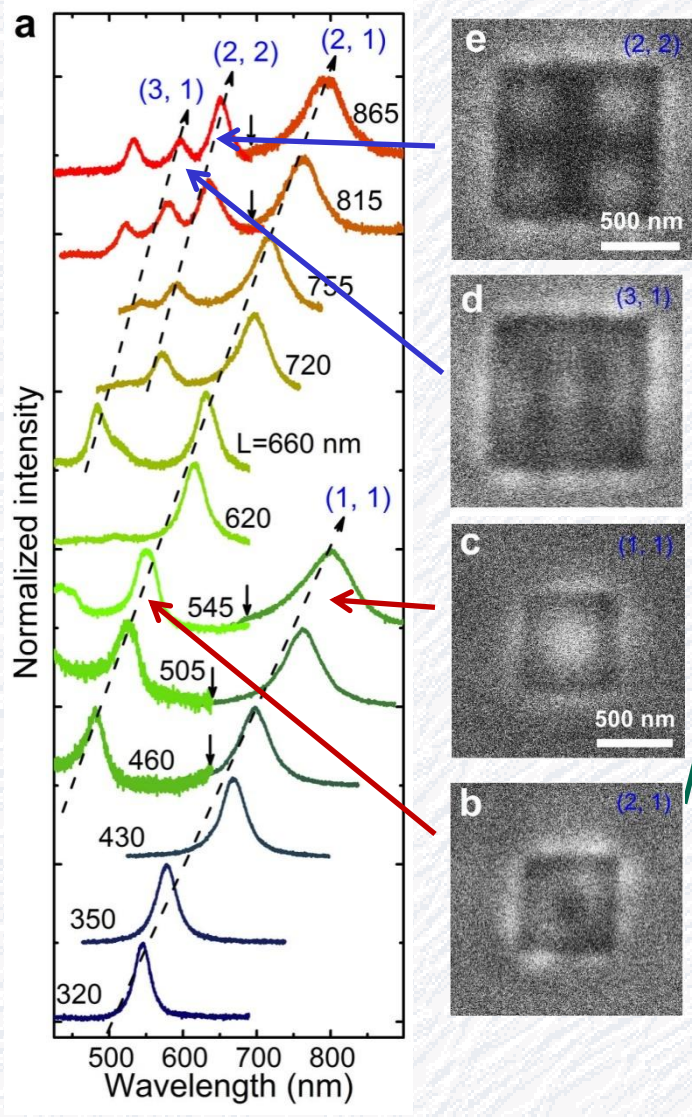


Kuttge et al., Nano Lett. 10, 1537 (2010)

# 1、正方形纳米腔中的模式

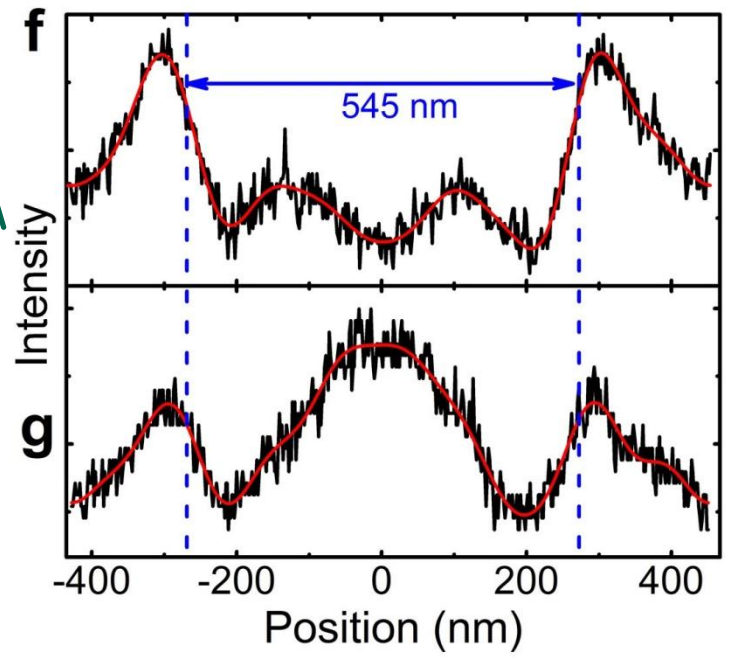


正方形腔的电镜照片



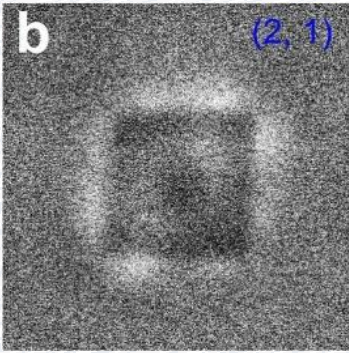
CL谱

模式

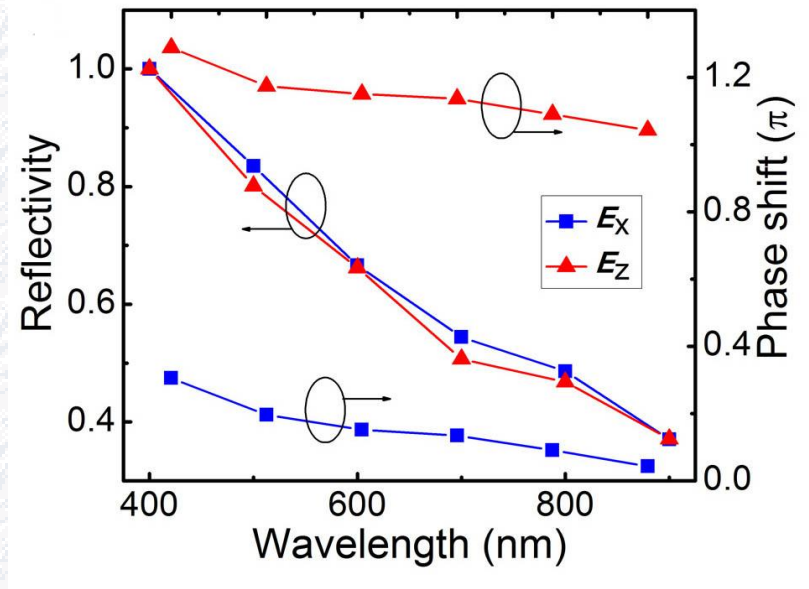


沿对称轴的强度分布

模式(m,n) : m, n分别为沿两个正交方向的波腹数目

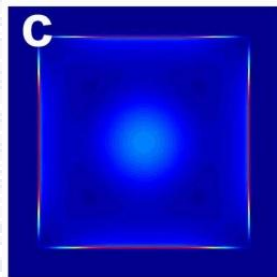
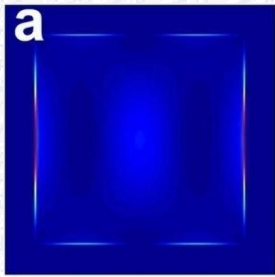


$\lambda=550\text{nm}$   
 $l=545\text{nm}$

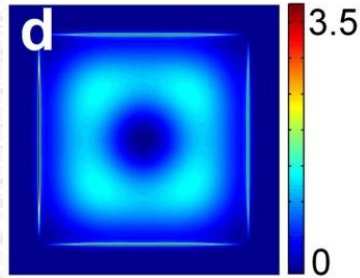
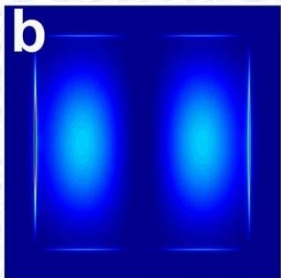


300nm高反射器的反射率和相位

$|\mathbf{E}_{\parallel}|^2$



$|\mathbf{E}_{\perp}|^2$



(2,1) mode理论计算

实验证明：电子束局域激发

SPP电场的垂直分量

正方形纳米腔的共振条件：

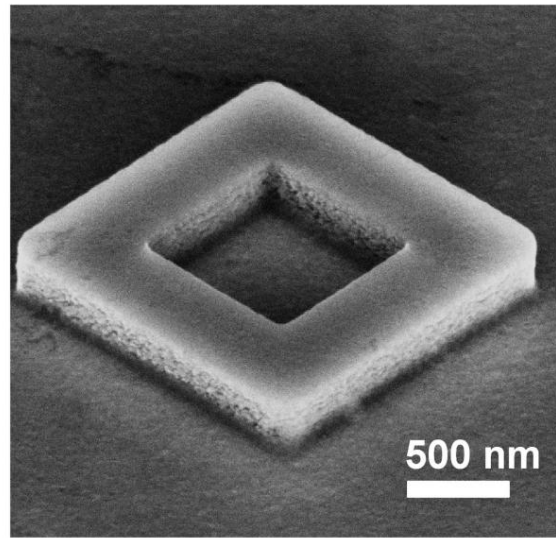
$$L + 2\delta(\lambda_{\text{SPP}}) = \sqrt{m^2 + n^2} \cdot \frac{\lambda_{\text{SPP}}}{2}$$

↑  
穿透深度

$$\delta(\lambda_{\text{SPP}}) = 0 \text{ 近似下的模体积： } V = \lambda_{\text{SPP}}^3 \left(1 + |\epsilon'_m|\right) \left(32\pi \sqrt{|\epsilon'_m|}\right)^{-1}$$

$$320 \text{ nm边长的腔： } V = 0.035 \lambda_{\text{SPP}}^3 = 0.0049 \mu\text{m}^3$$

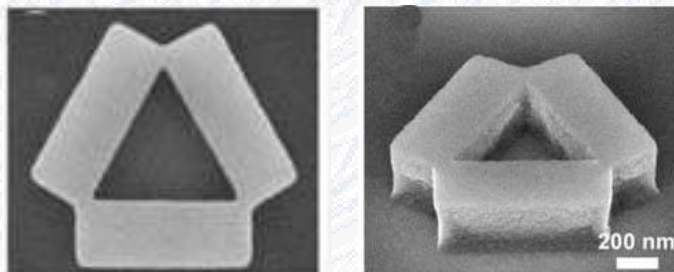
# 金属反射器高度对共振波长的影响 —— 源于对SPP的三维局域



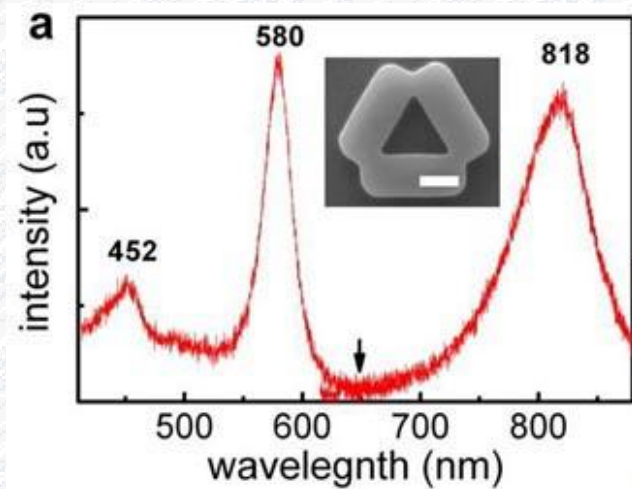
边长	350nm	350nm
模式	(1, 1)	(1, 1)
反射器高度	300nm	500nm
共振波长	577nm	655nm

X. L. Zhu et al., **Phys. Rev. Lett.** 105, 127402 (2010).

## 2、三角形纳米腔中的模式

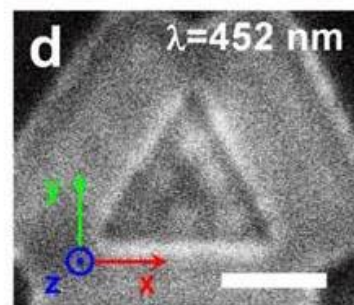
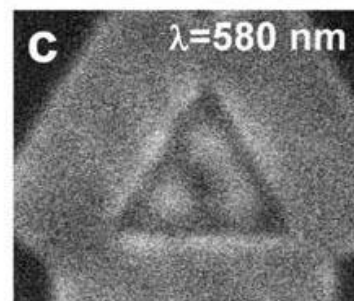
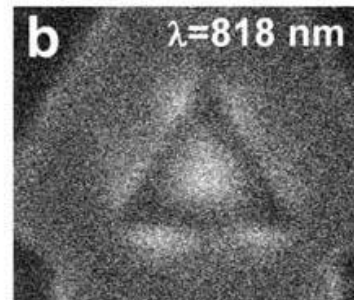


三角形腔的电镜照片

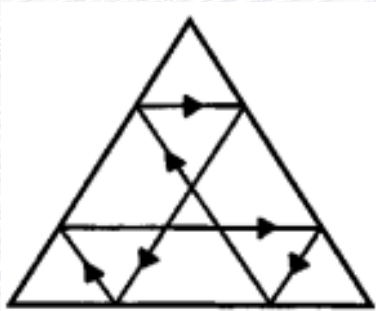


CL谱

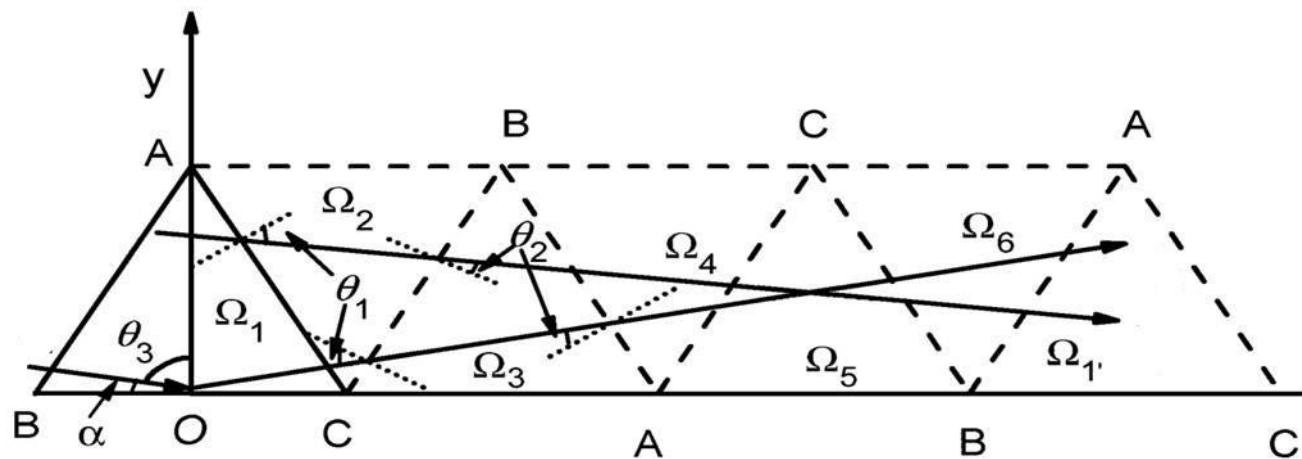
( $a=935\text{nm}$ ;  $h=300\text{nm}$ )



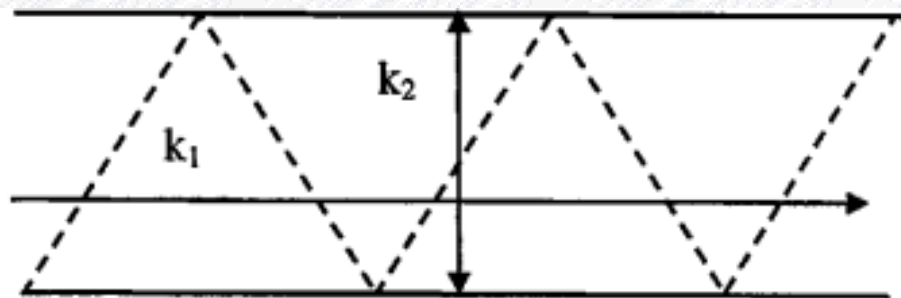
模式



腔的模式



三角形腔的展开



腔中正交的两个波矢

(n, m)模式条件:  $k_2 = \frac{2n\pi}{\sqrt{3}a}, \quad n = 1, 2, 3, \dots$   $k_1 = \pm \frac{2m\pi}{3a}, \quad m = 1, 2, 3, \dots$

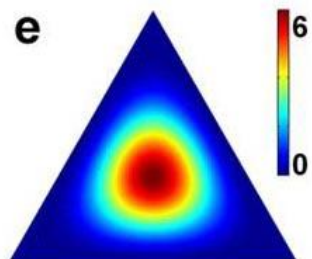
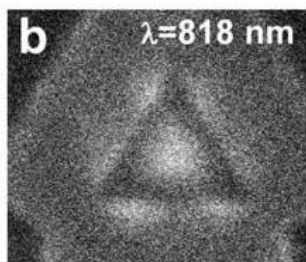


实验

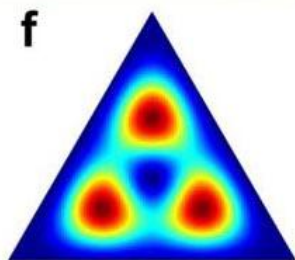
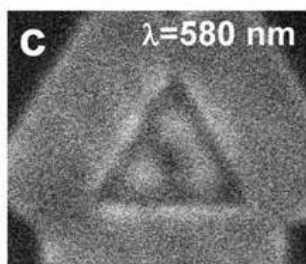
理论

$|\mathbf{E}_{\parallel}|^2$

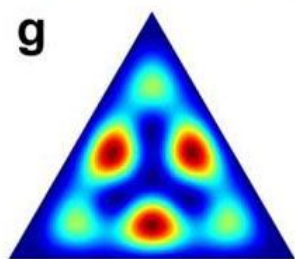
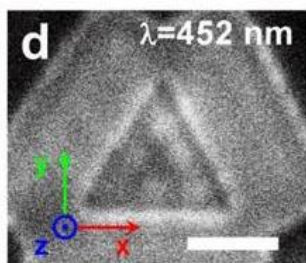
$|\mathbf{E}_{\perp}|^2$



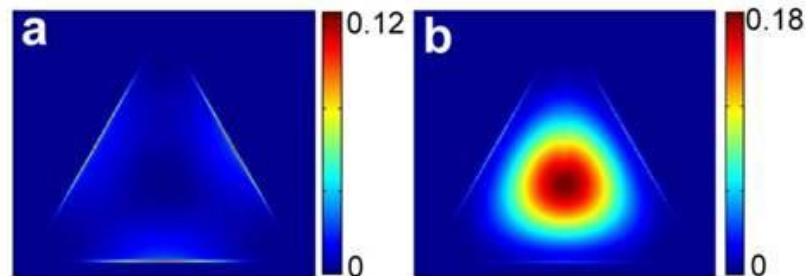
(1, 3)



(1, 5)/(2, 4)

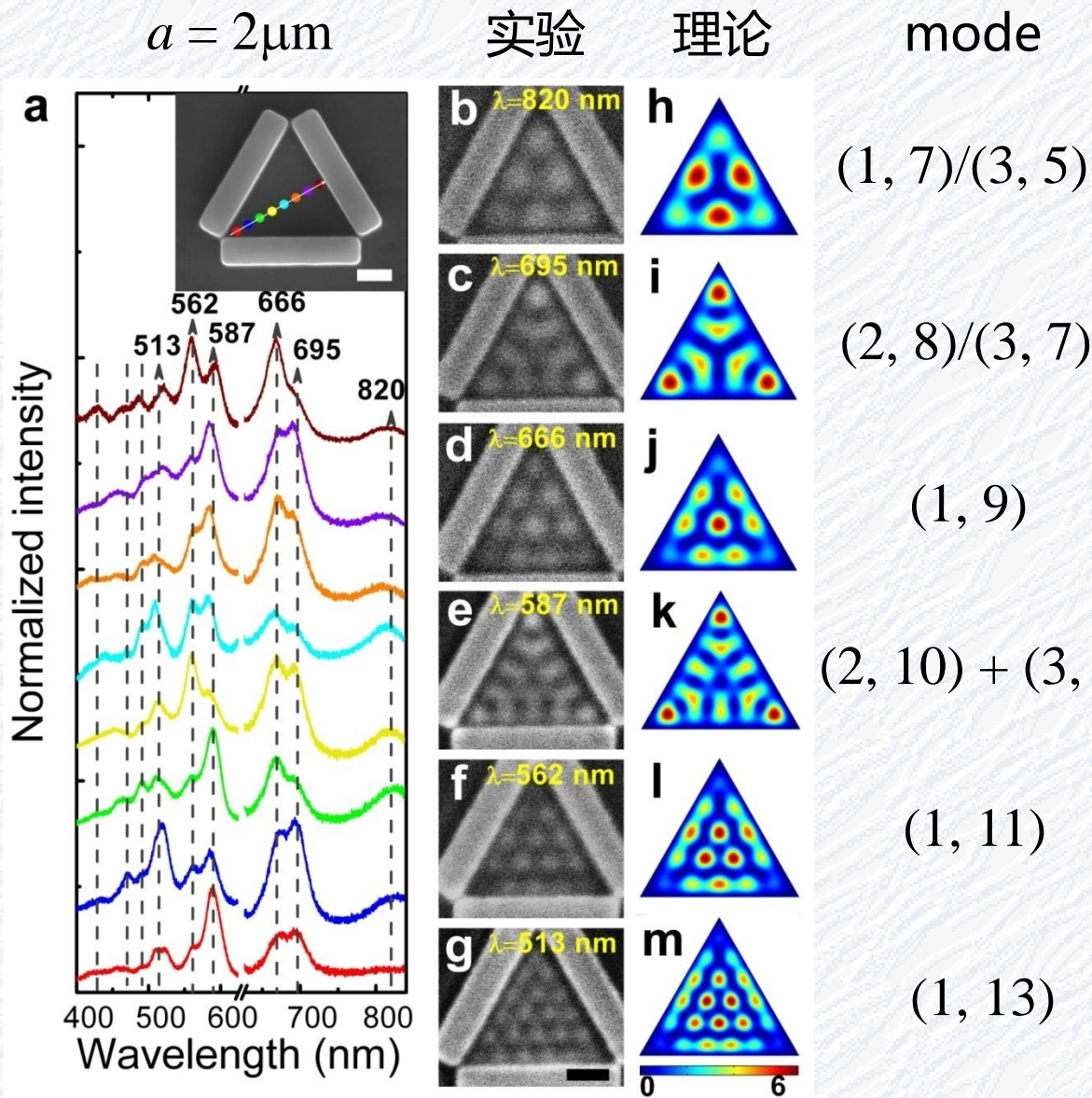


(1, 7)/(3, 5)



FDTD计算结果

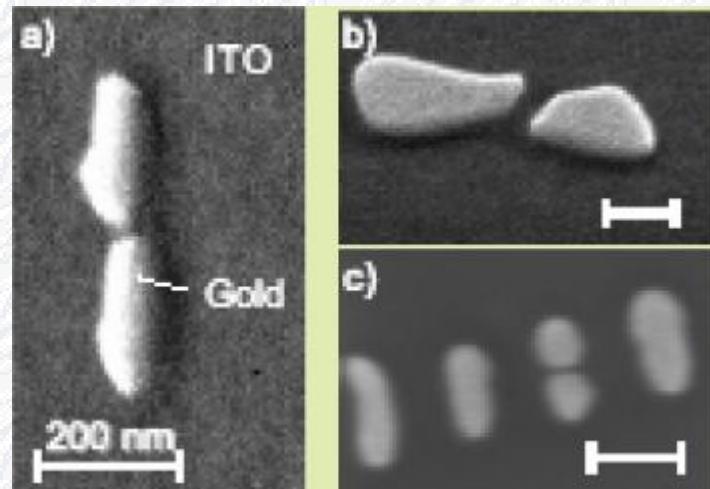
↑  
边界  $E = 0$



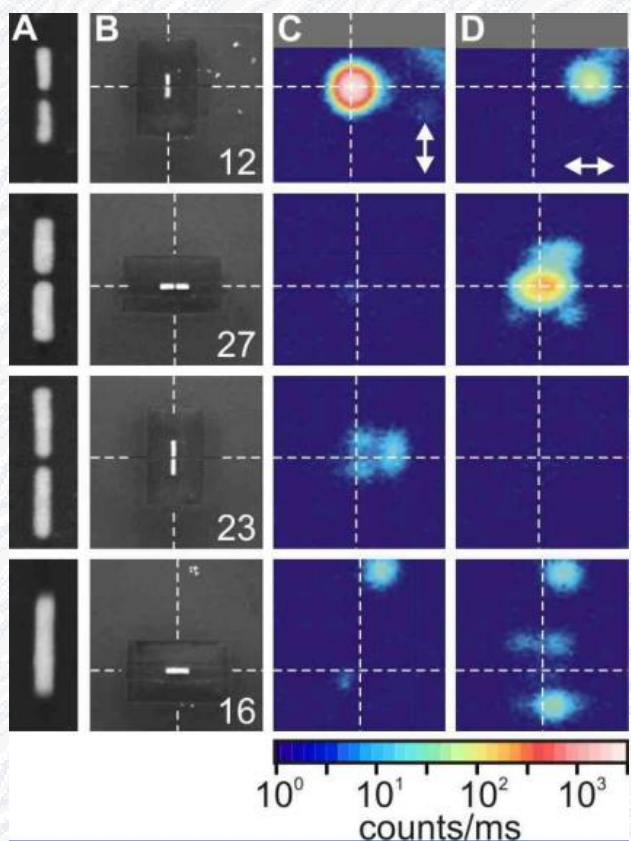
### 三、光学天线中的场增强和模式



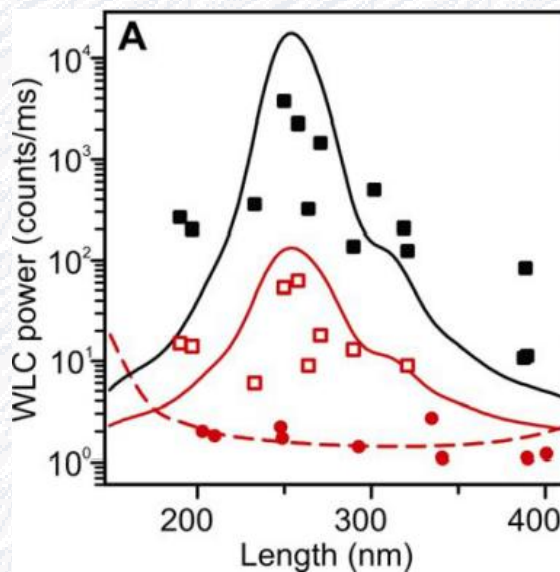
无线电天线



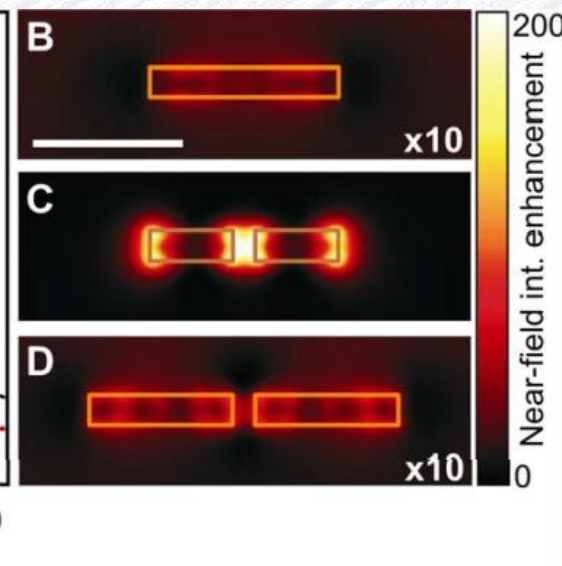
光学天线



天线样品

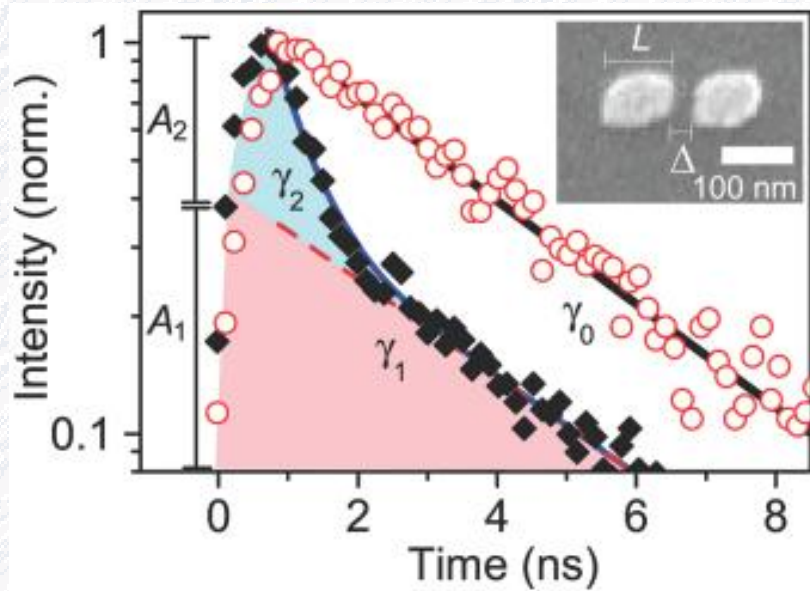


白光强度

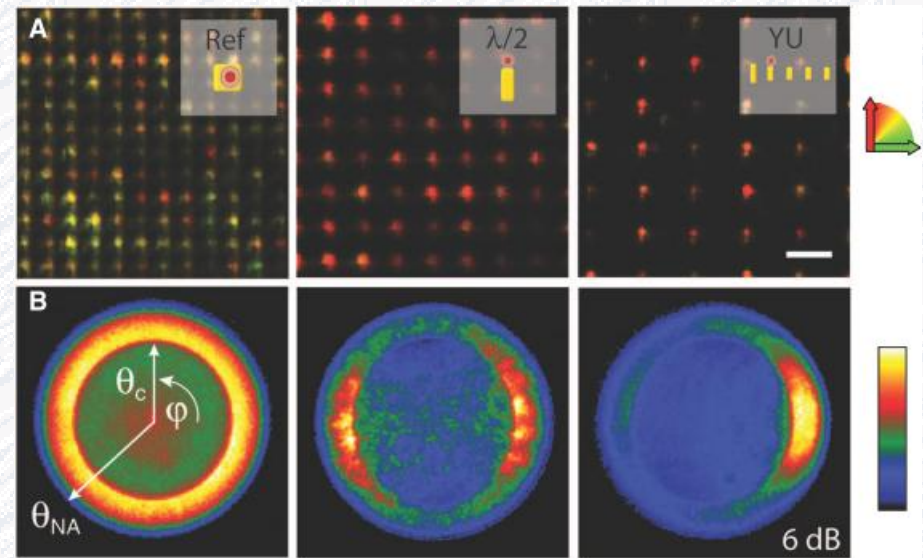
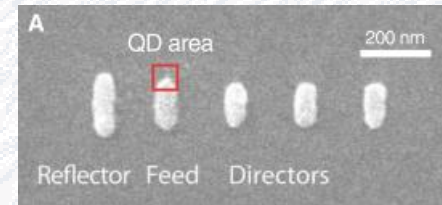


场增强因子

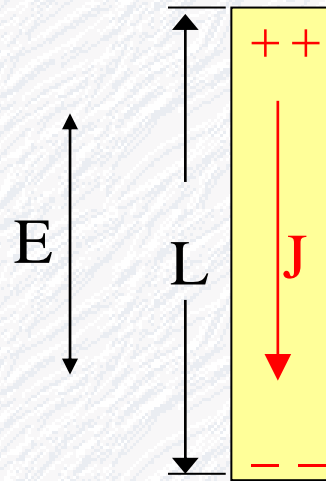
Muhlschlegel et al., Science 308, 1607 (2005).



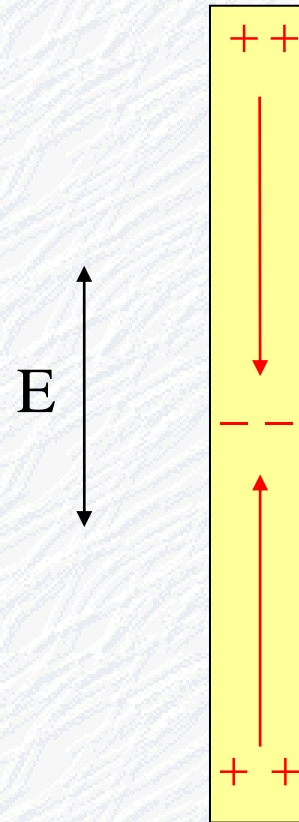
Muskens et al., Nano Lett. 7, 2871 (2007).



Curto et al., Science 329, 930 (2010).

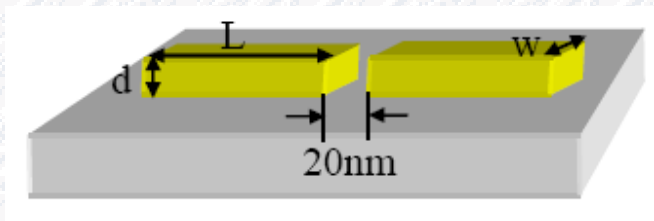


电偶极

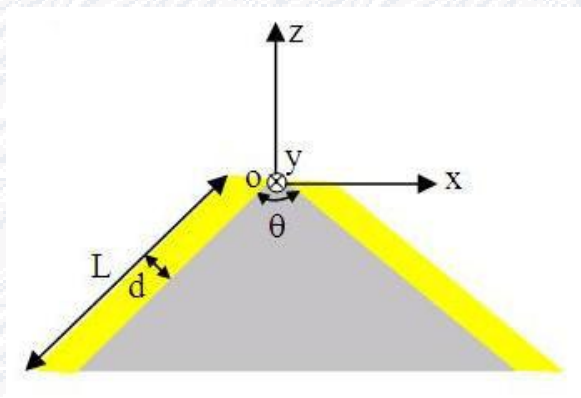


电四极

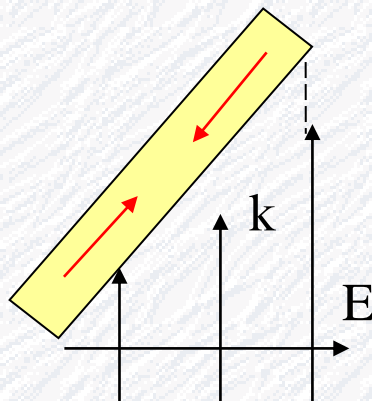
# 1、V形光学天线中的模式和场增强



偶极天线



V形天线



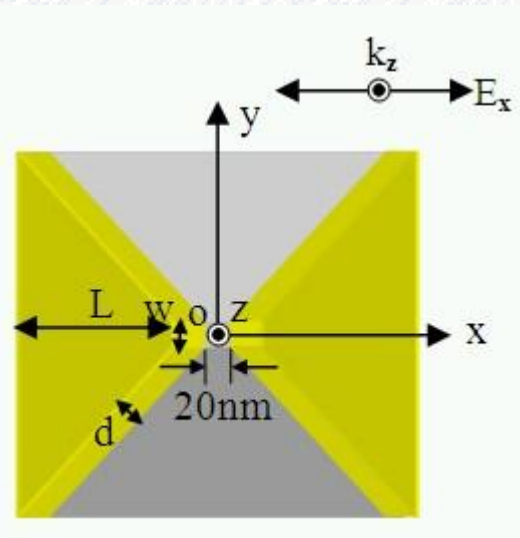
天线臂倾斜的作用：

1. 天线方向性改善  
导致场增强的增加；
2. 电四极的激发。

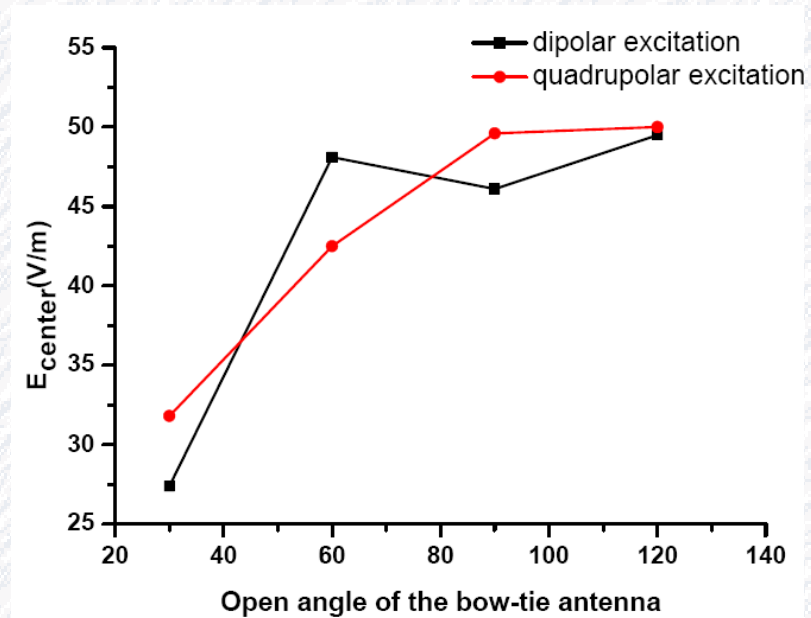
电场强度的增强：

偶极：234  $\rightarrow$  2342

四极：32  $\rightarrow$  949



V形领结天线

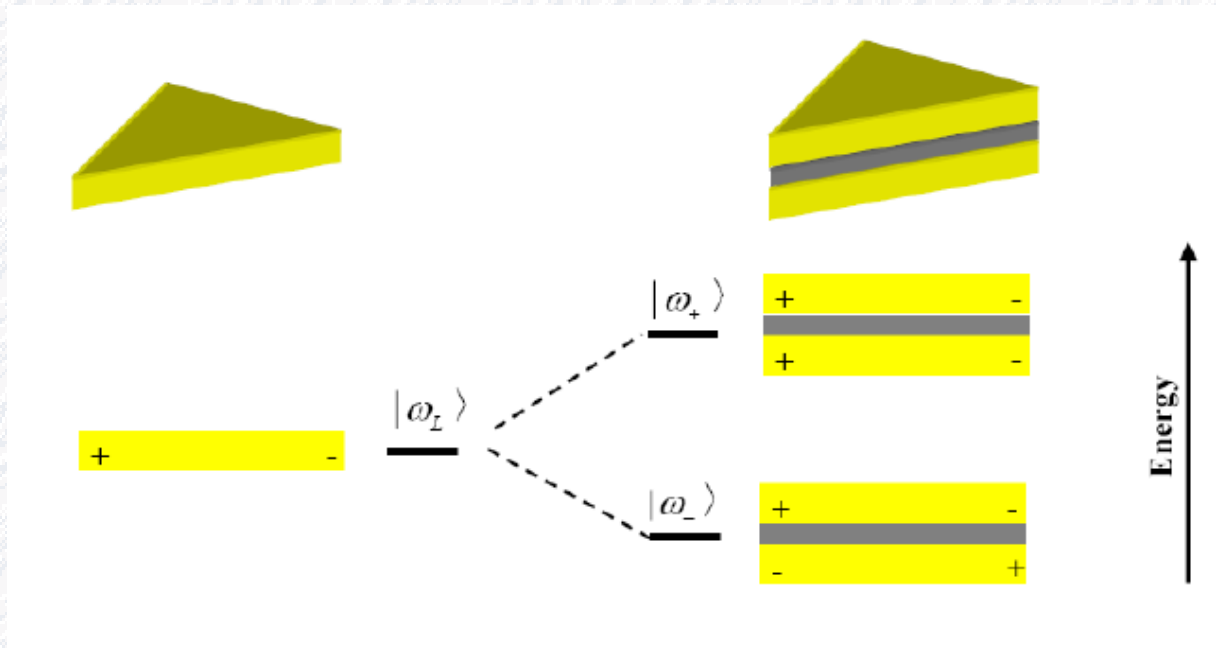


V形领结天线电场振幅增强因子

Jing Yang et al., Opt. Express 15, 16852 (2007).

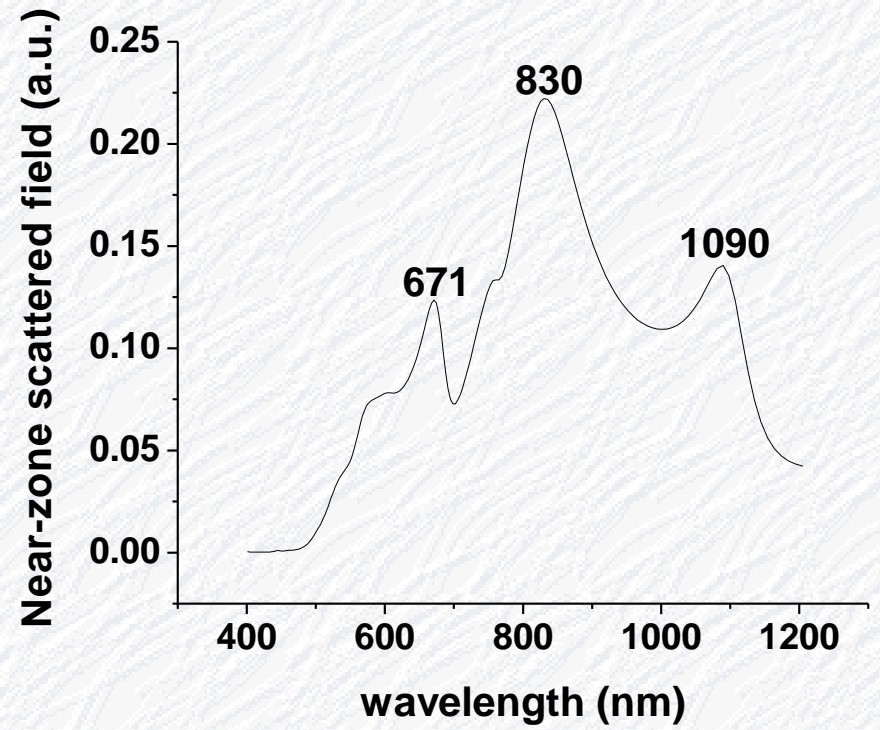
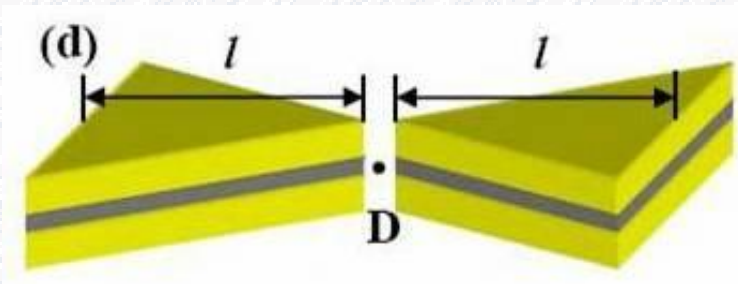


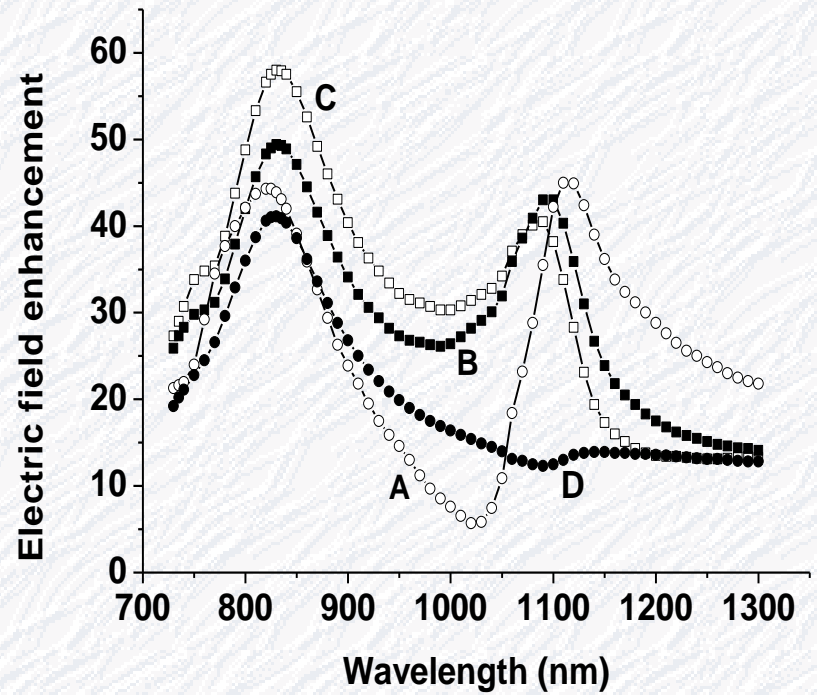
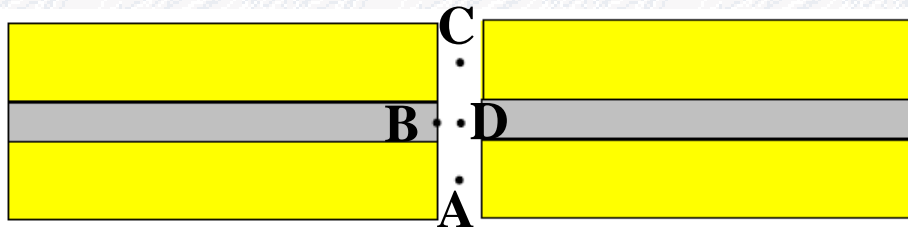
## 2、三明治结构光学天线中的模式和场增强



三明治结构光学天线中的能级劈裂

共振时的电流





Lisheng Wang et al., Opt. Commun. 281, 5444 (2008).

### 3、利用MIM结构纳米棒中的共振实现亚波长成像



透镜成像



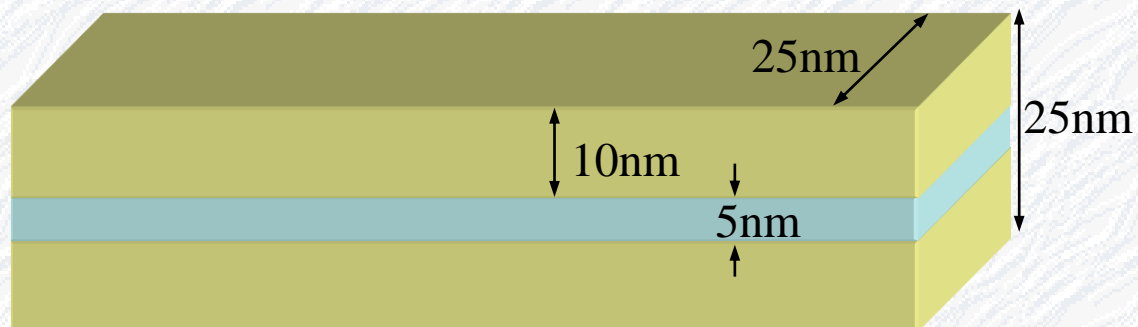
光纤束成像

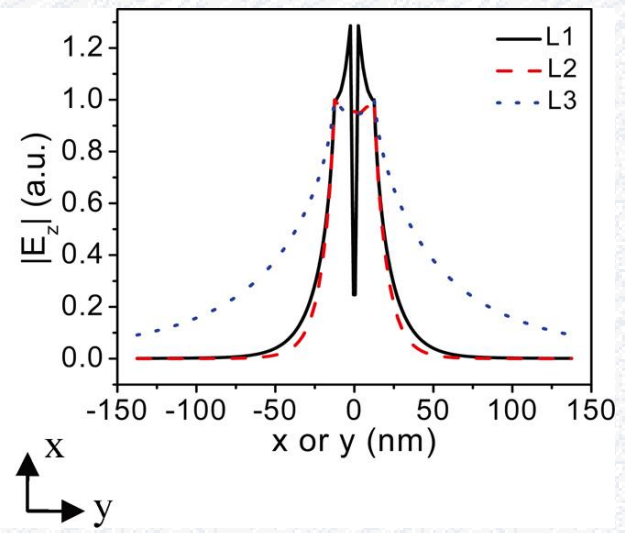
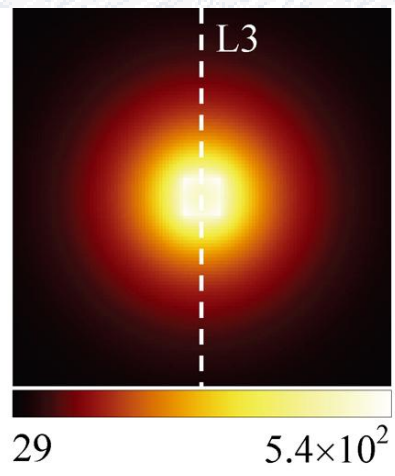
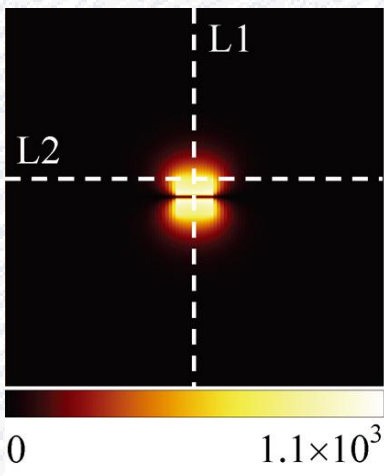
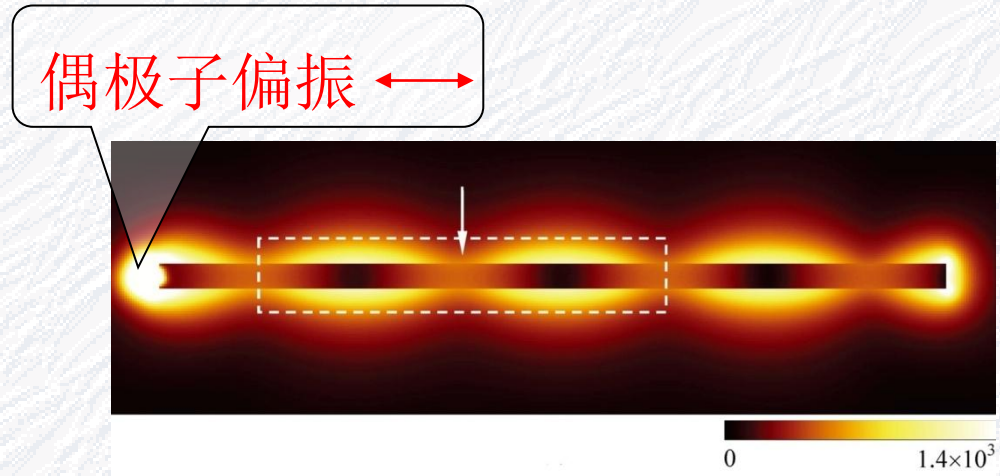
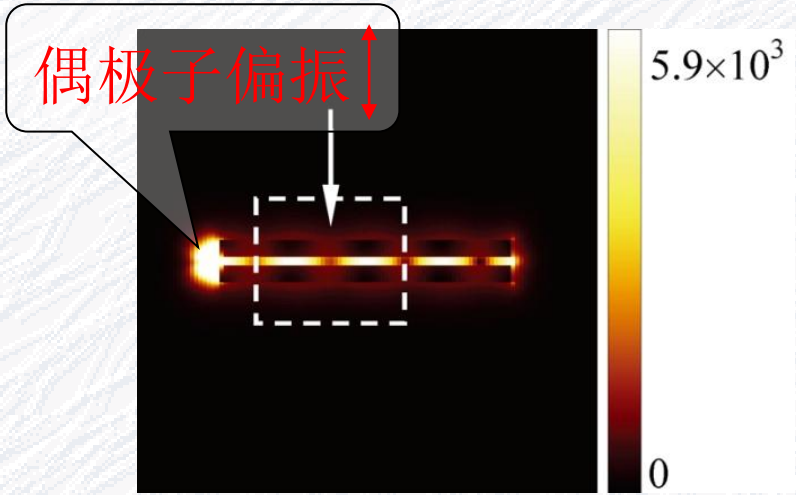
## 两种SPP共振波导

Au

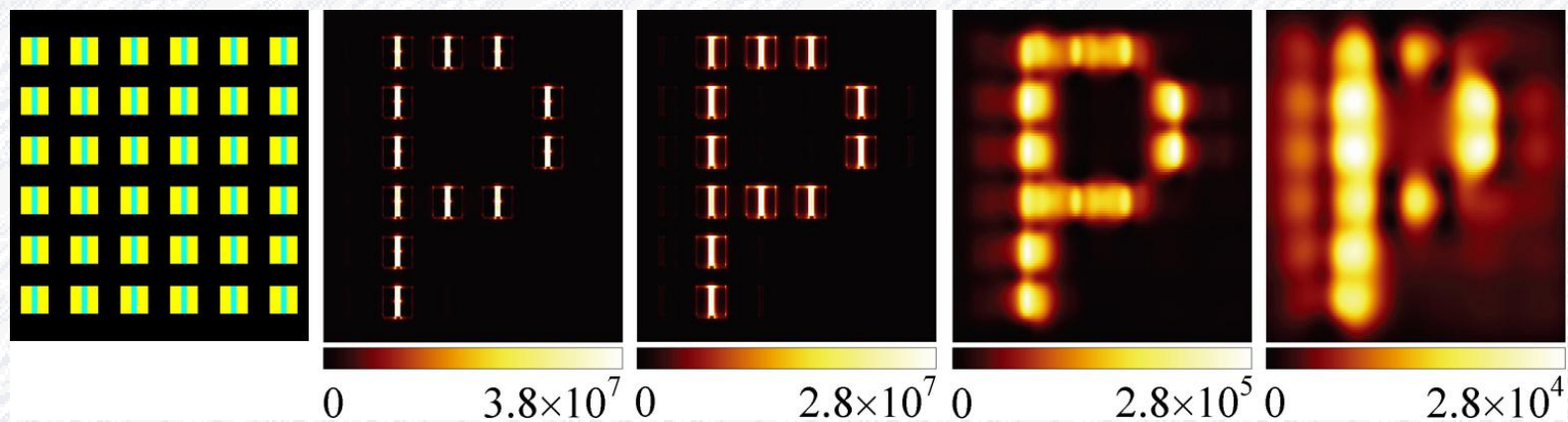


Au-SiO<sub>2</sub>-Au结构

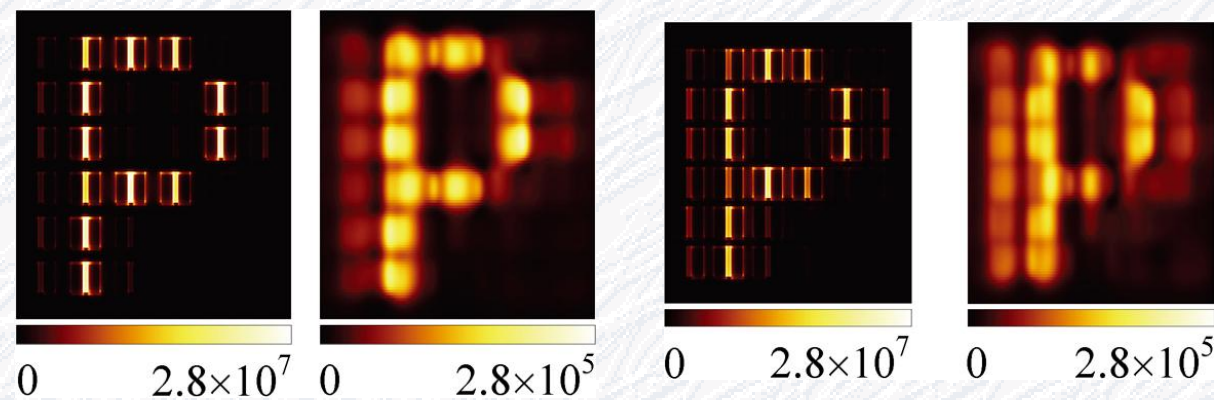




横截面光强分布



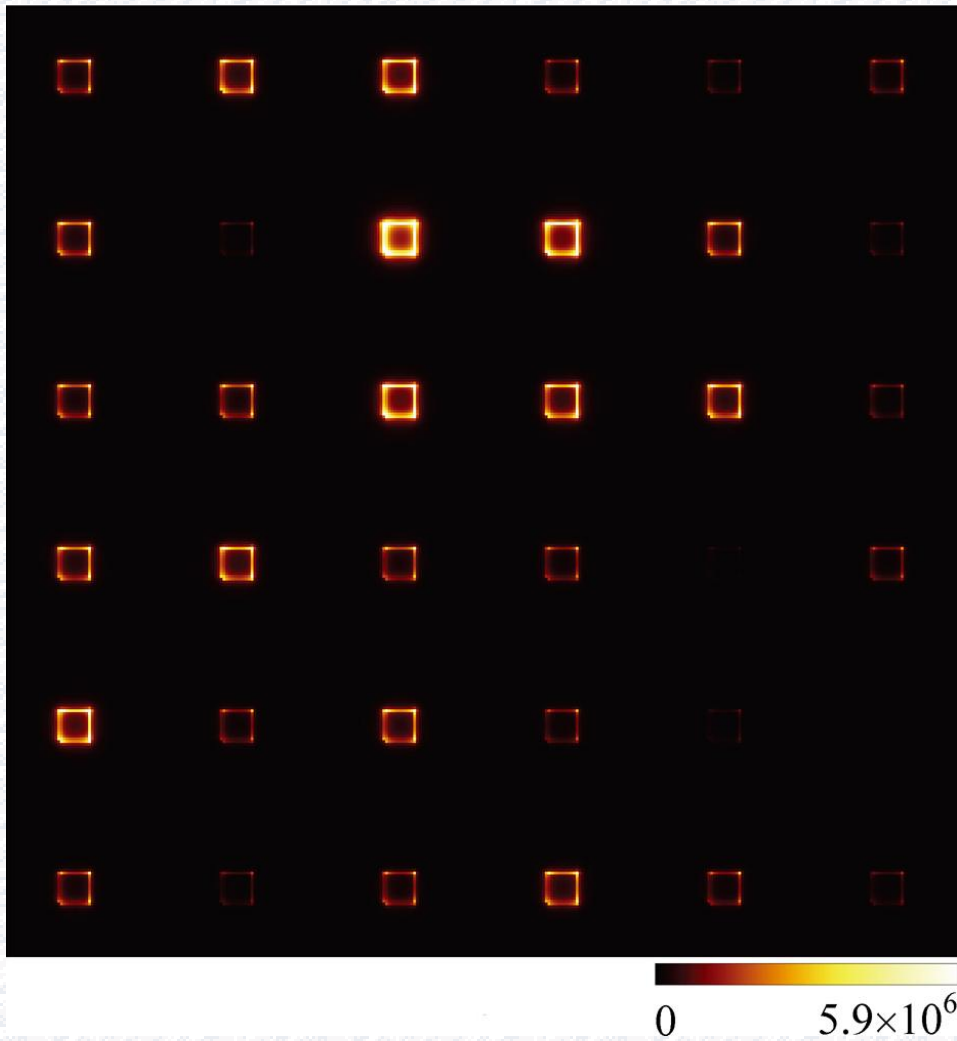
MIM 间隔20nm



MIM 间隔15nm

MIM 间隔10nm

分辨率极限:  
40nm  $\sim \lambda/20$

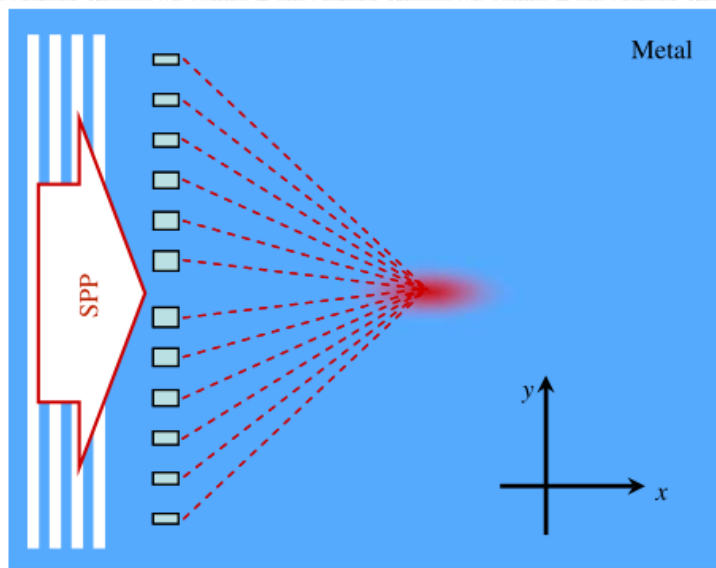


Au 间隔120nm

Xiaofei Wu et al., Opt. Express **17**, 2818 (2009).



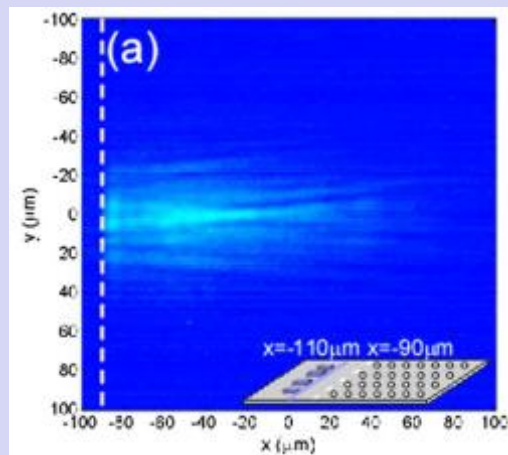
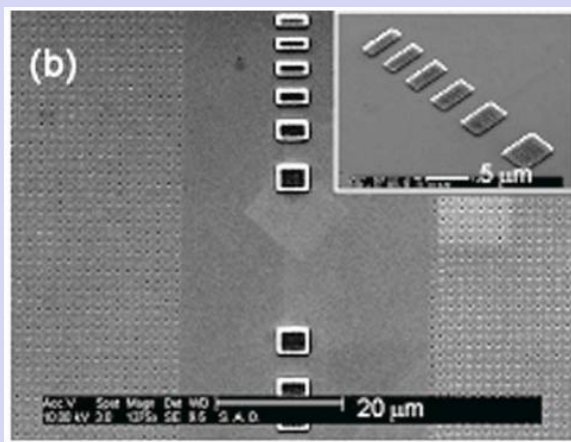
## 四、表面等离激元的波前调控



前人的方法：在金属膜上利用散射结构调控SPP强度

缺点：调控精度差、不能直接调控相位

波带片结构实现SPP聚焦：



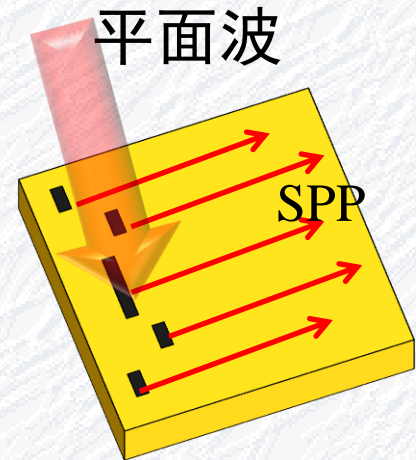
Feng et al., Appl. Phys. Lett. 91, 081101 (2007)

# SPP的波前调控方法

我们的思想：

利用耦合栅位置和结构的变化，实现光与SPP耦合的同时对SPP波前精确调控。

位置 —— 相对相位，结构 —— 强度



优点：

- ✓ 高精度；
- ✓ 直接调控相位和强度；
- ✓ 耦合和调控同时实现；
- ✓ 灵活实现多种功能。

计算方法：

耦合栅上的每一点可以看做是一个SPP点源

↓ 惠更斯-菲涅尔原理

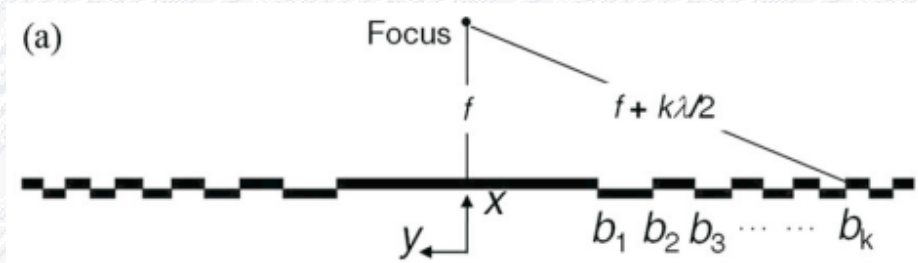
辐射特性、相位、损耗等



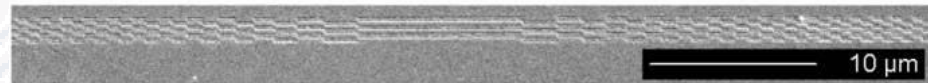
场分布

# 1. 三维光和二维SPP间的成像

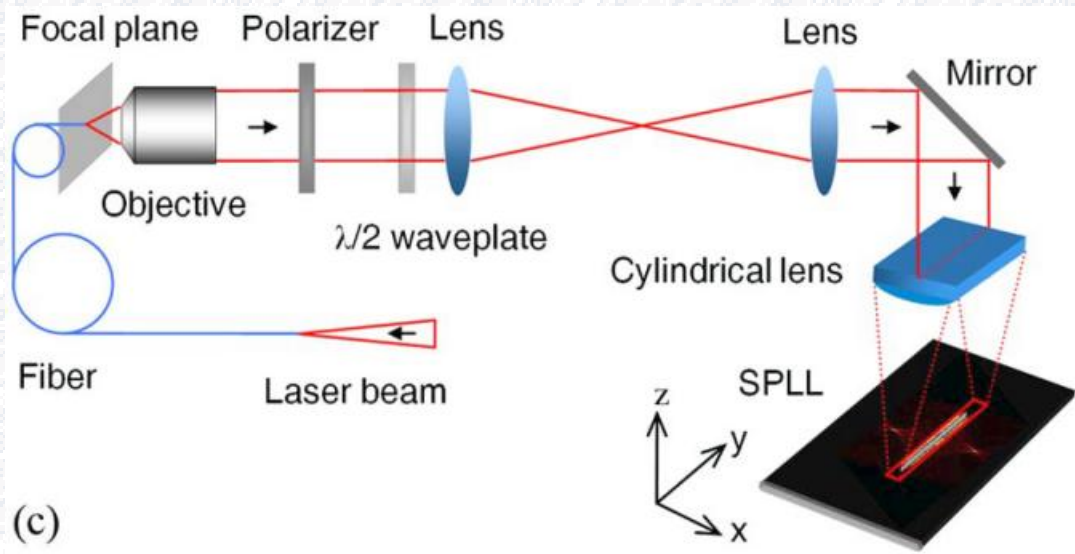
SPP激发耦合  
透镜设计原理:

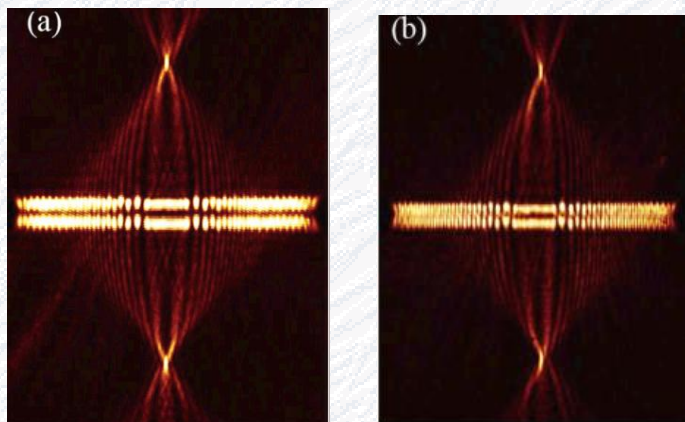


电镜照片:

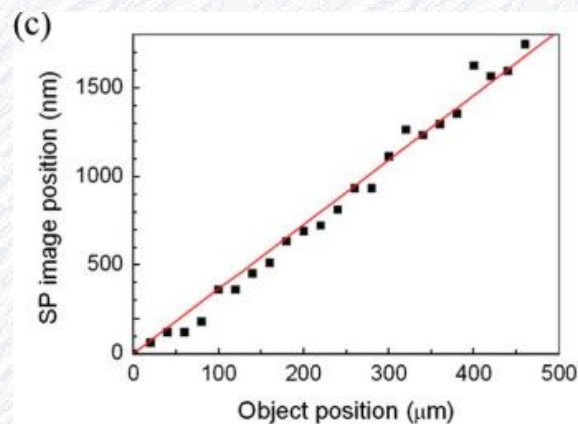


实验装置:

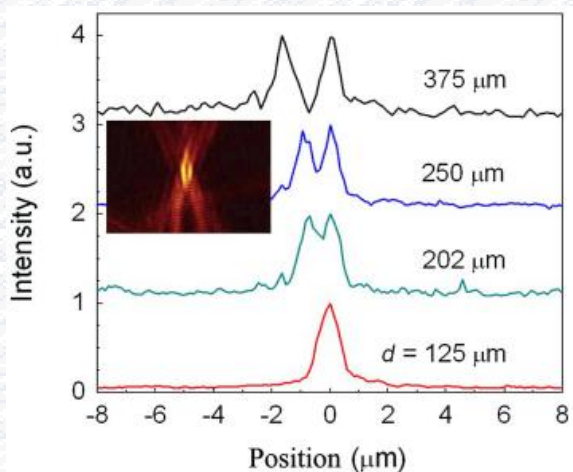




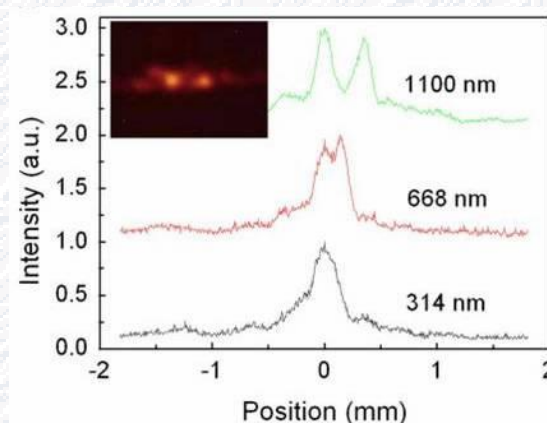
透镜的聚焦



物像关系



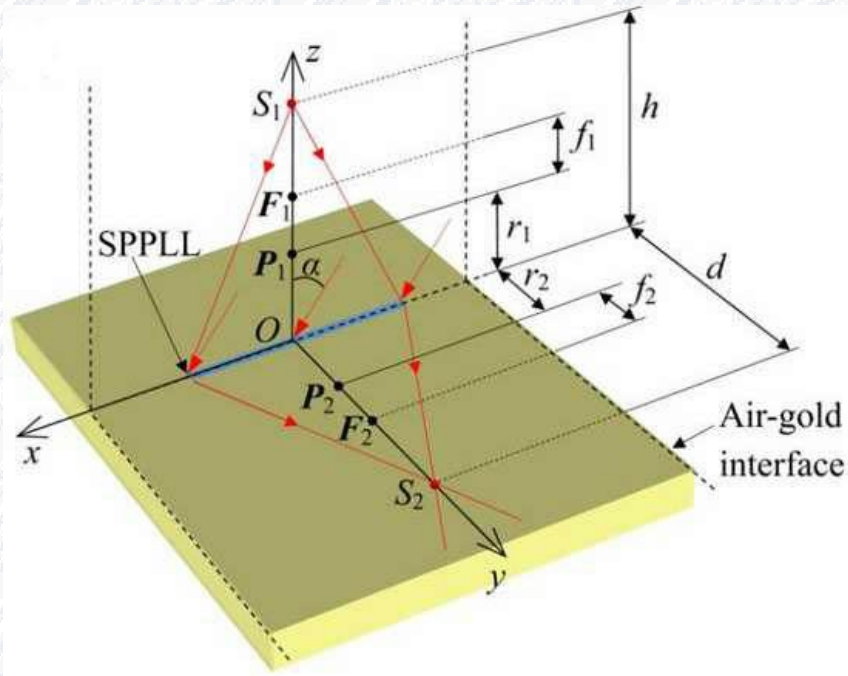
三维远场到SPP成像



两个SPP点源到远场的成像

Jiayuan Wang et al., *Appl. Phys. Lett.* 94, 081116 (2009).

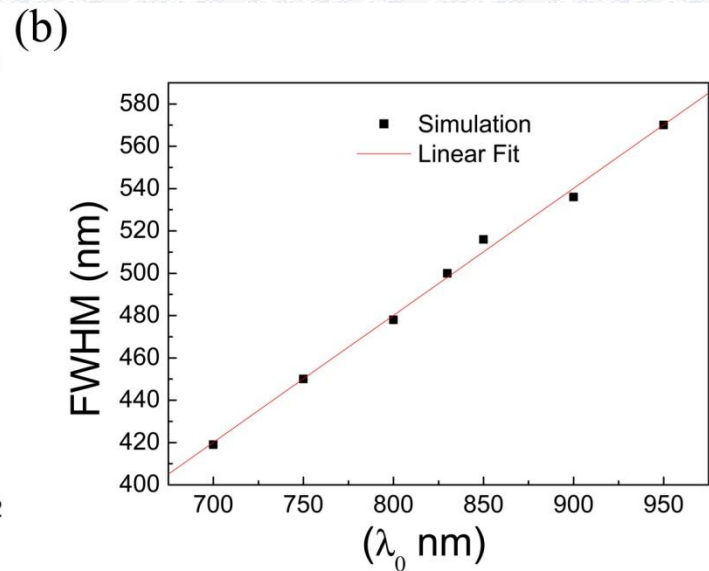
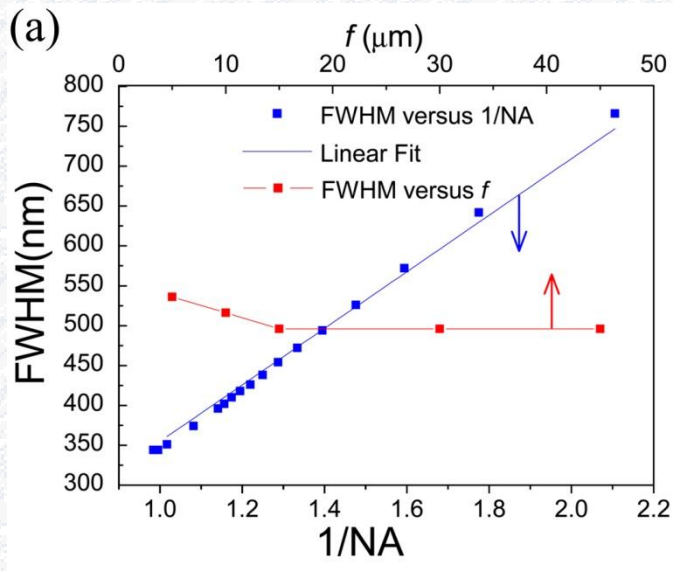
# □ 成像特性



成像可用厚透镜公式表示：

$$\frac{f_1}{h - r_1} + \frac{f_2}{d - r_2} = 1$$

成像示意图



焦点半宽随焦距和NA的变化      焦点半宽随波长的变化

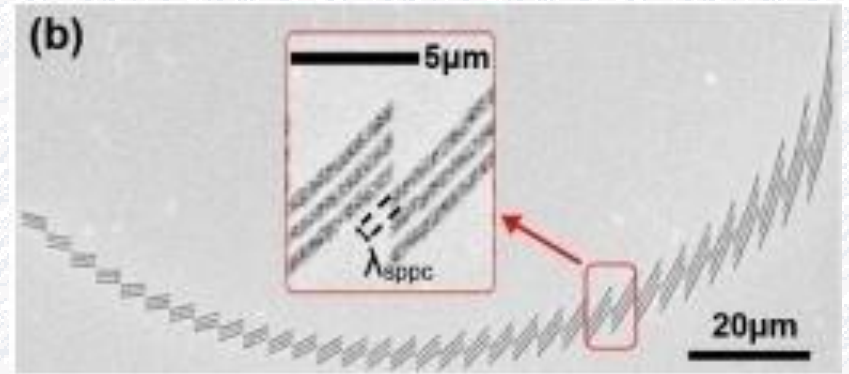
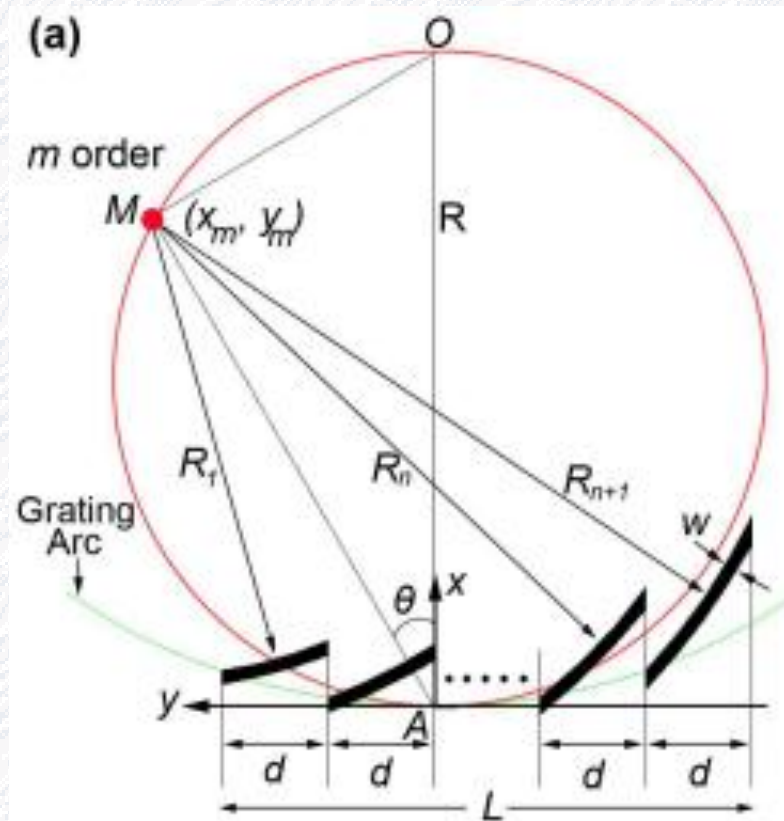
SPP激发耦合透镜： $\text{FWHM} = 0.42\lambda_0/\text{NA}$

普通理想透镜： $\text{FWHM} = 0.51\lambda_0/\text{NA}$

分辨率提高的原因：SPP在垂直于金属膜分量的场增强

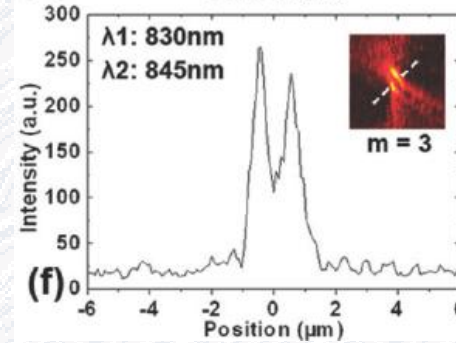
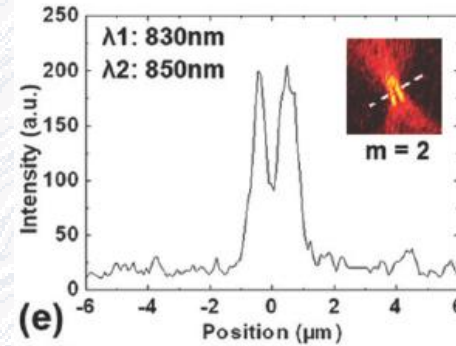
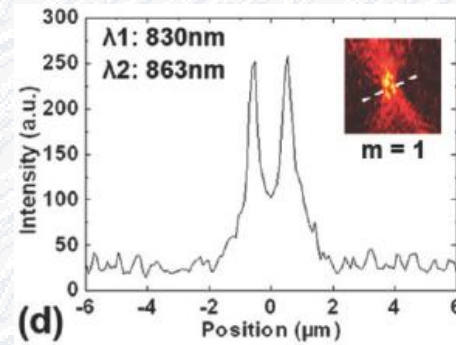
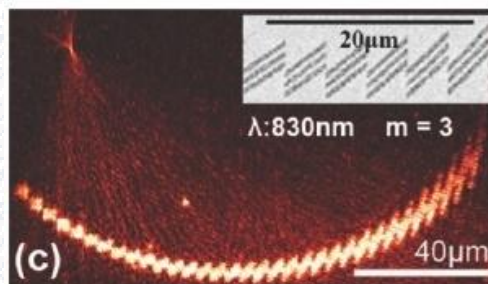
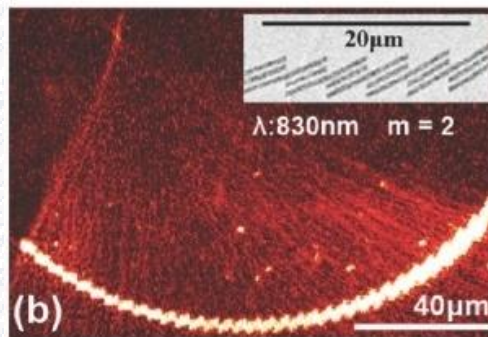
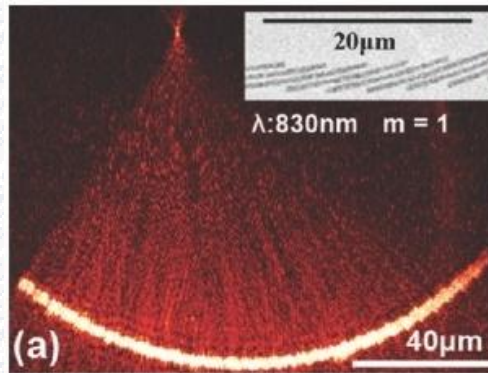
Jiayuan Wang et al., *Opt. Express* 18, 6686-6692 (2010)

## 2. SPP波分复用器



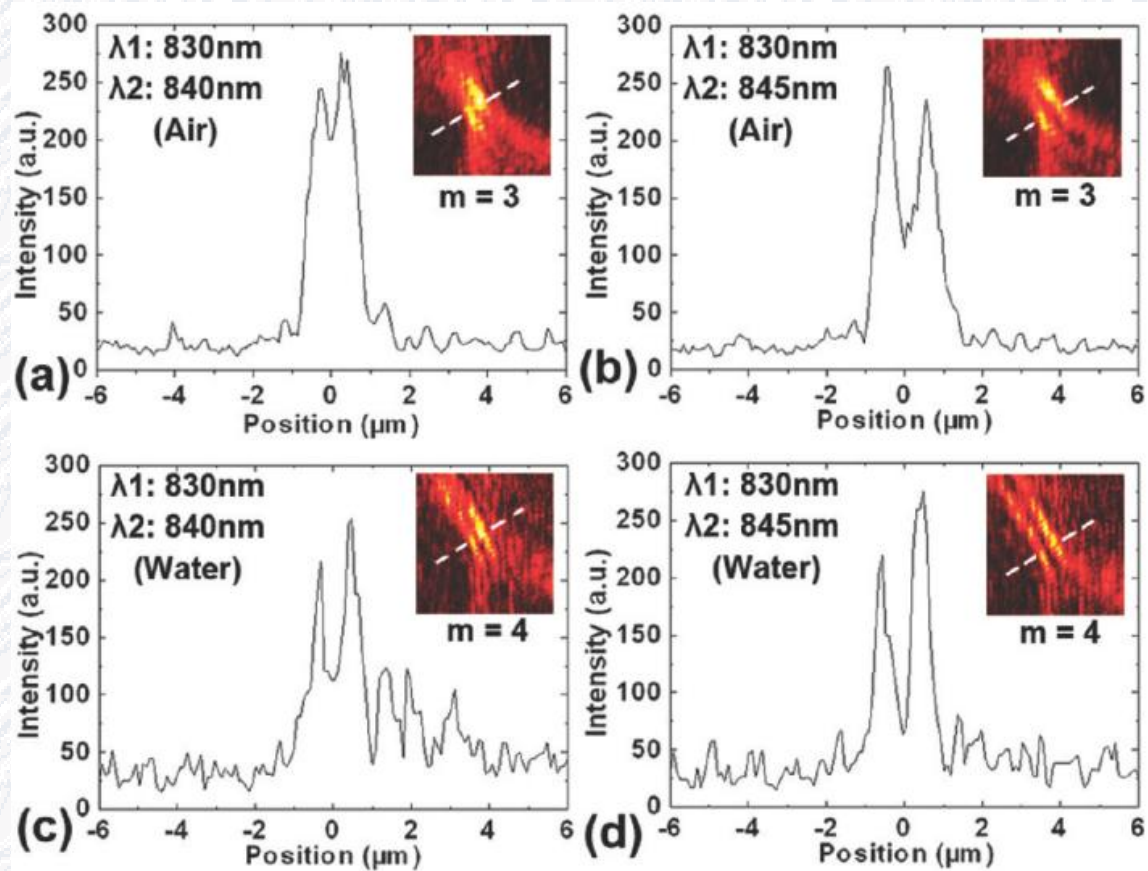
电镜照片

设计原理

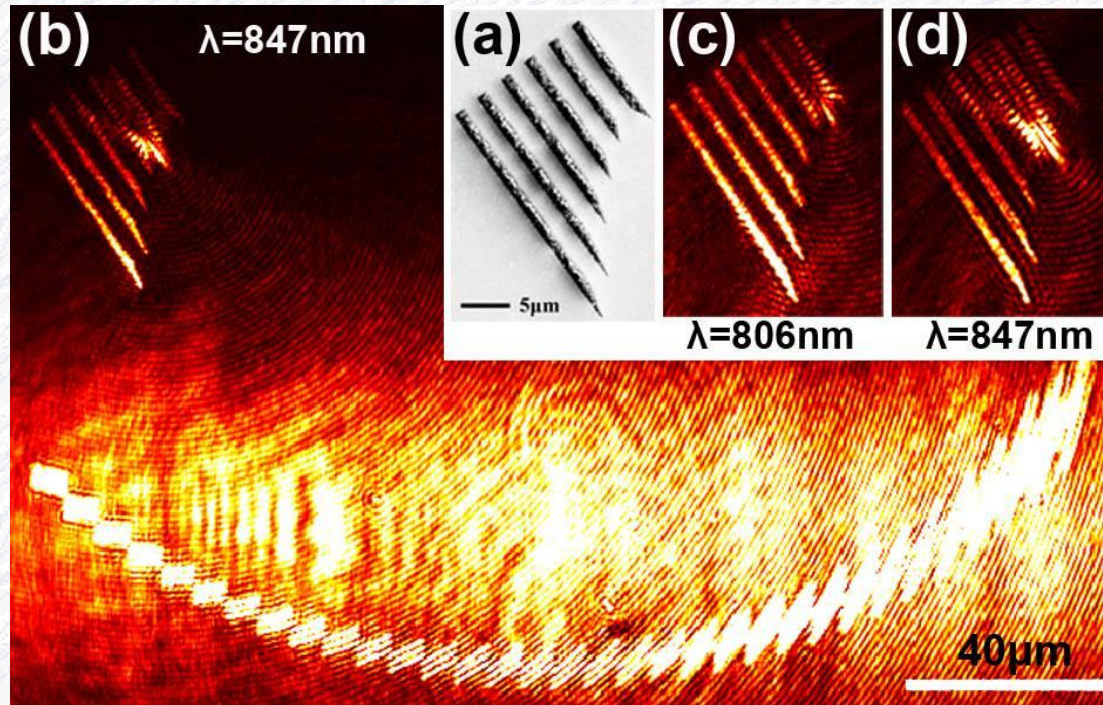


## 实验结果





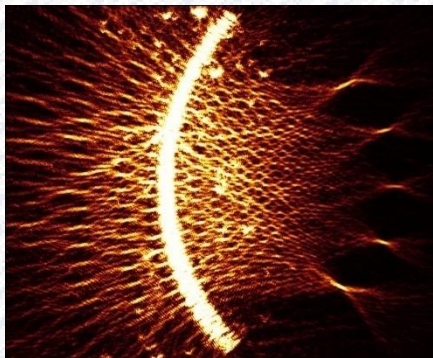
介质为空气和水的比较



## 波导耦合实验结果

Chenglong Zhao & Jiasen Zhang, **ACS Nano**, published online.

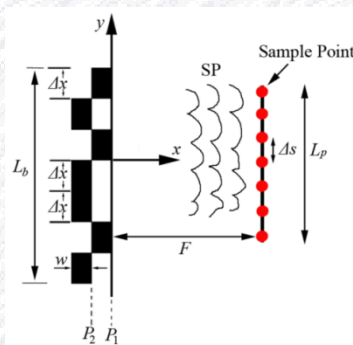
## □ SPP多焦点聚焦



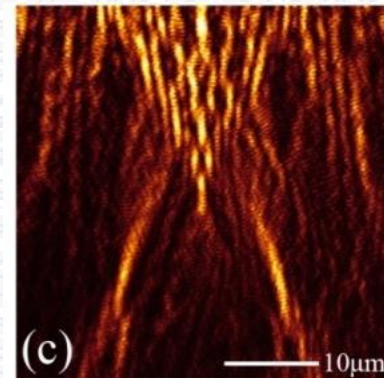
5焦点聚焦实验结果

Appl. Phys. Lett. 94, 111105(2009)

## □ SPP二元光学



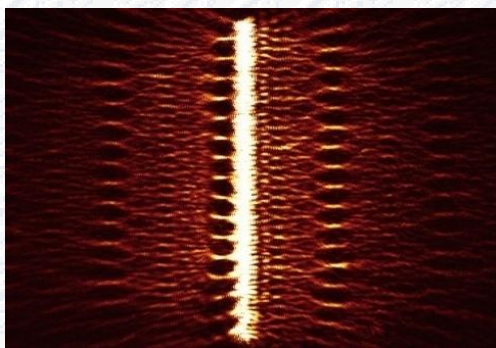
$\Delta x$ : 像素大小  
 $P_1, P_2$ : 离散化相位



不等焦距SPP聚焦

Opt. Lett. 34, 2417 (2009)

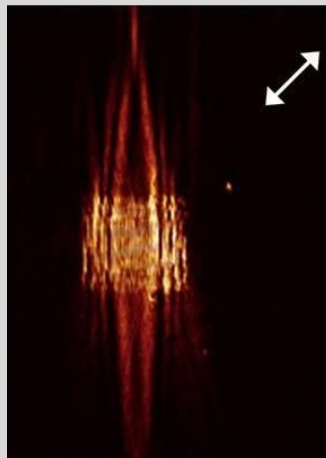
## □ SPP泰伯效应验证



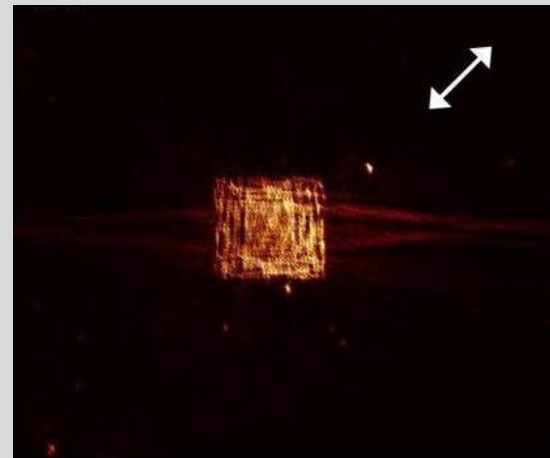
SPP点源阵列

Opt. Express 17, 19757 (2009)

## □ 不同波长SPP分束和聚焦



$\lambda_1 = 809 \text{ nm}$



$\lambda_2 = 873 \text{ nm}$

## 五、总结

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- 利用SPP的共振和场增强可望实现纳米尺度光子学原型器件
- 光信息远距离传输仍然依赖于光纤，因此需要实现光纤和SPP器件之间的联接
- 微米尺度的SPP器件和集成更接近实用化

# 应用上需要解决的问题

- 传输损耗：SPP长程模式、有源介质产生增益
- SPP纳米源：SPP纳米激光器、硅基SPP纳米源
- 原型器件的实现：无源和有源器件
- 器件的集成
- 与传统光集成器件的联接和兼容



谢谢!

張家  
森印