



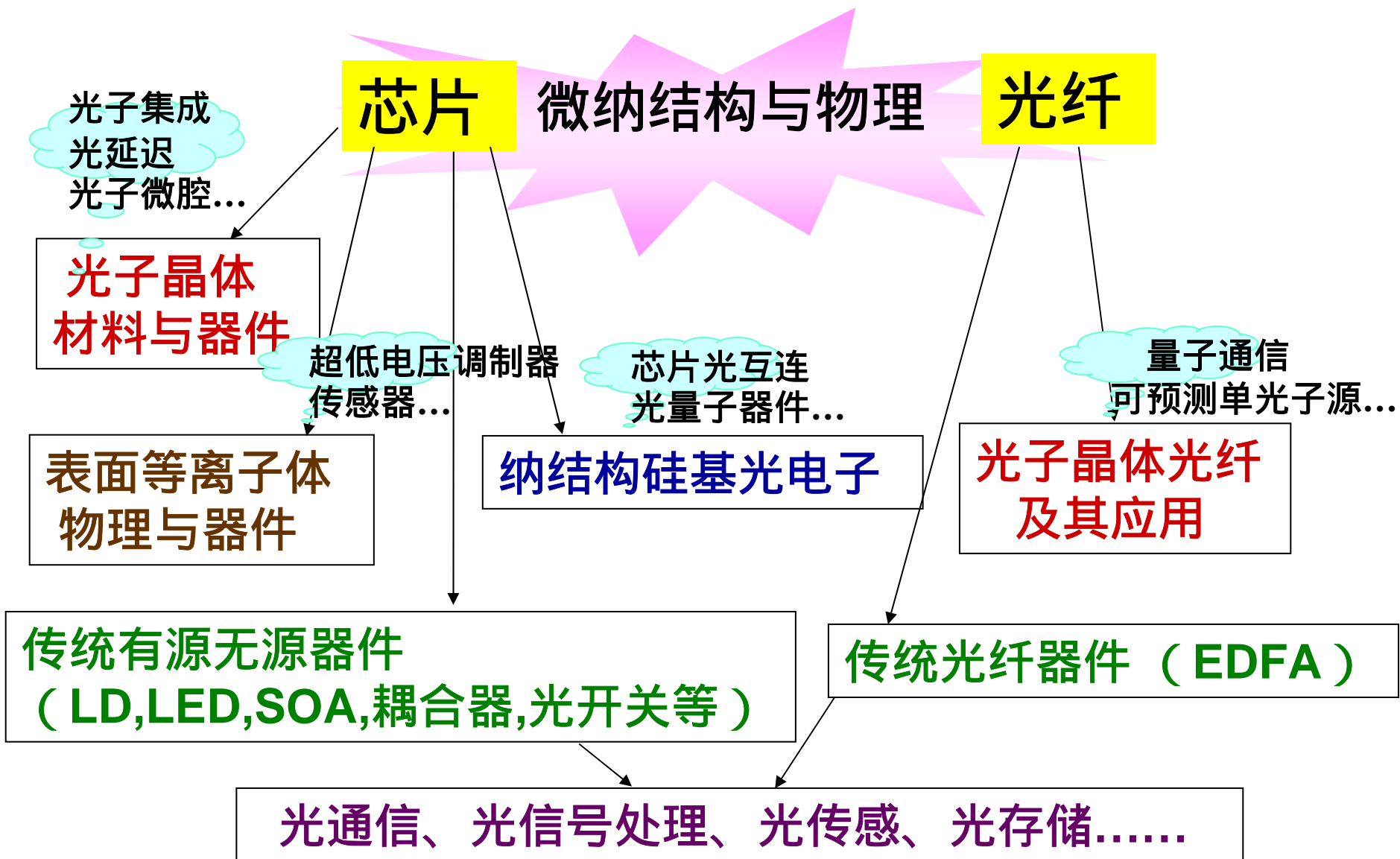
# 纳结构光电子器件

*Research on Nano-Optoelectronics*

清华大学 电子工程系 黄翊东



# 纳结构光电子器件



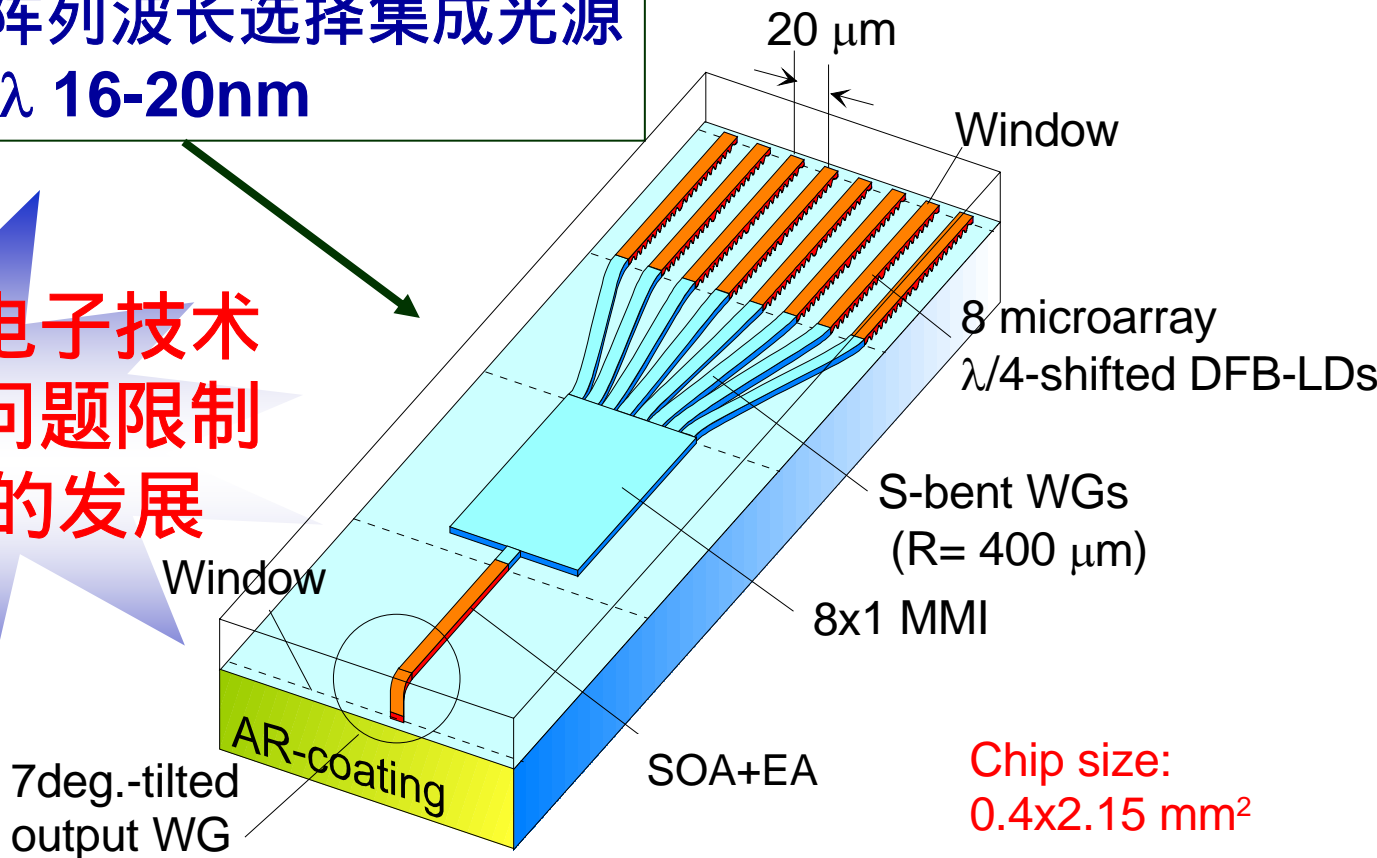
光电子器件技术突破期待着

新材料、新原理、新技术的出现

已经产品化的8阵列波长选择集成光源

$\Delta\lambda$  16-20nm

传统的集成光电子技术  
所不能解决的问题限制  
了光电子器件的发展



# 微纳结构与物理

## 芯片

## 光纤

光子集成  
光延迟  
光子微腔...

光子晶体  
材料与器件

超低电压调制器  
传感器...

芯片光互连  
光量子器件...

量子通信  
可预测单光子源...

表面等离子体  
物理与器件

纳结构硅基光电子

光子晶体光纤  
及其应用

传统有源无源器件  
(LD,LED,SOA,耦合器,光开关等)

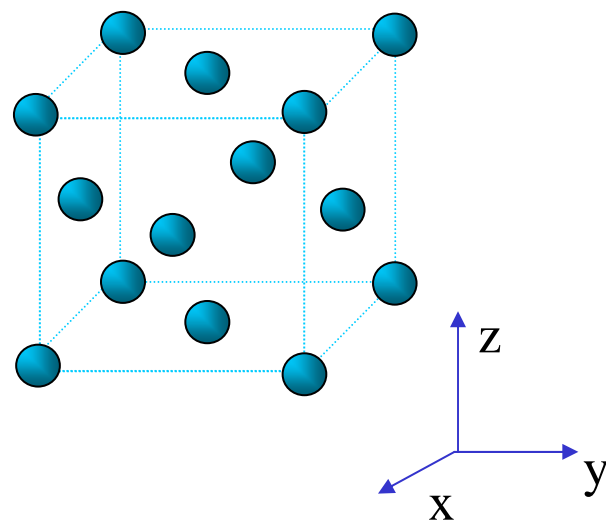
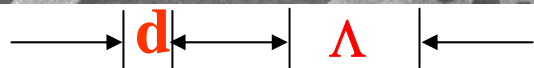
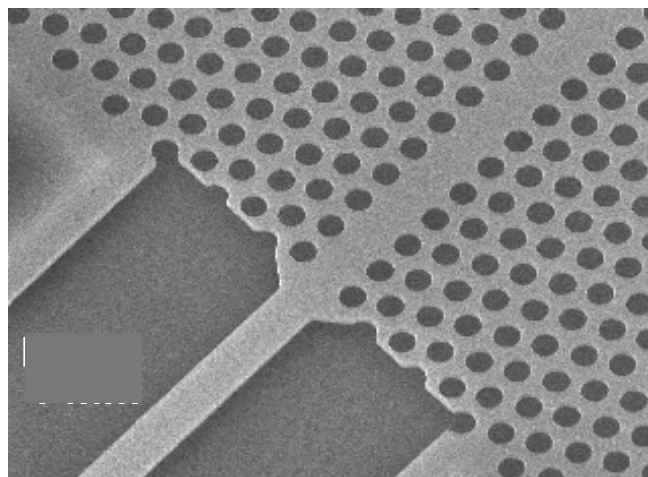
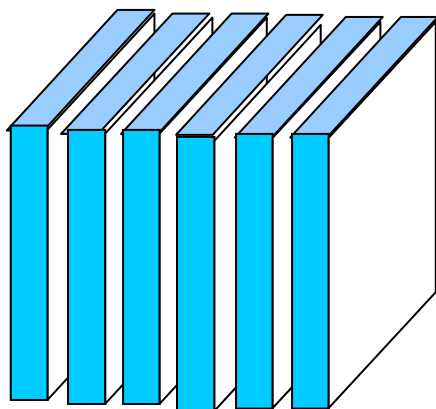
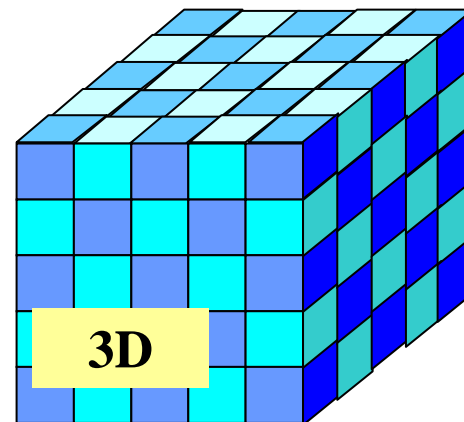
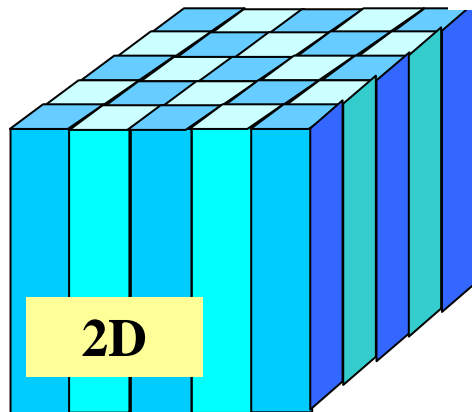
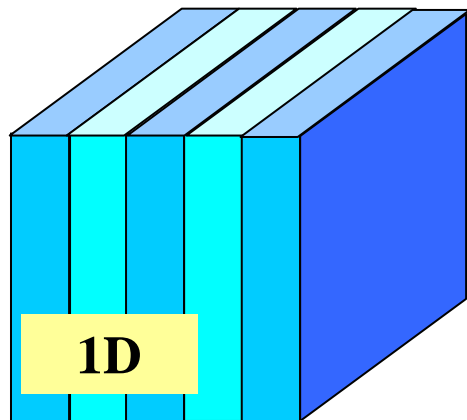
EDFA

光通信、光信号处理、光传感、光存储.....

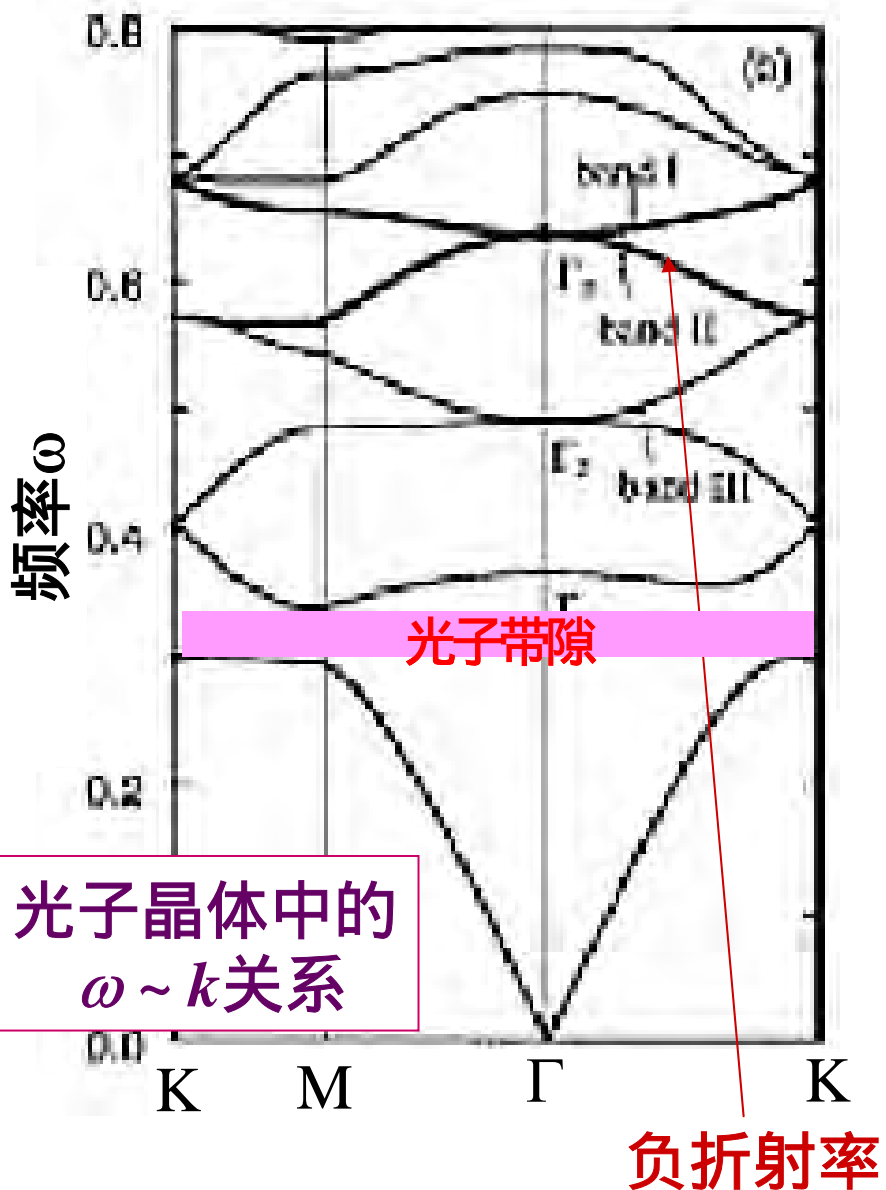
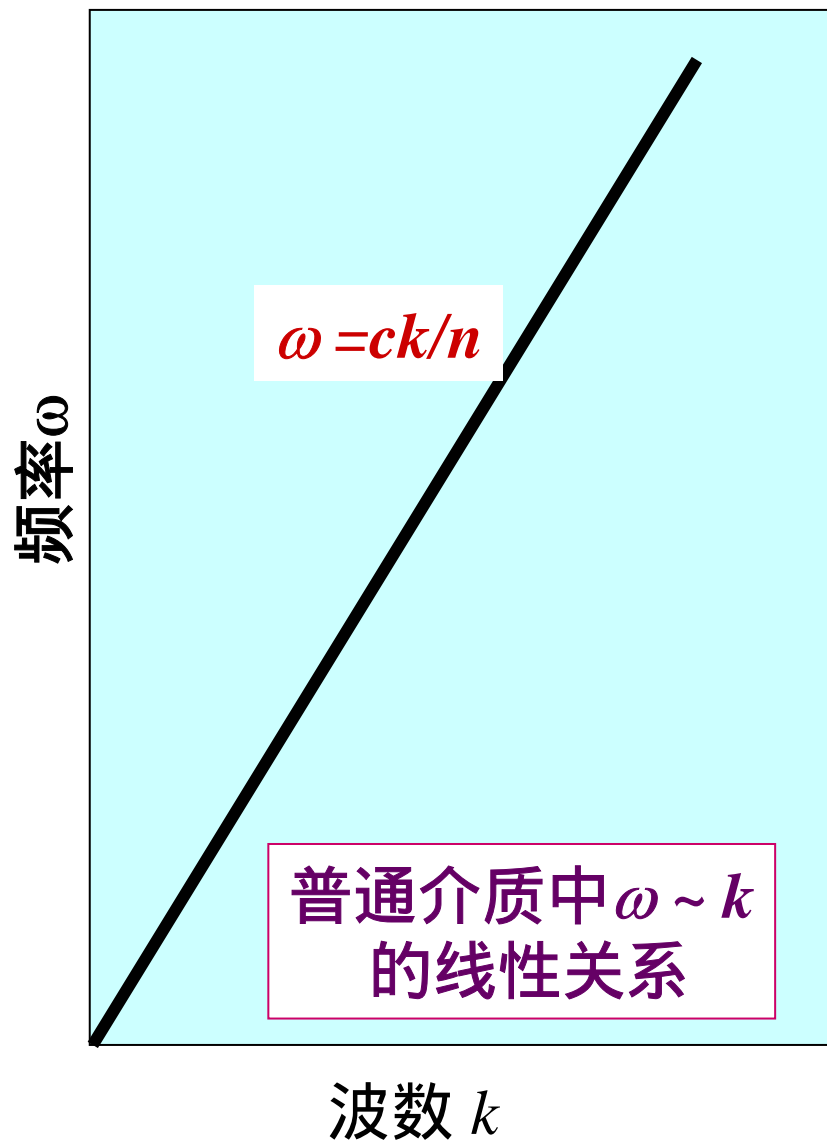


# 光子晶体

- 由介电常数不同的介质材料在空间周期性排列而构成, 变化周期为**波长量级**



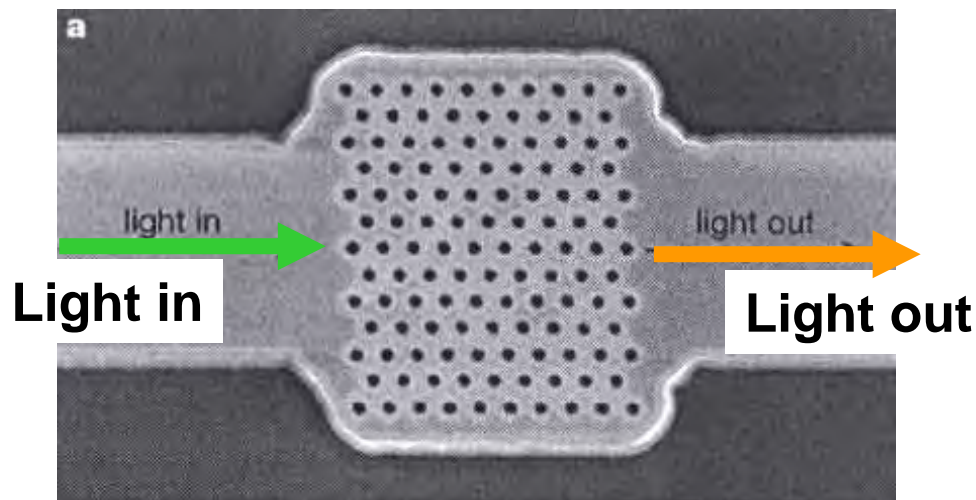
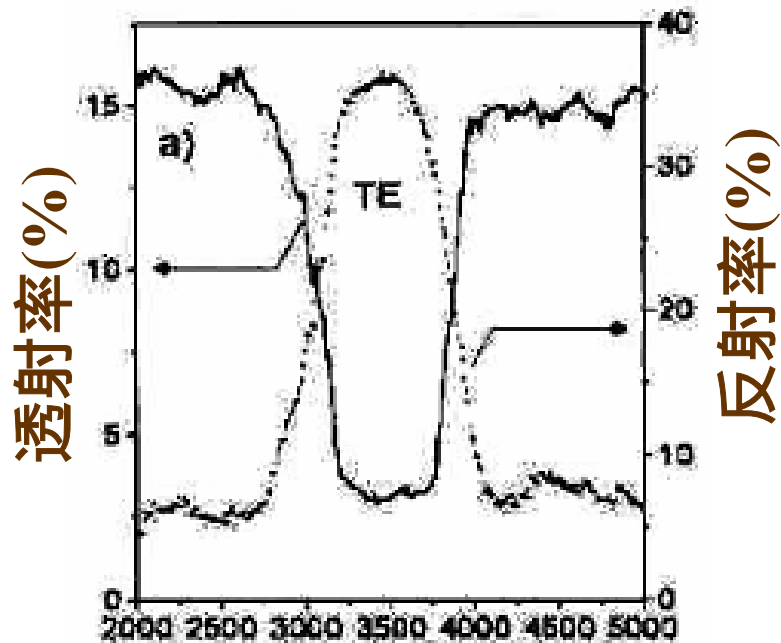
# 光子晶体的光带结构图



# 光子带隙限制作用

## 光子带隙

- 禁止频率落在带隙内的光传播
- 抑制频率落在带隙内的原子和分子的自发辐射



# 带隙材料-光子晶体

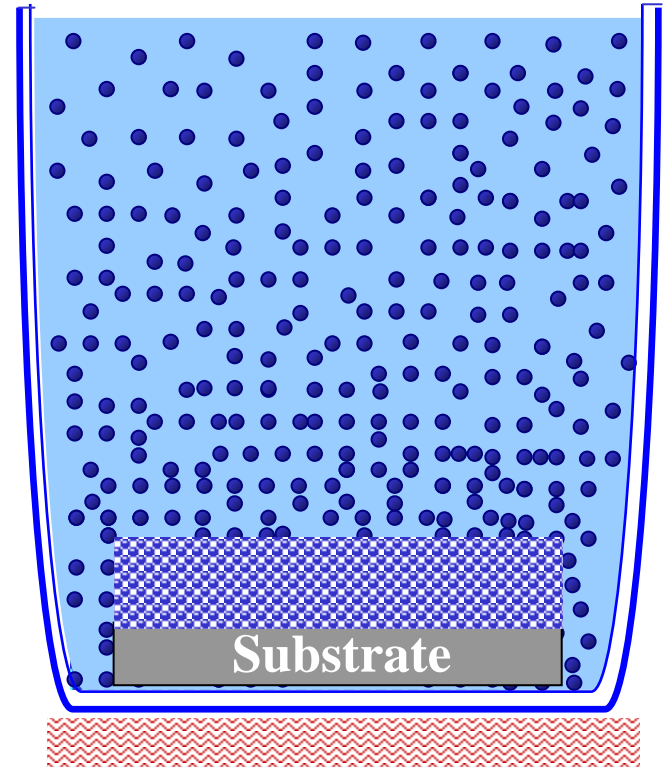
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- 1987年 E.Yablonoitch和 S.John 各自独立提出“光子晶体”的概念 ( [Phys.Rev.Lett,1987,58,2059](#) )  
( [Phys.Rev.Lett,1987,58,2486](#) )
- 1990年 K.M.Ho 首先从理论上提出了光子晶体的可行性结构 ( [Phys.Rev.Lett,1990,65,3152](#) )
- 1991年 E.Yablonovit 制做了第一个具有光子禁带的光子晶体 ( [Phys.Rev.Lett,1991,67,2259](#) )
- 1999年初被Science 杂志评为年度十大科技成就之一 ( [Science, Dec.17,1999,pp.2239-2243](#) )
- 近年来,在《自然》《科学》杂志上已有数十篇论文发表,国外每年发表数百篇有关光子晶体的论文

# 三维光子晶体的实验研制

## 自组装机

- 聚合物分子溶液，聚合物分子在溶液里就自我组成中空的球体，数十亿的球体以一种精确而有序的方式聚集在一起，最后形成更大的结构。
- 把胶体颗粒（如硅土颗粒）悬浮在液体中。经过一段时间，悬浮的胶体颗粒会从无序的结构相变成有序的面心立方结构而形成胶体晶体。
- 胶体晶体的空隙可以填充各种无机或有机物，将胶体颗粒去除就能得到空气孔结构的光子晶体。

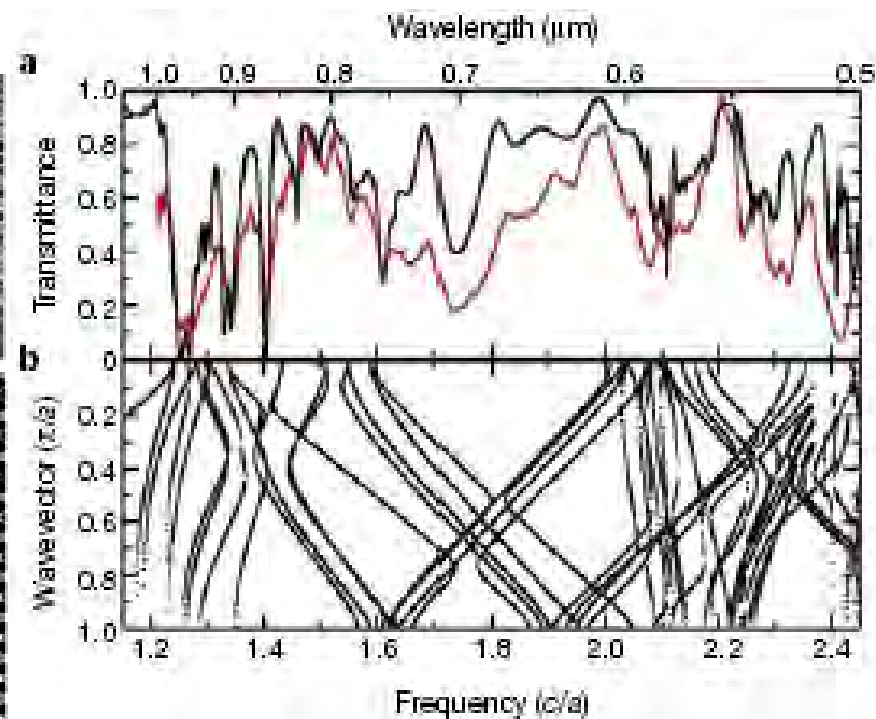
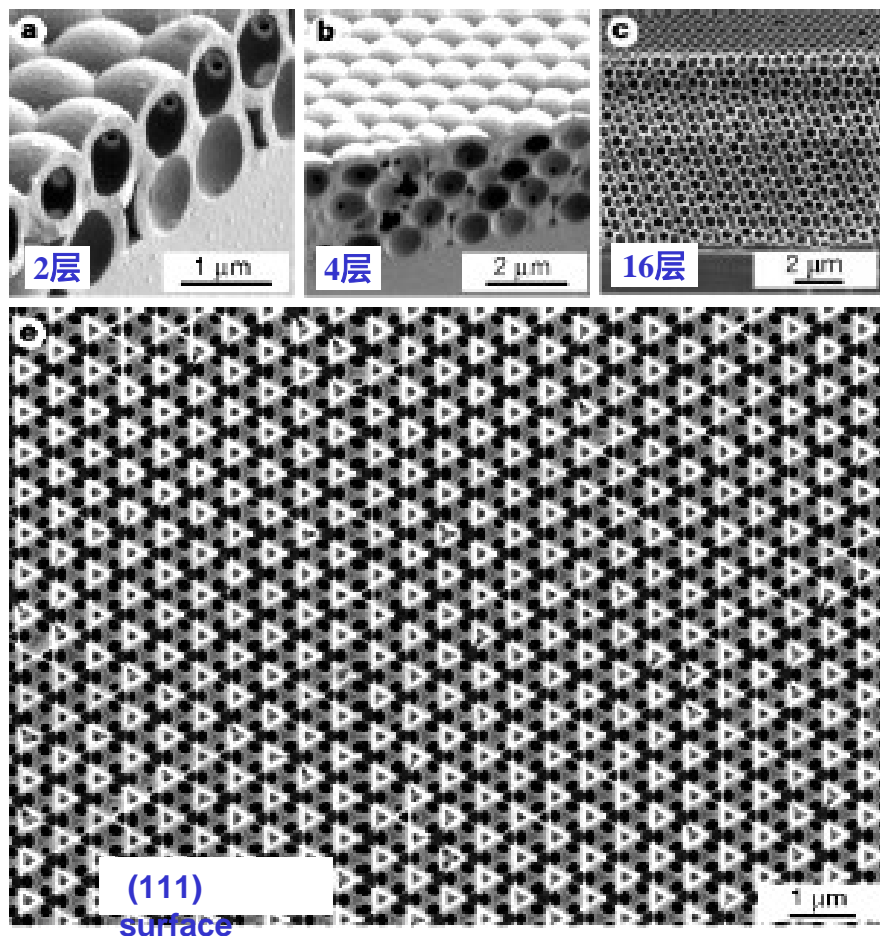


介电常数比较小而禁带窄小

H. Miguez, et.al., "Photonic crystal properties of packed submicrometric  $\text{SiO}_2$  spheres", *APL*, 1997, 7:1148-1150

# 三维光子晶体的实验研制

## 胶体粒子自组装法 (Sol-gel)



空气球大小 : (a, b): 1 $\mu\text{m}$ ,  
(c, e): 670nm

a. 透射谱 : — 理论  
— 实验

b. 理论计算的光子能带

# 纳米激光加工

## 双光子吸收光聚合

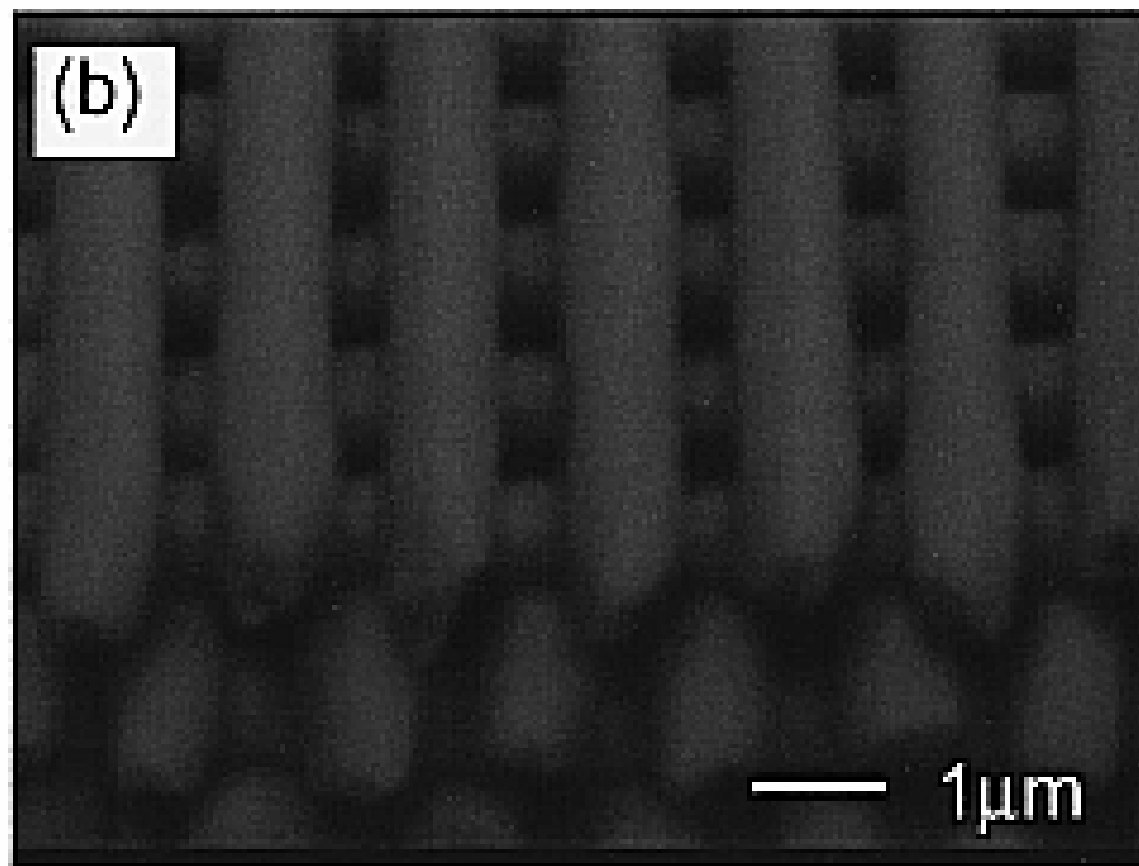
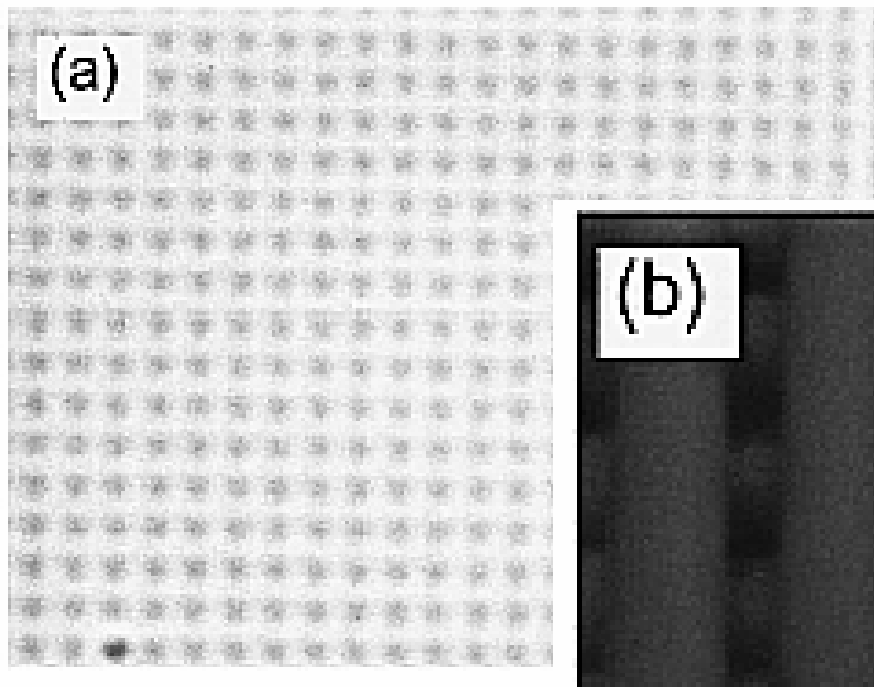


**纳米牛**  
(体长 $10\mu\text{m}$ )

将近红外飞秒激光脉冲聚焦于光聚合性树脂。树脂的吸收在紫外和蓝光波段，光聚合或光固化反应只能通过双光子吸收并且被局域于激光焦点的微小体积内。在树脂内根据预先编制的CAD三维图样扫描，可以制备任意三维器件结构

波长： $800\rightarrow 400\text{nm}$   
脉冲： $5\text{KHz}, 130\text{fs}$   
分辨率： $120\text{nm}$

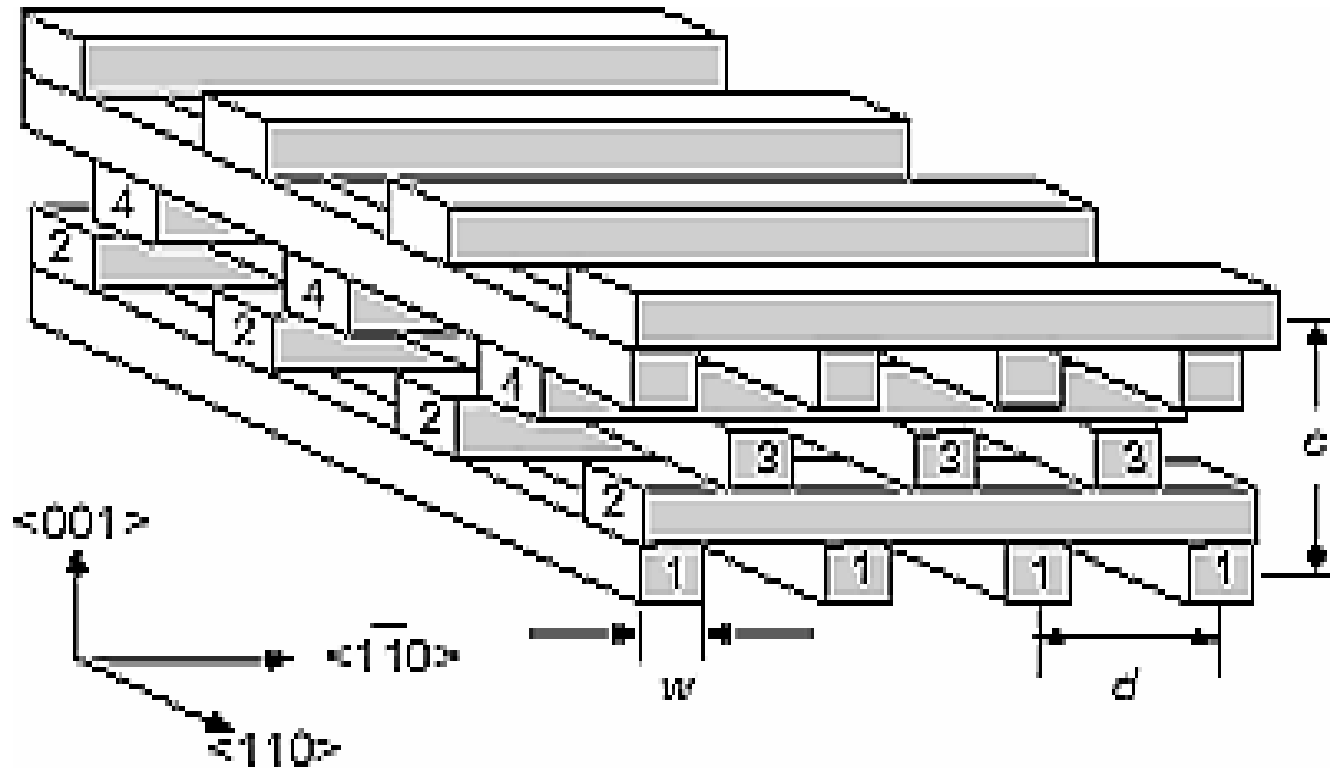
# 纳米激光加工





# 三维光子晶体的实验研制

## 3D PC 的基板融接制作法—积木法

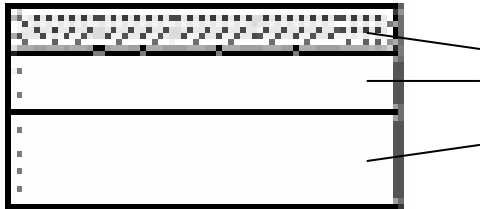


调整 $w, d, c$ , 光子禁带从远红外至 $1.35-1.95\mu\text{m}$ .

S. Y. Lin, et.al., "A three-dimensional photonic crystal operating at infrared wavelengths", *NATURE*, 1998, 394(16):251- 253

# 三维光子晶体的实验研制

## 3D PC 的基板融接制作法

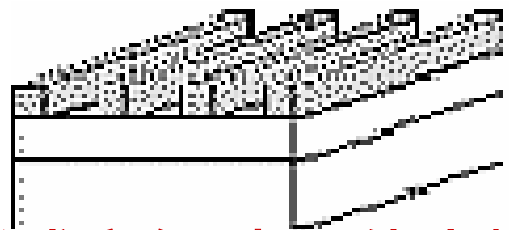


GaAs(or InP)  
AlGaAs(or InGaAsP)  
GaAs (or InP) SUB.

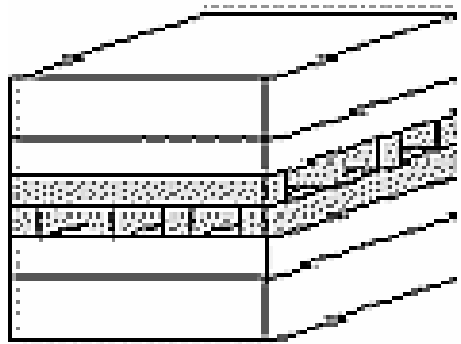
结晶生长



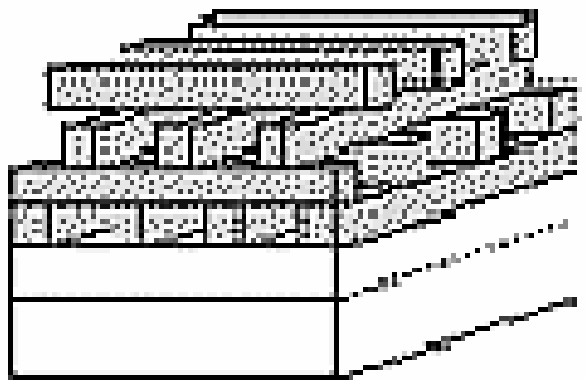
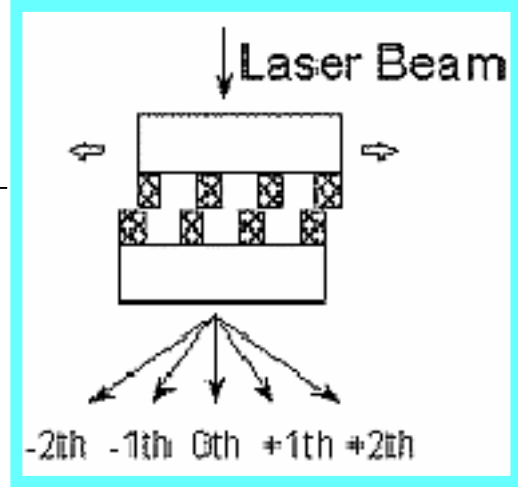
除去上层衬底



形成空气/半导体光栅



Wafer融接

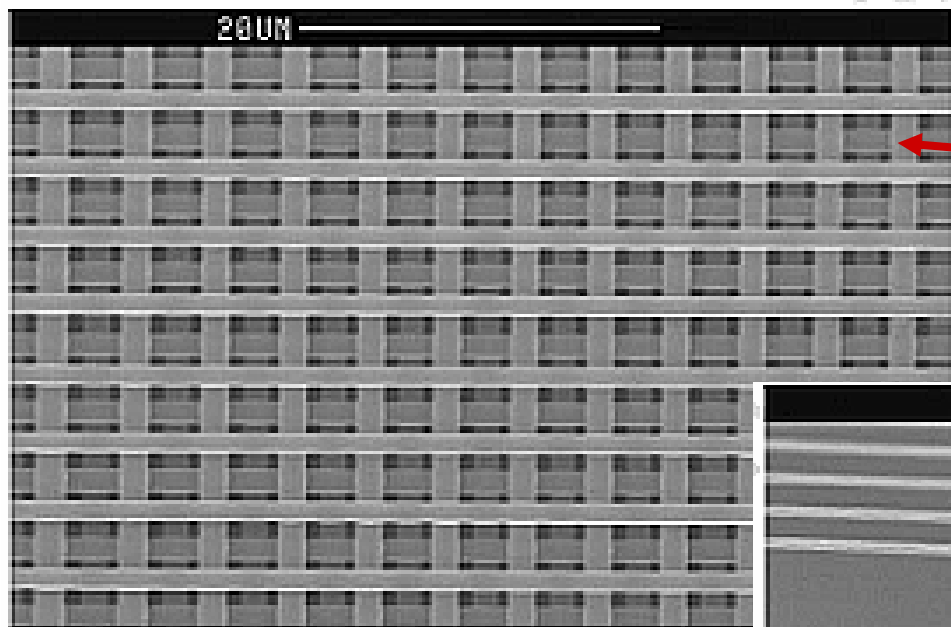


重复上述操作  
实现积木结构

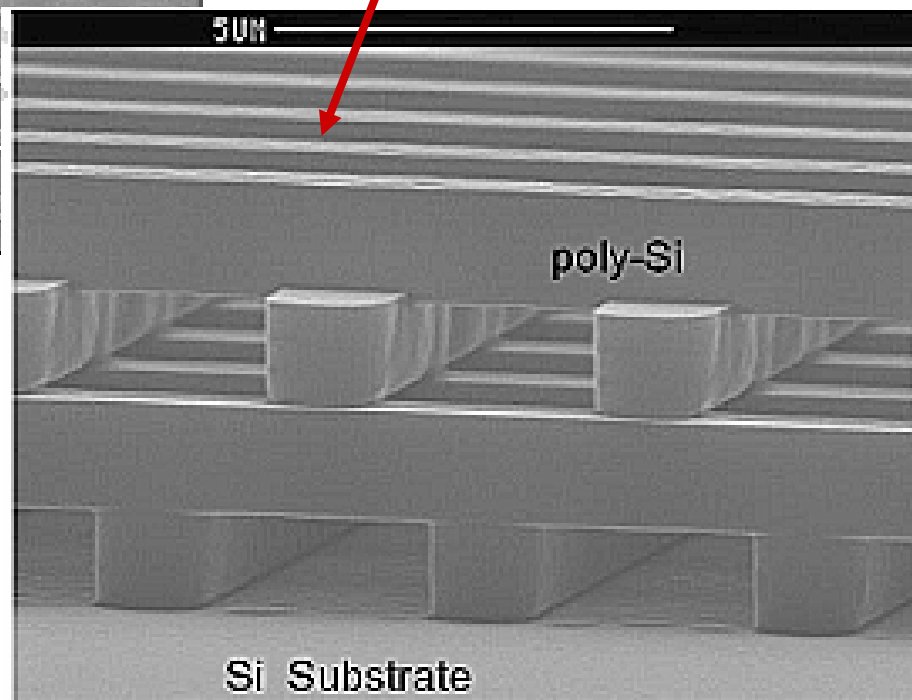
# 三维光子晶体的实验研制

## 3D PC 的基板融接制作法

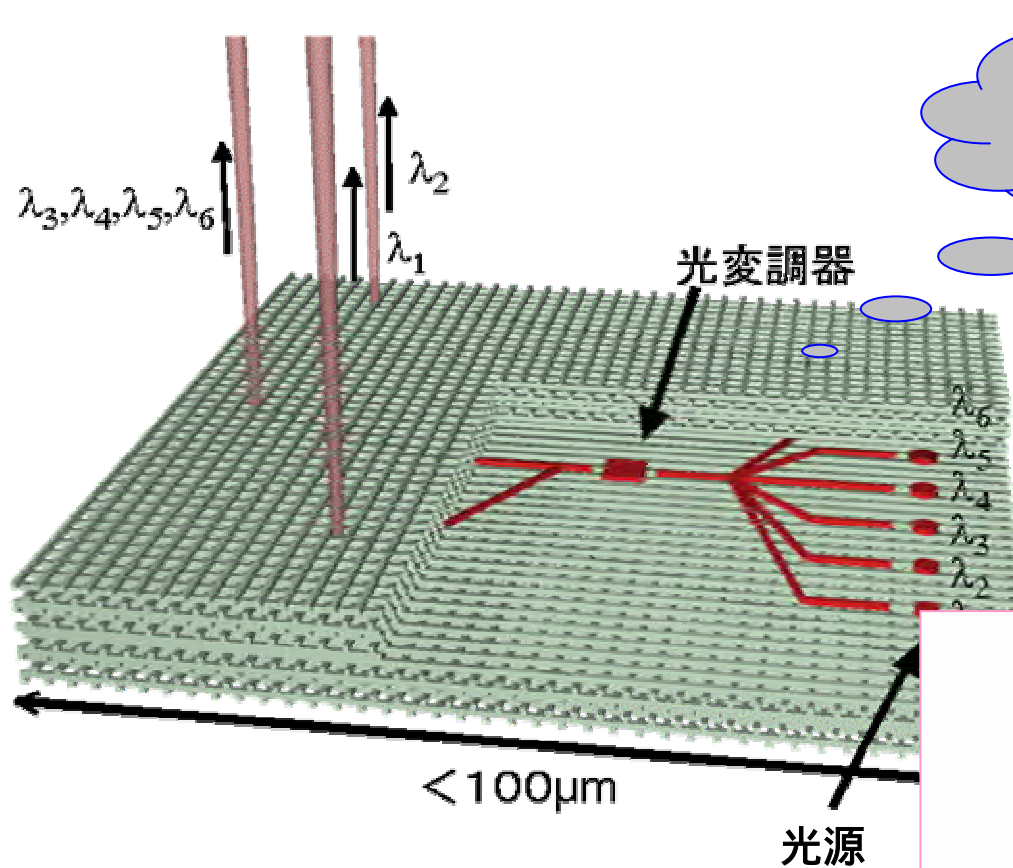
实际制作的三维光子晶体



SEM写真

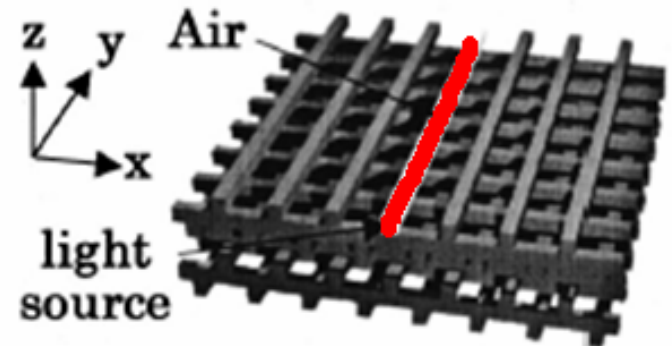


# 三维光子晶体集成光器件



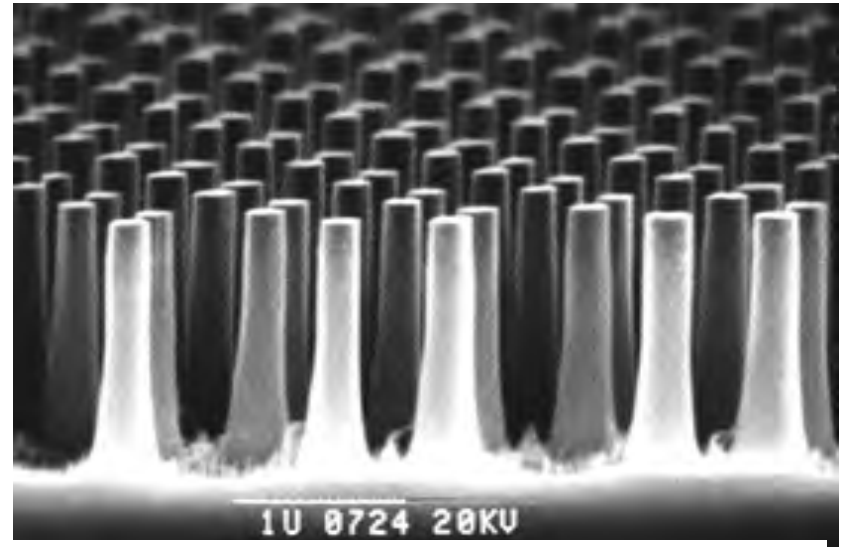
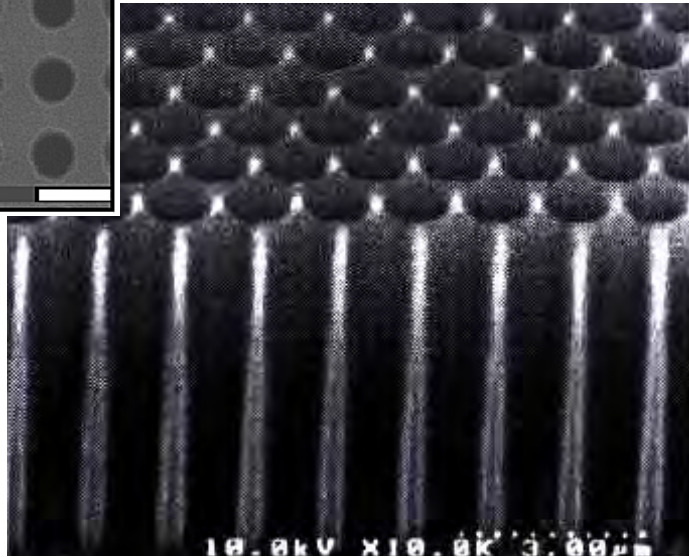
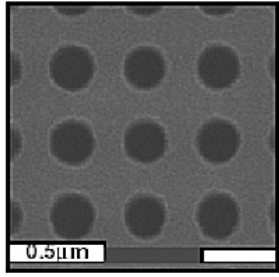
集成光子回路构想图

积木法制作的三维PC



# 二维平板光子晶体

## 研究光子集成的材料平台



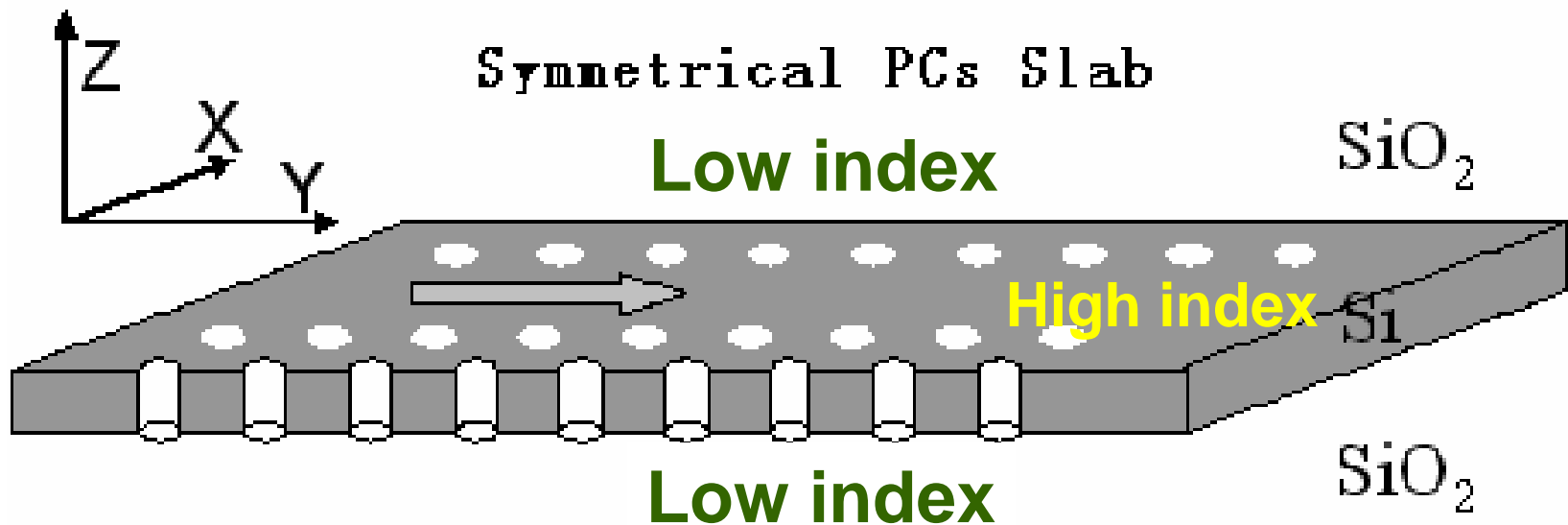
/工艺实现切实可行

/适合平面集成及各种缺陷或发光物质的引入

/便于实现光子集成芯片所必需的电注入结构

/未来三维光子晶体集成芯片的基础结构单元

# 2D Slab Photonic Crystal

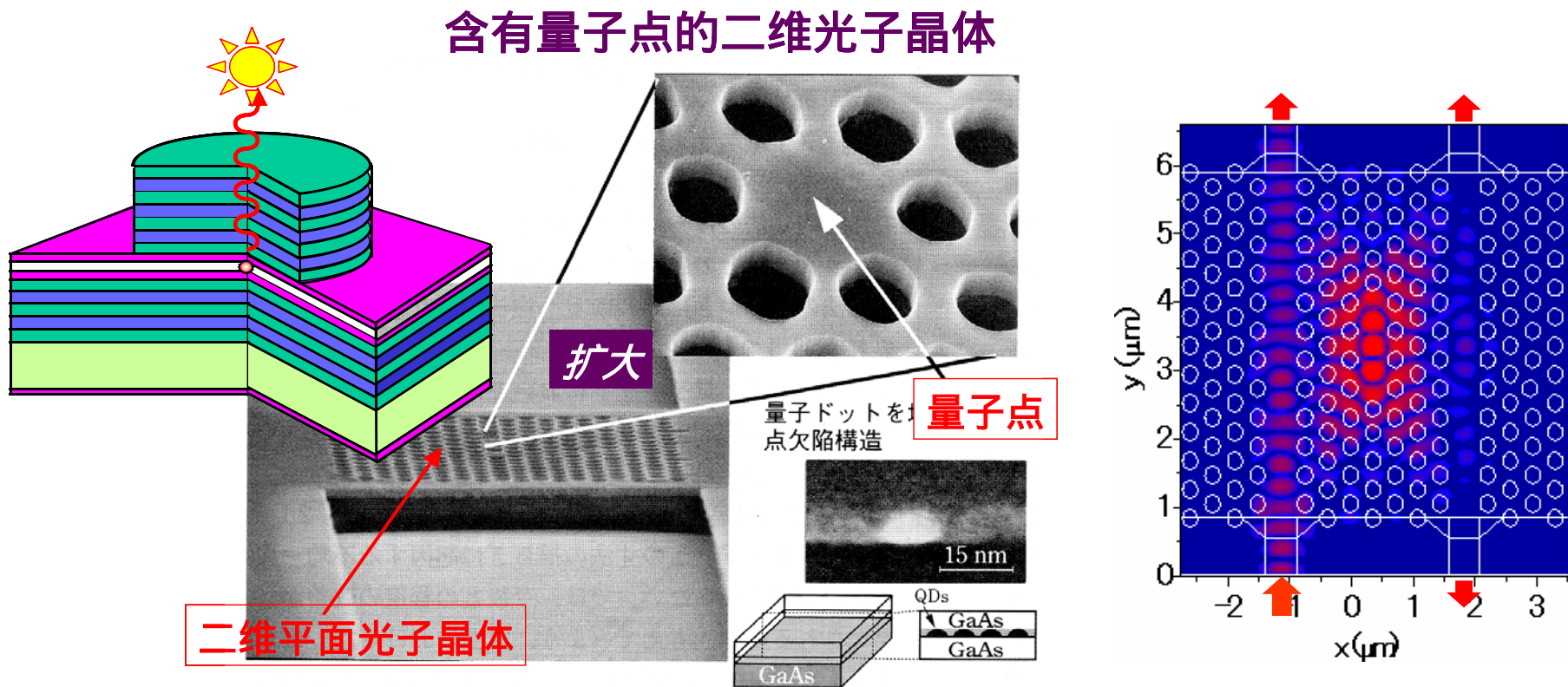


**in-plane band-gaps provided by 2D PC  
also show their potential for applications**

# 光子晶体材料与器件

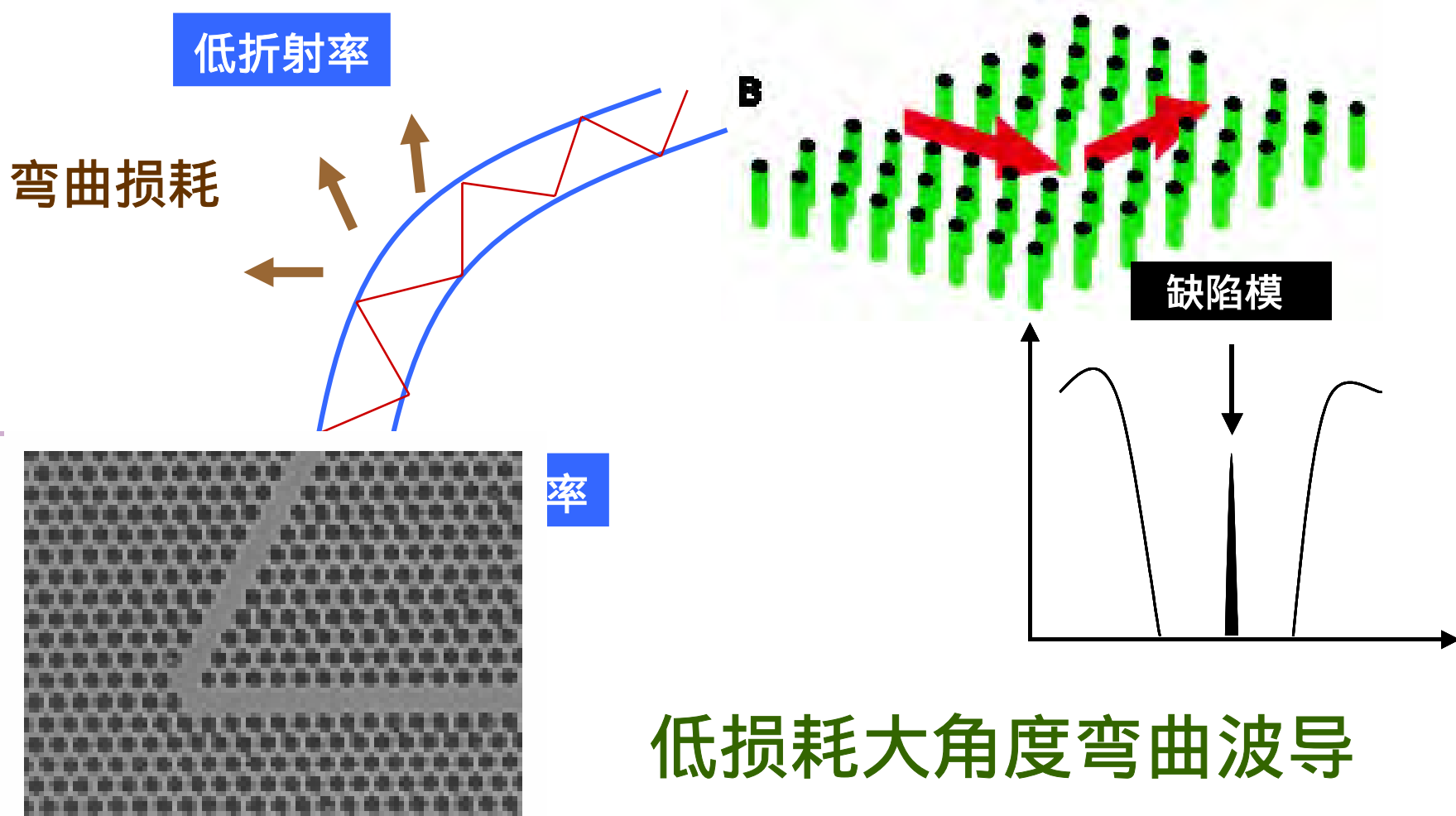
## 光子微腔效应-单光子源

## 双光子纠缠对



基于光子晶体材料的单体器件将具有新的功能及特性

# 光子晶体器件及其集成技术



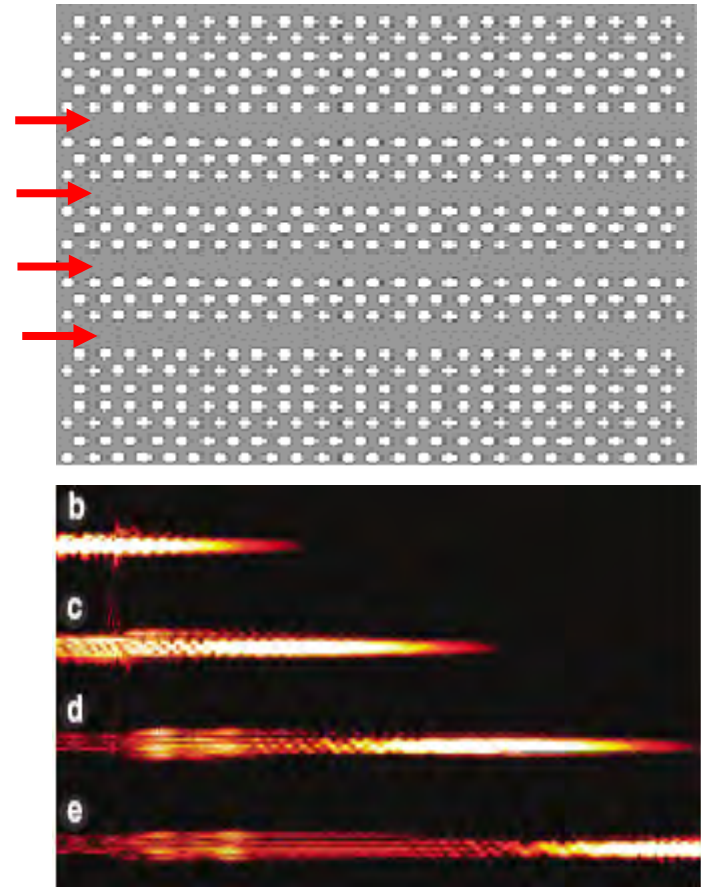
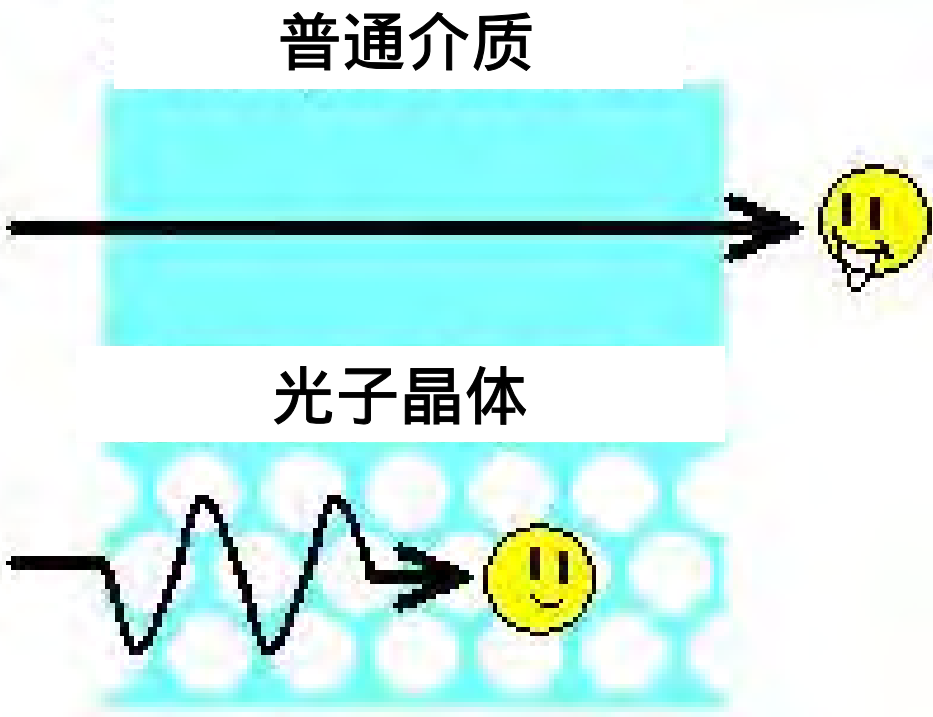
光子晶体材料集成器件将实现微纳尺度的超小型化



# 光子晶体材料与器件

## 光群速度调控

## 可集成光真时延迟器



基于光子晶体材料的单体器件将具有新的功能及特性

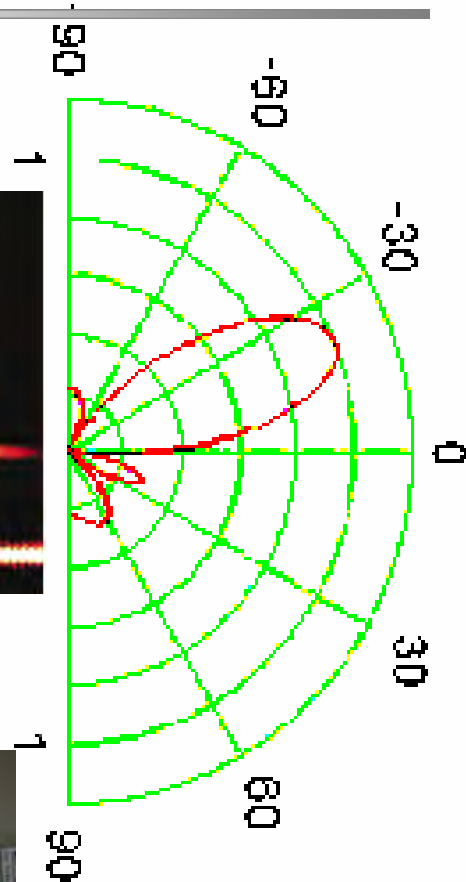
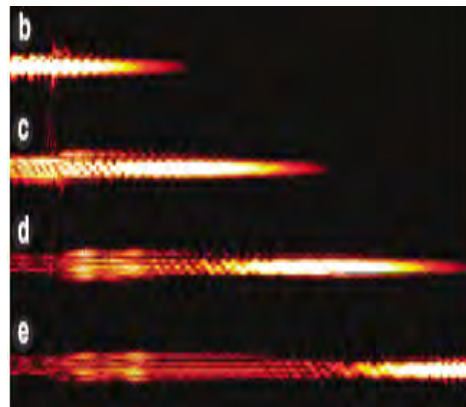
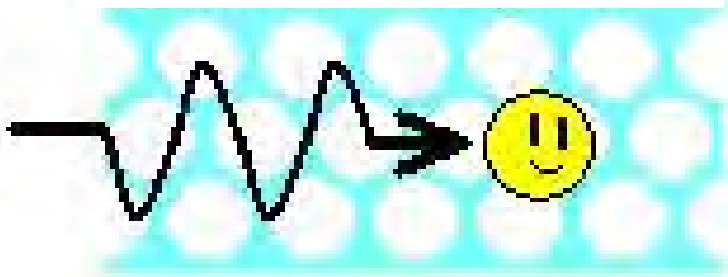
# 新型光电子器件

## 光群速度调控

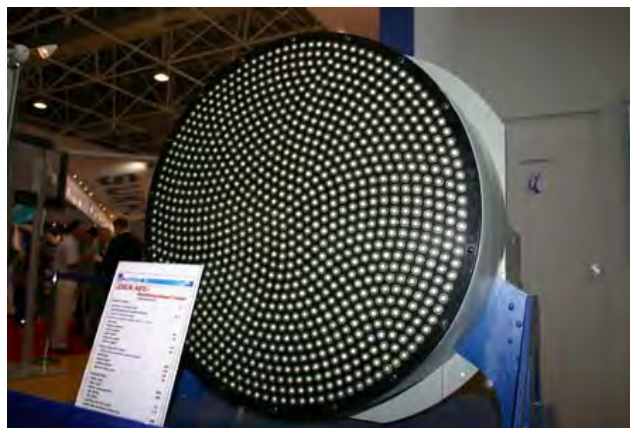
普通介质



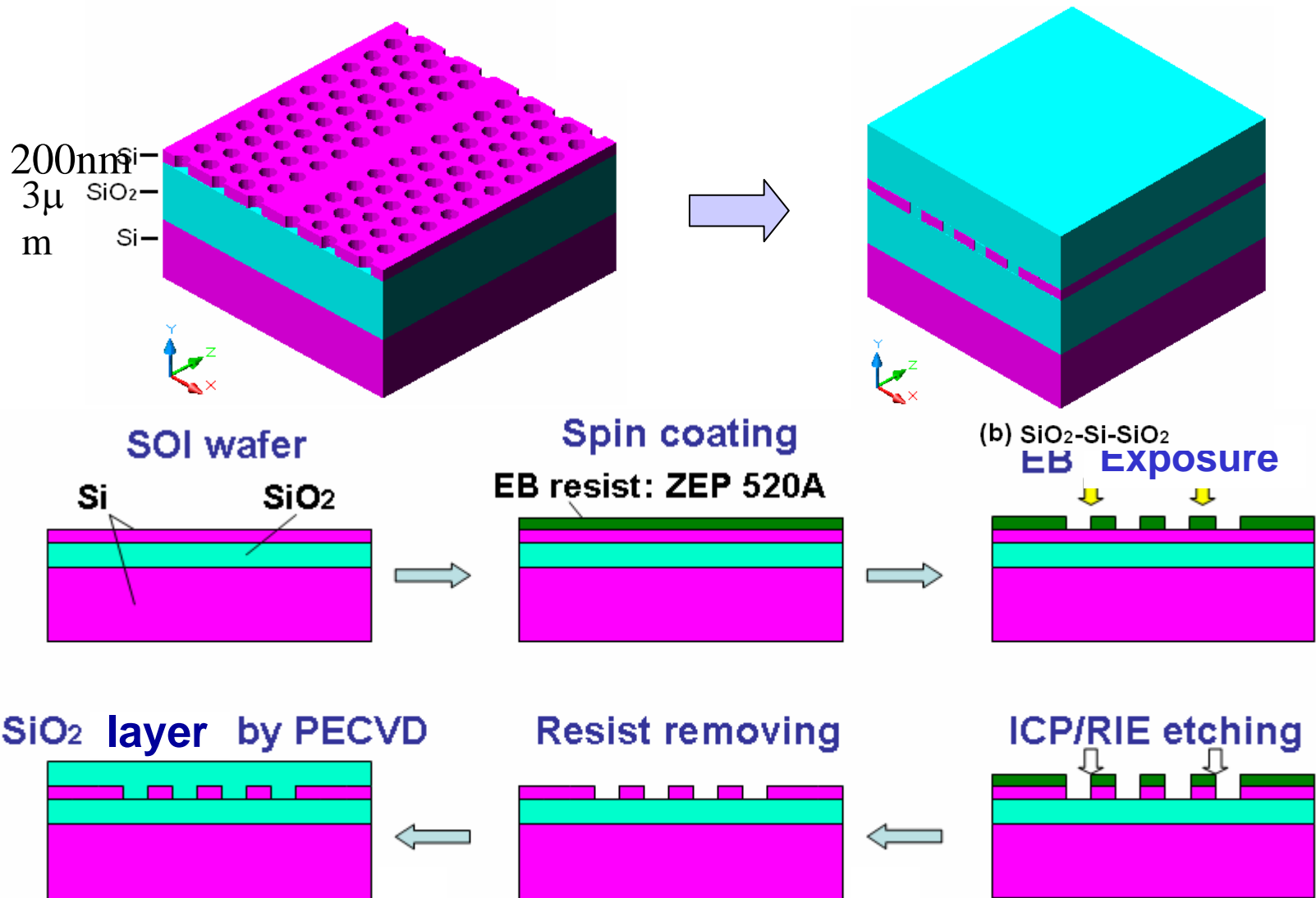
光子晶体



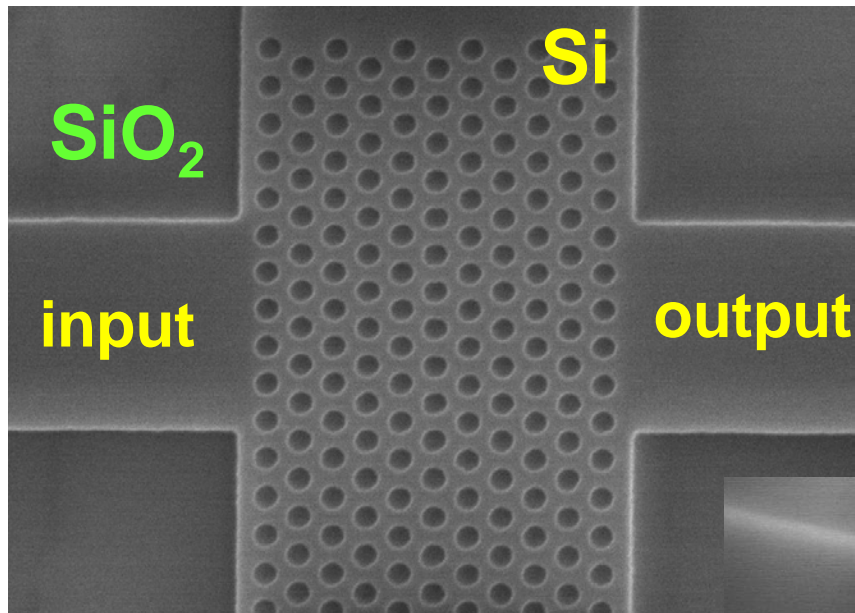
## 相控阵雷达



# 光子晶体慢光波导的制作



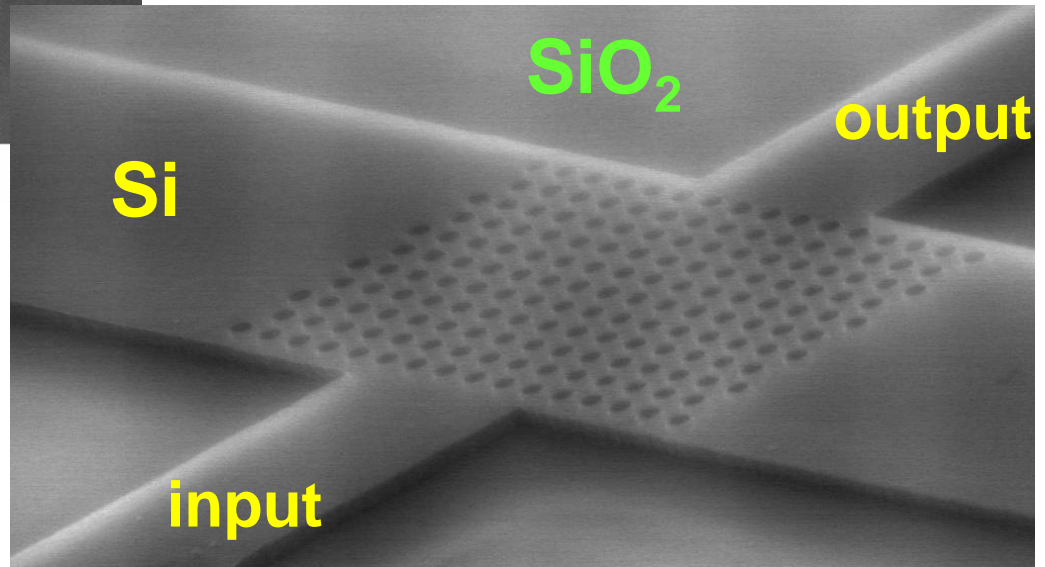
# 实现了二维平板光子晶体



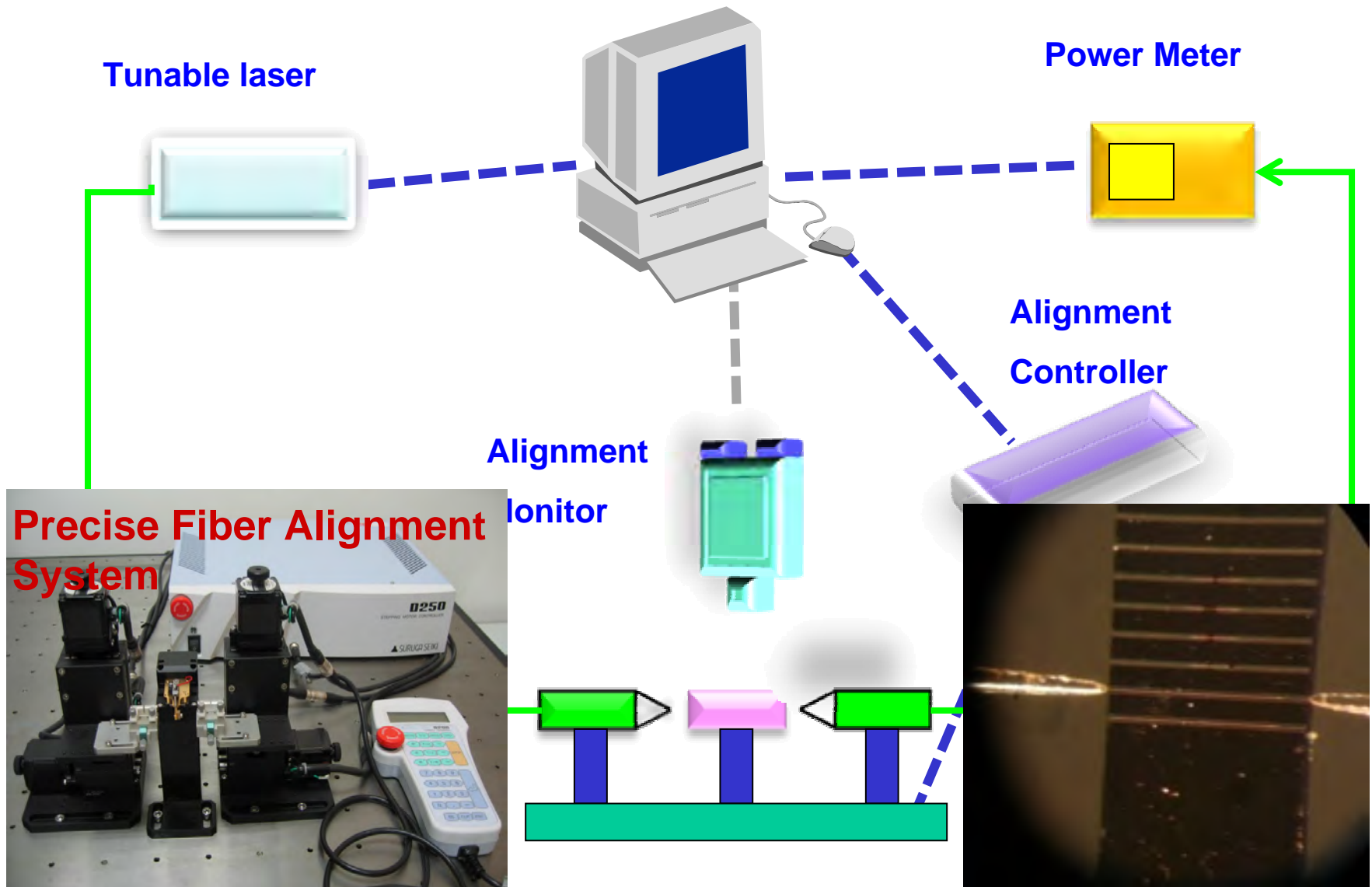
11 periods

4 $\mu$ m

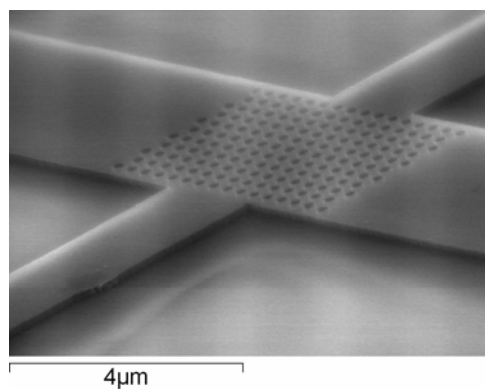
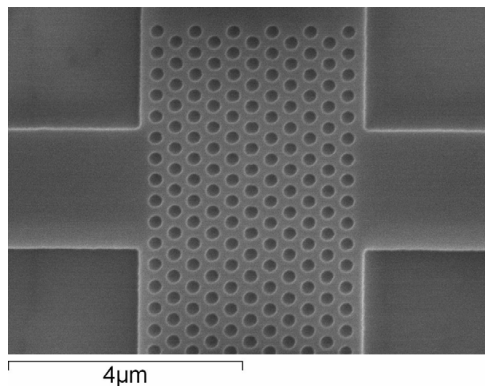
**2D PC with**  
**r=90nm**  
**a=340nm**  
**@SOI structure**



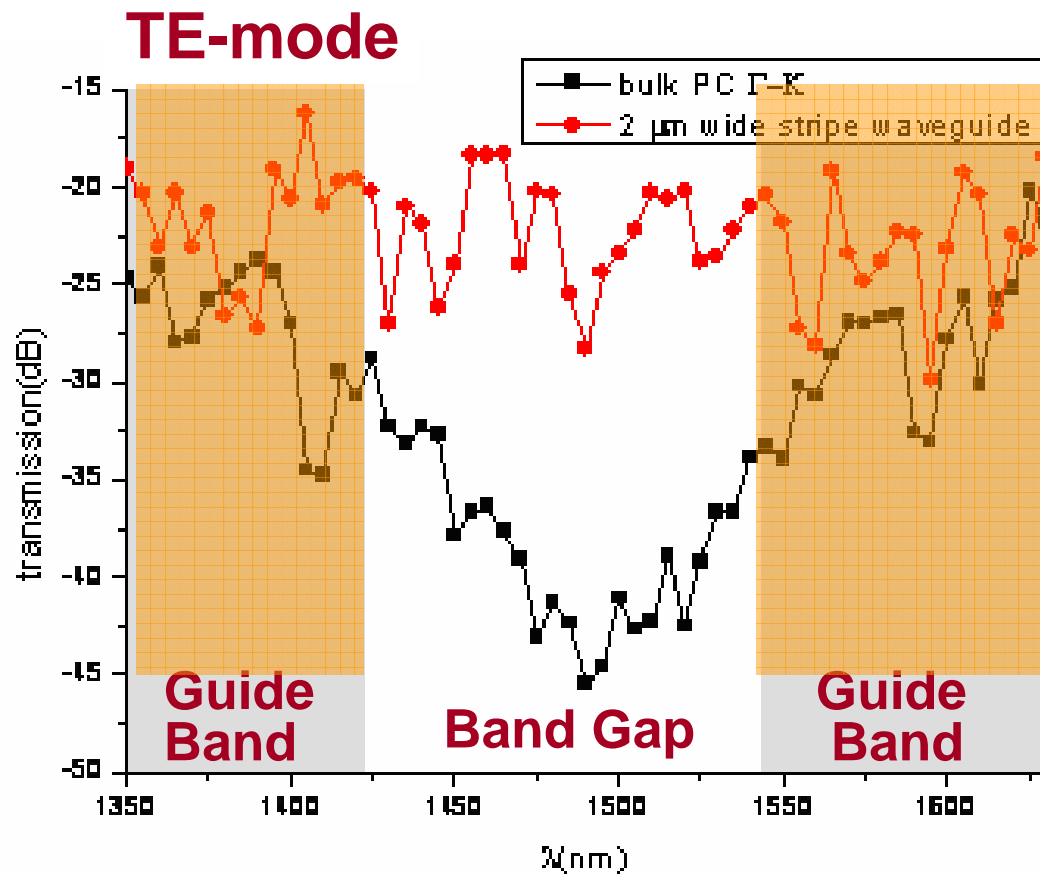
# Measurement System



# 实验确认带隙在 $1.55\mu\text{m}$ 波段



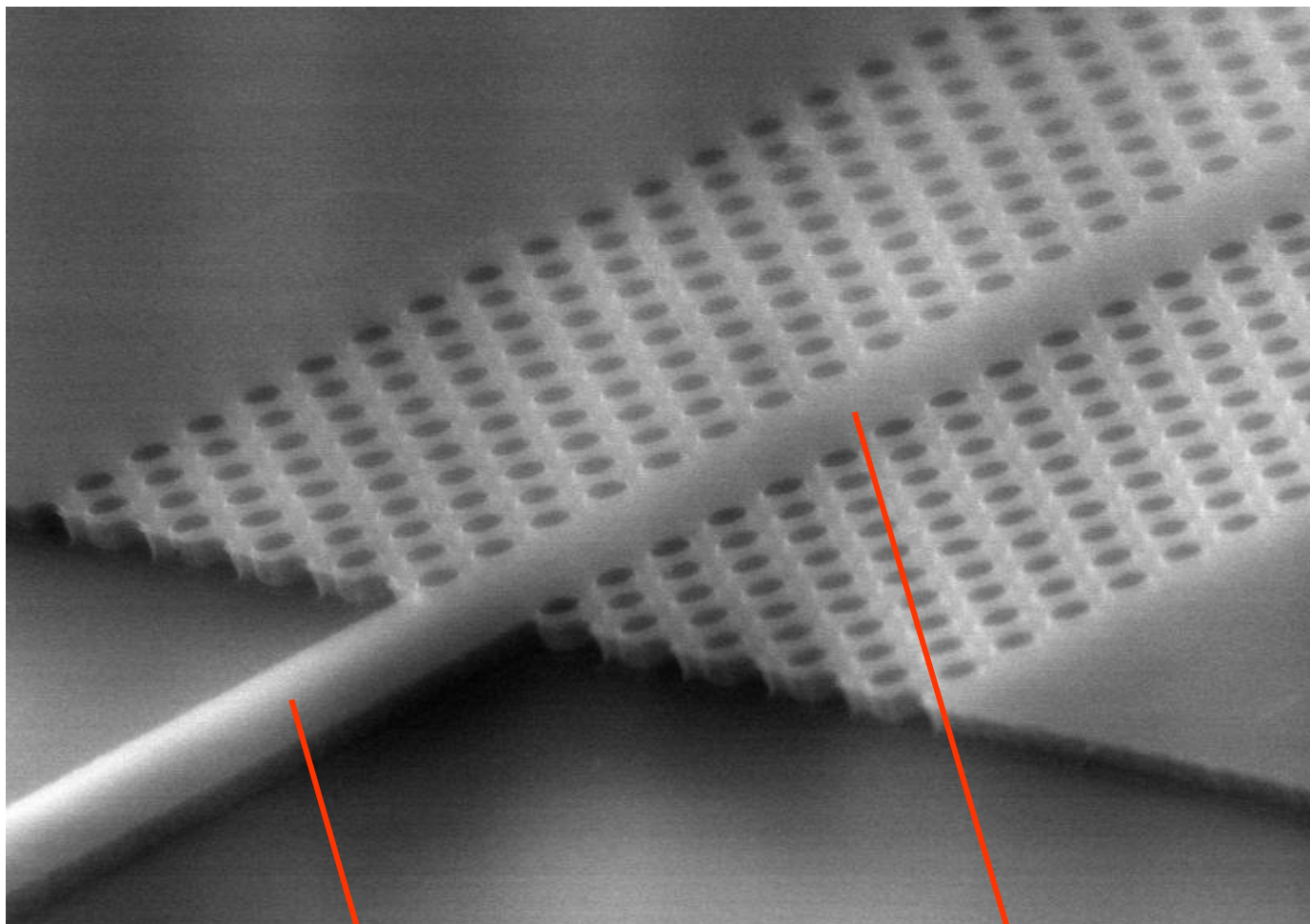
2D PC with  
 $r=90\text{nm}$   
 $a=340\text{nm}$   
@SOI structure



- Normalized transmission for TE polarization @1550nm
- Shade area represents simulation result, the measurement results fit it well



# 研制出光子晶体慢光波导

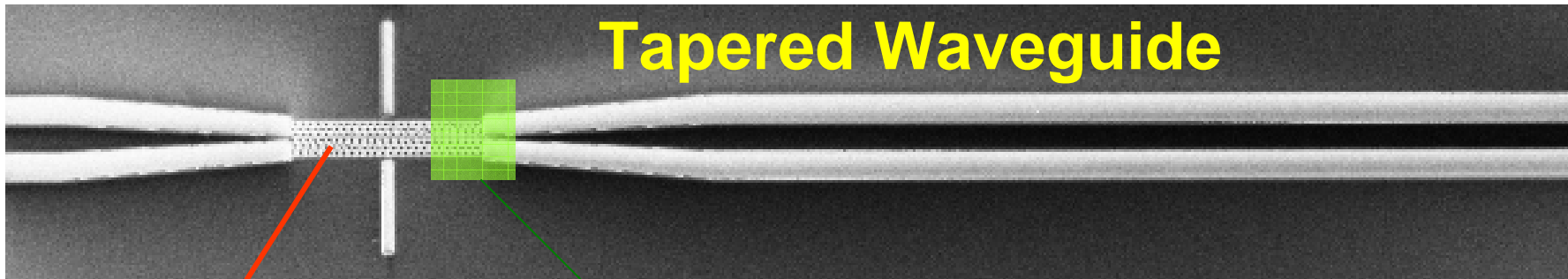


接续波导

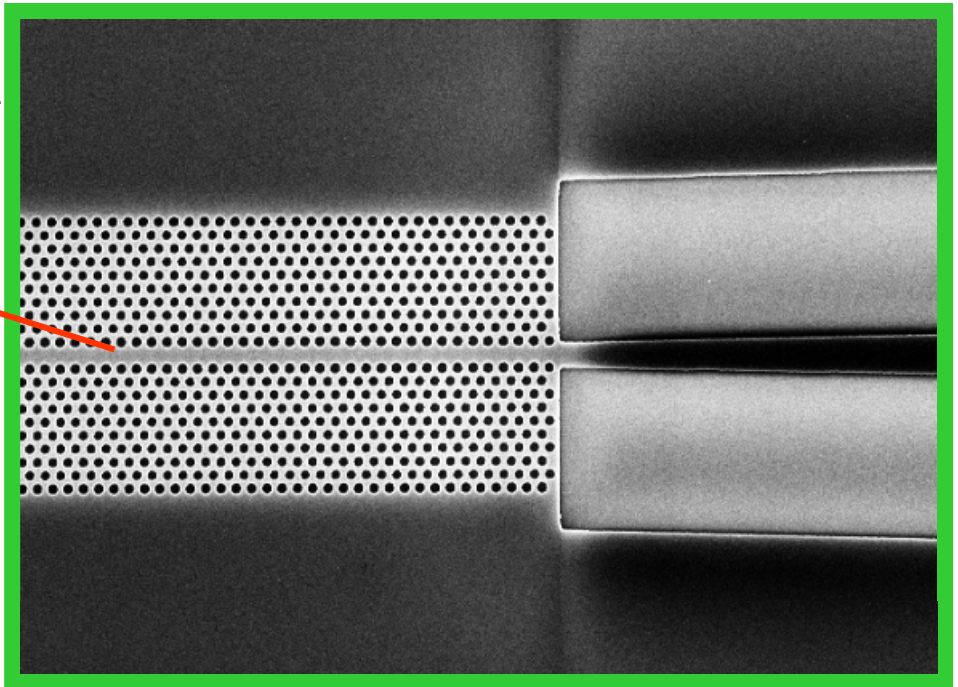
线缺陷带隙限制波导

# Photonic Crystal Waveguide

To Reduce Coupling Loss



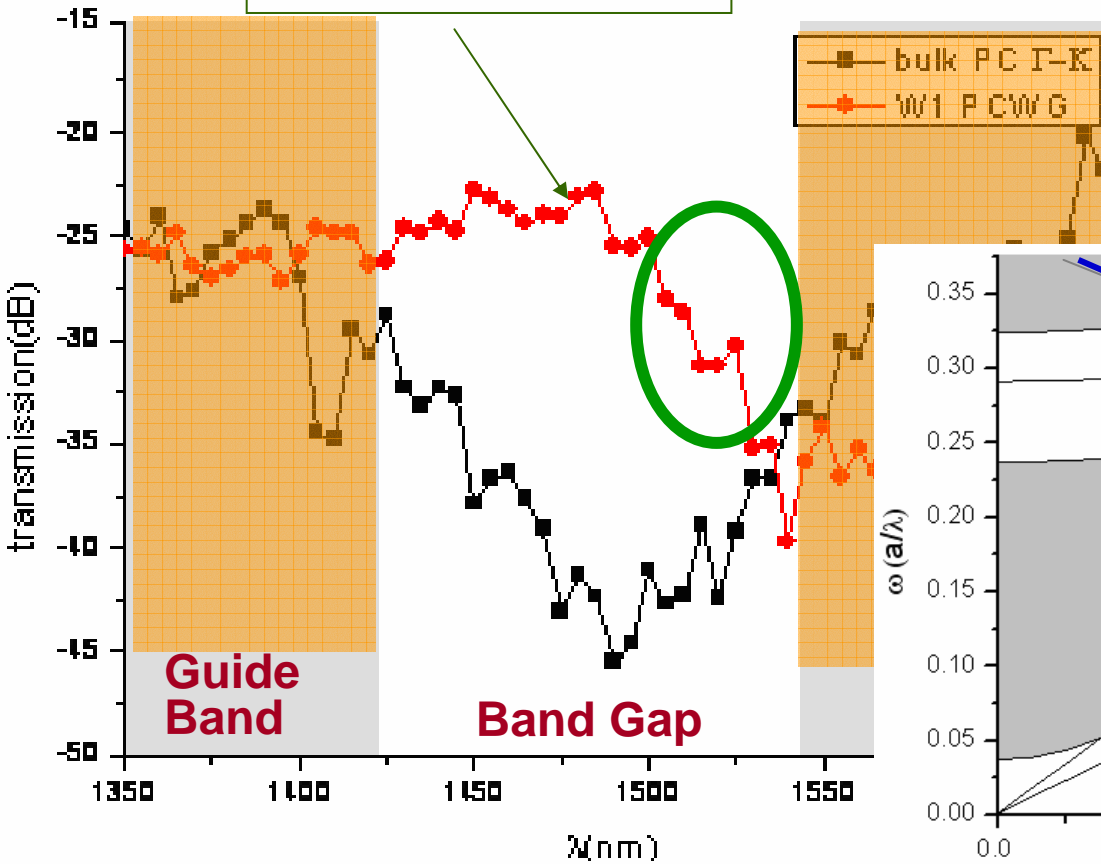
PC-Waveguide





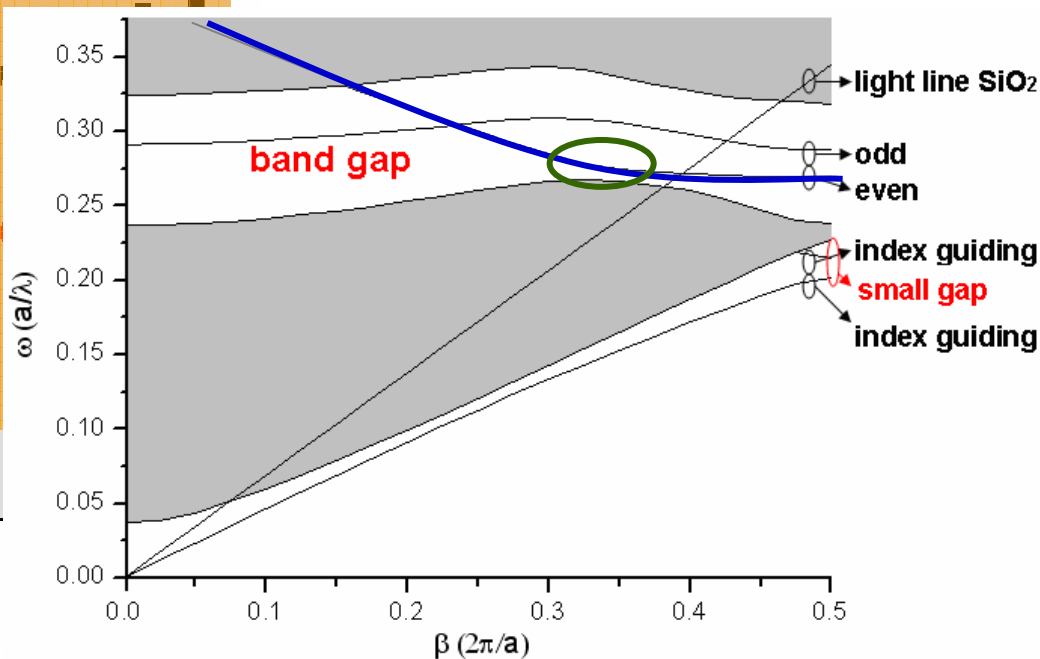
# 实验确认带隙波导缺陷导模

缺陷模式



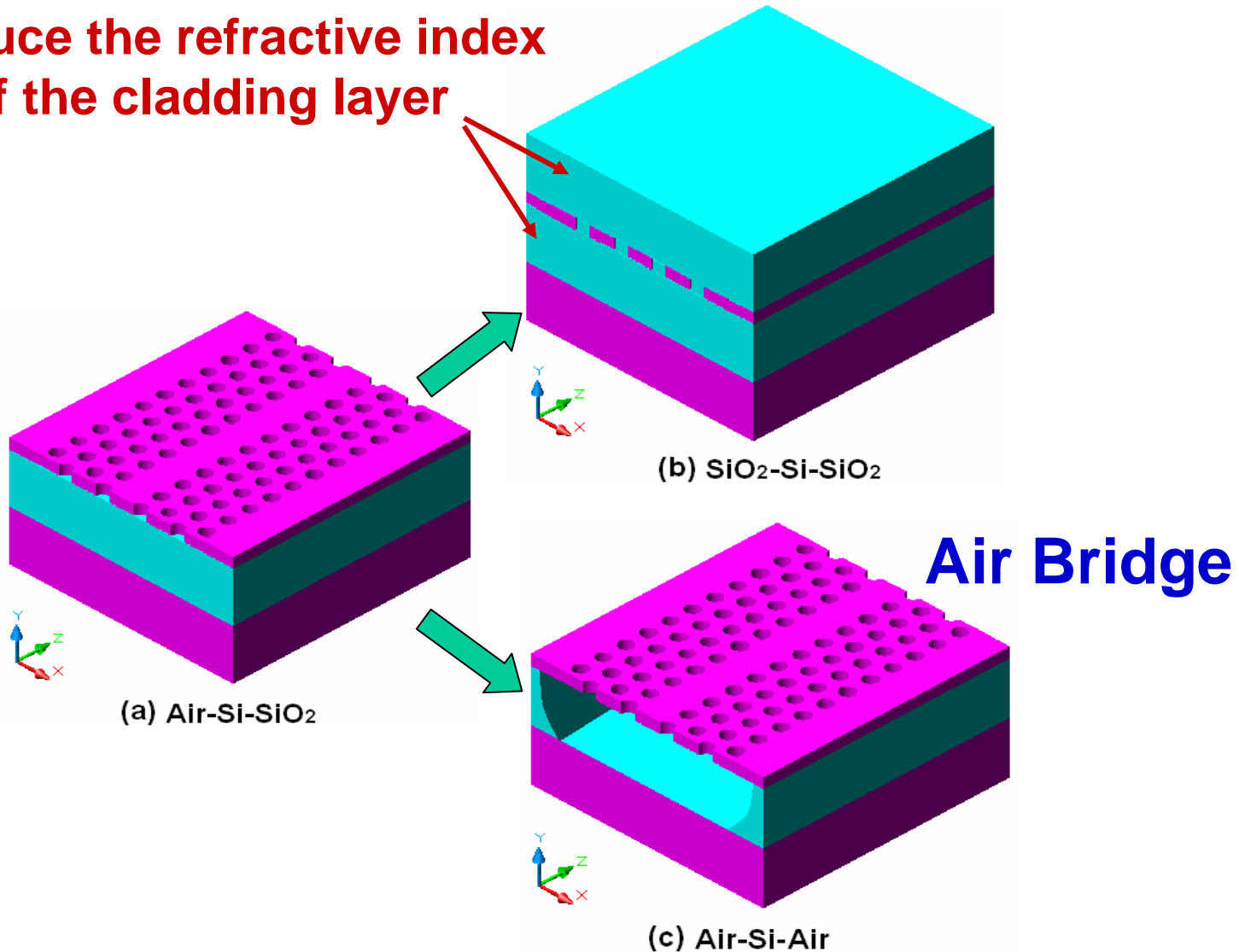
TE-mode

60 Periods



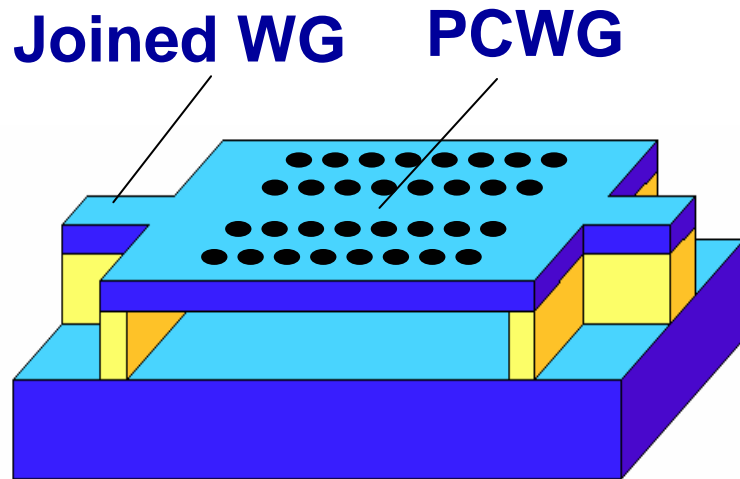
# PC-WG with Air Bridge Structure

Reduce the refractive index of the cladding layer

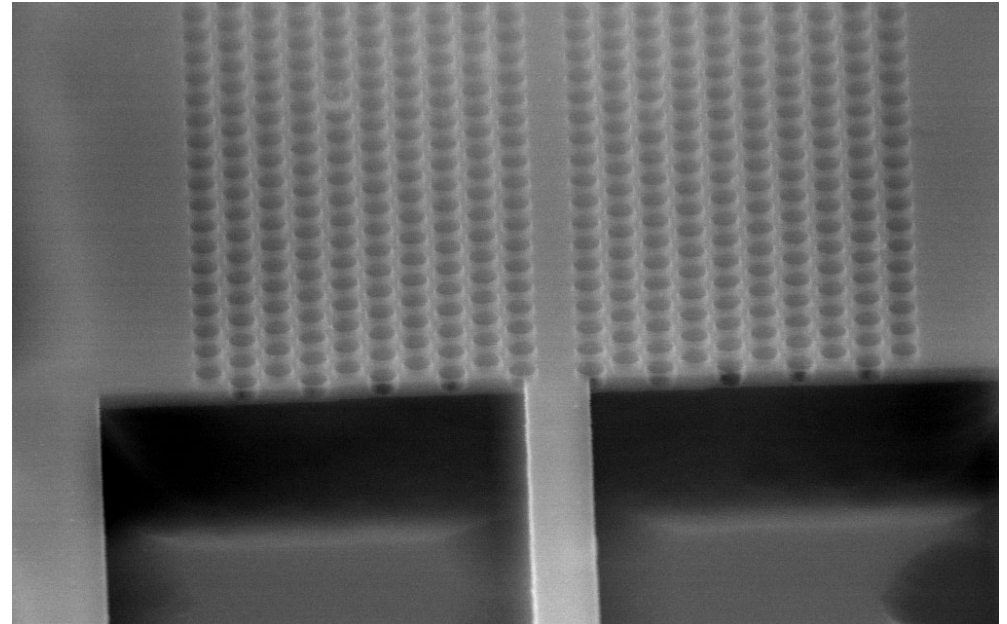


# PCWG with Air Bridge Structure

空气桥结构光子晶体波导

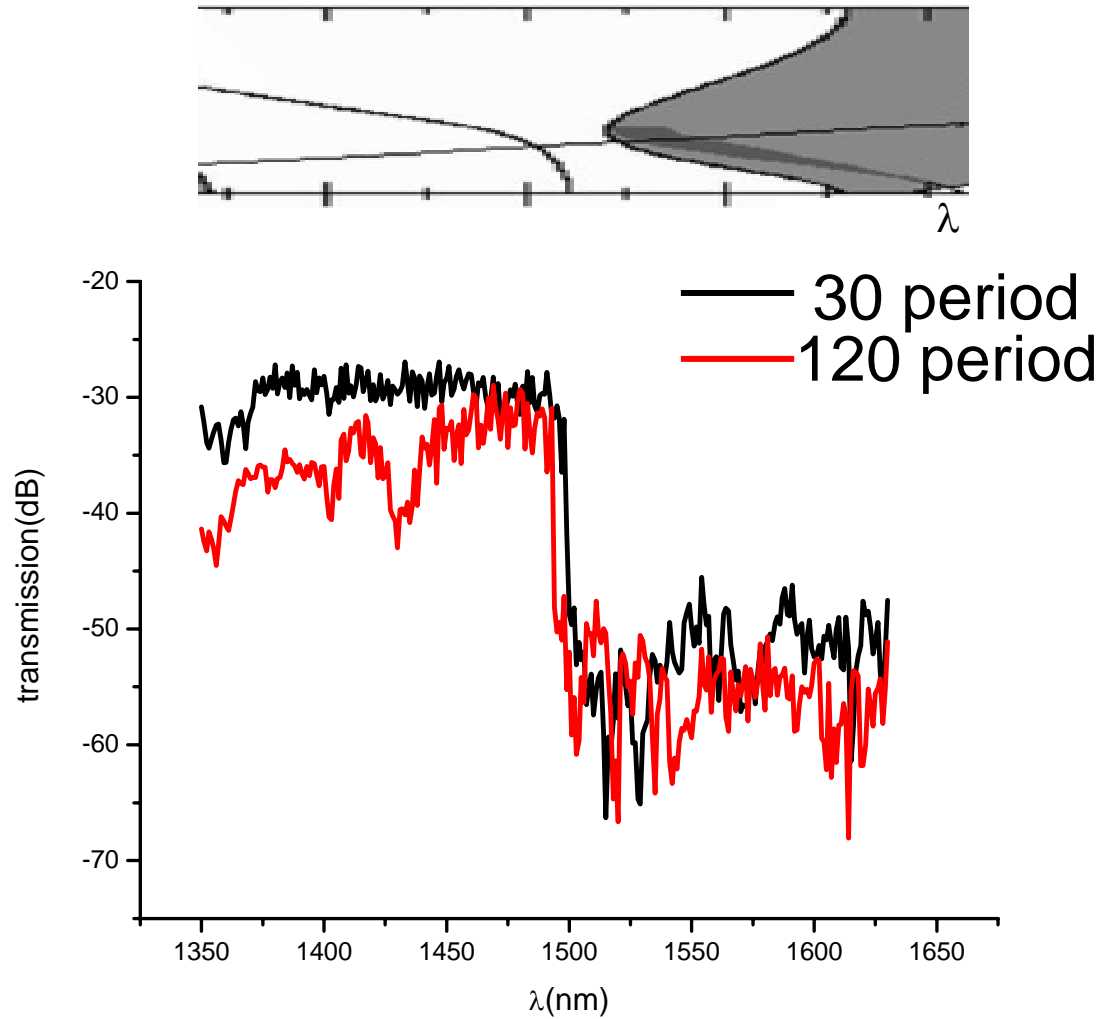


Air Bridge Structure



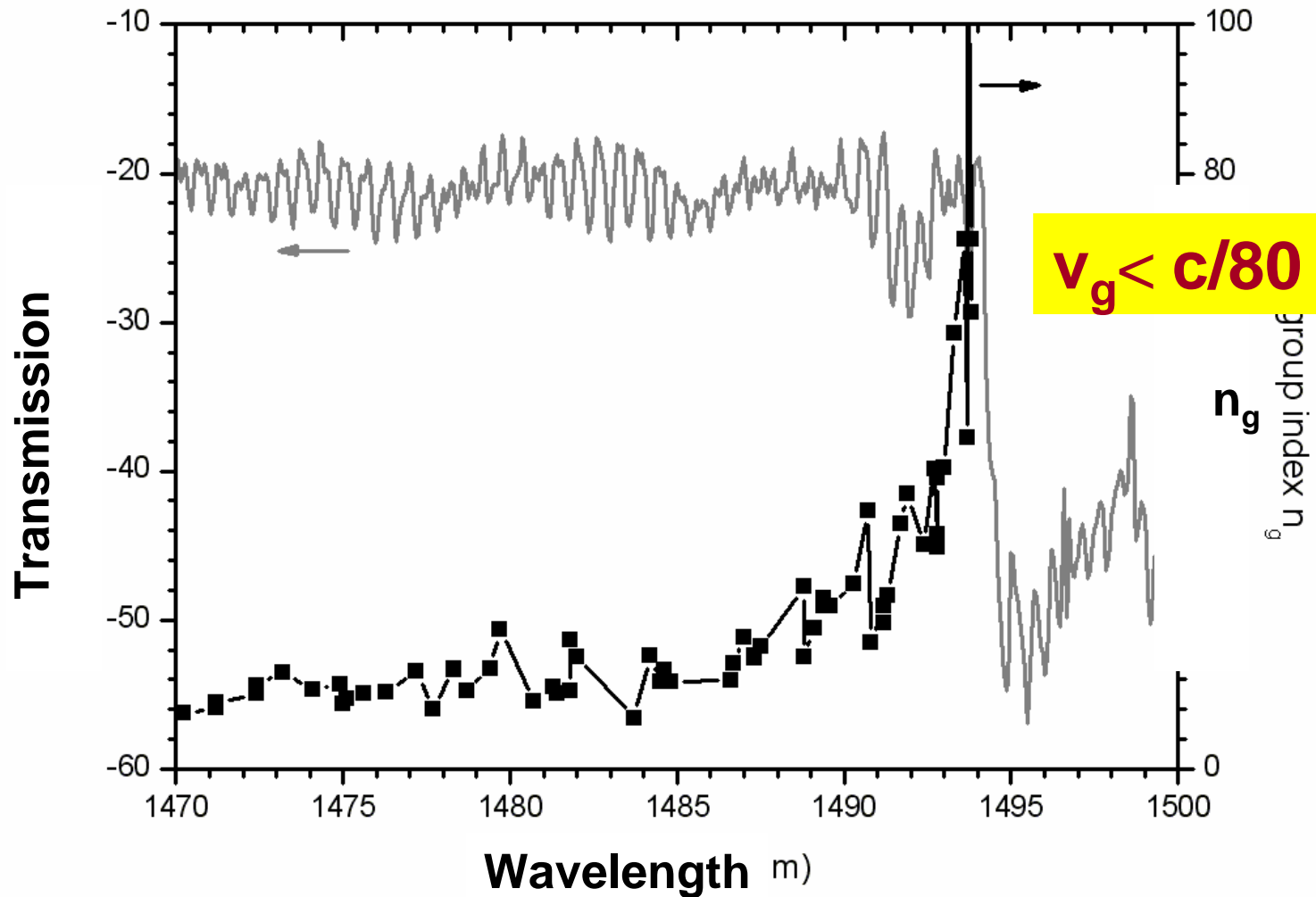
$$a = 420 \text{ nm} , r = 124 \text{ nm} , h = 200 \text{ nm}$$

# Measurement Results

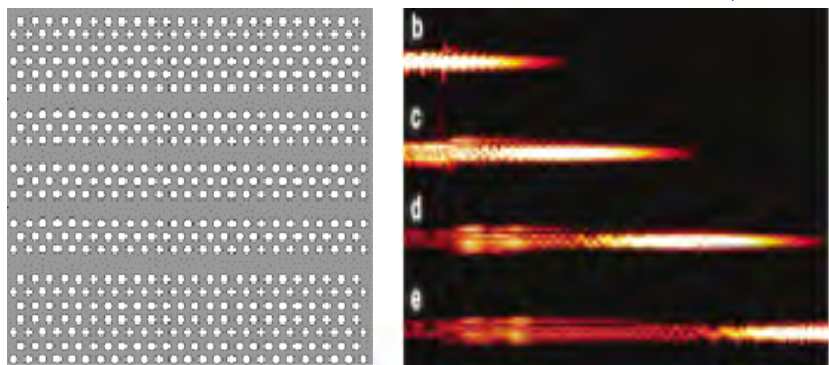


**$a = 420$  nm ,  $r = 124$  nm ,  $h = 200$  nm**

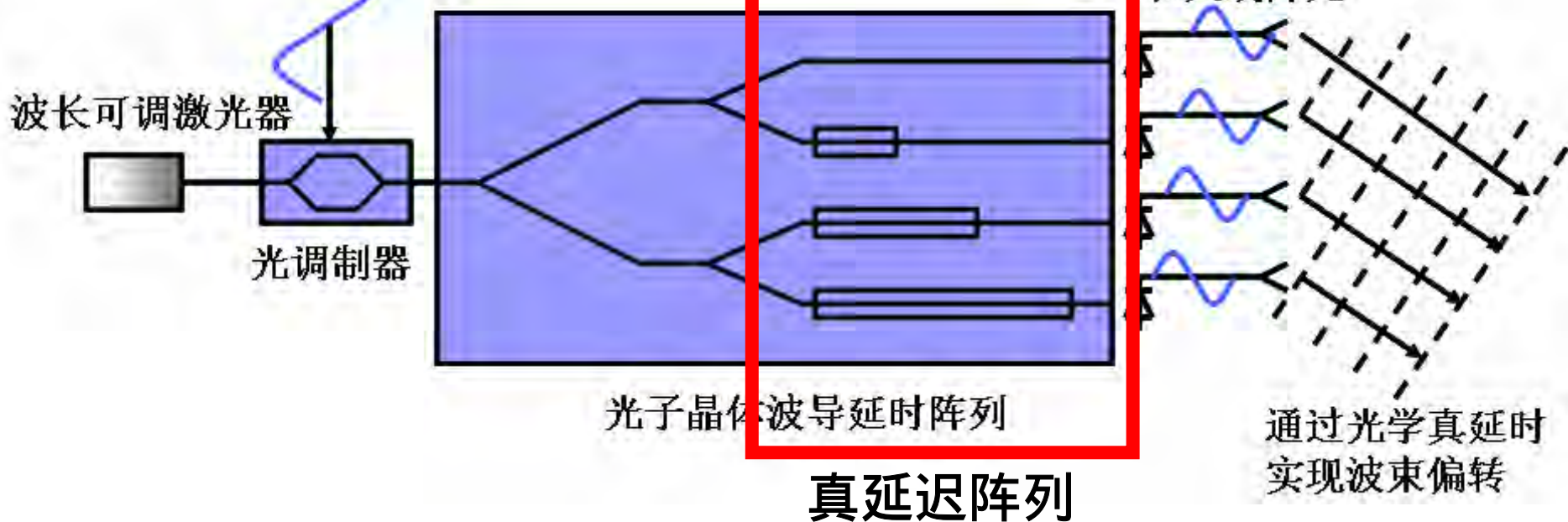
# 空气桥结构光波导群速度测试结果



# 光子晶体慢光波导 光学真延迟结构设计

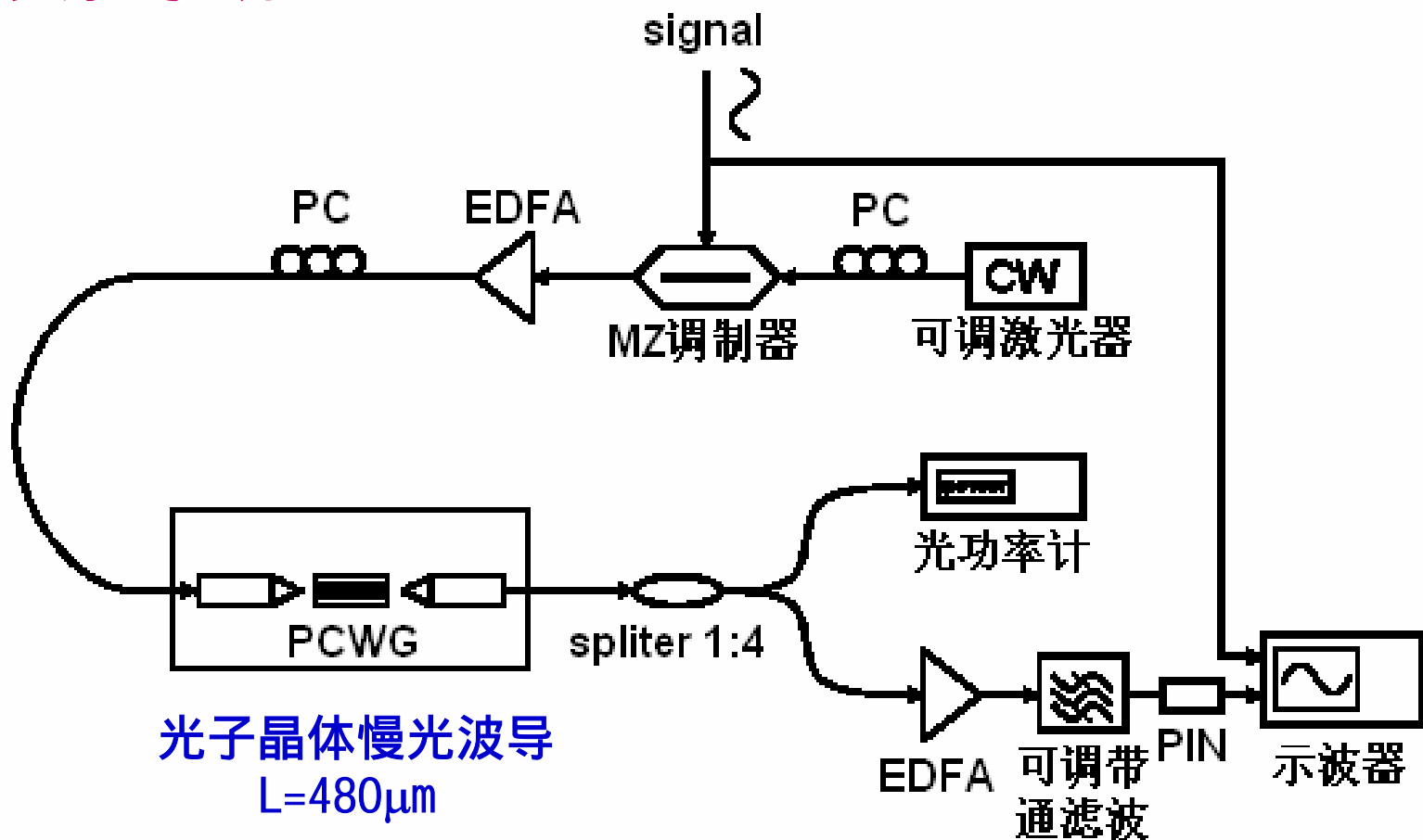


Controllable Light Group Velocity



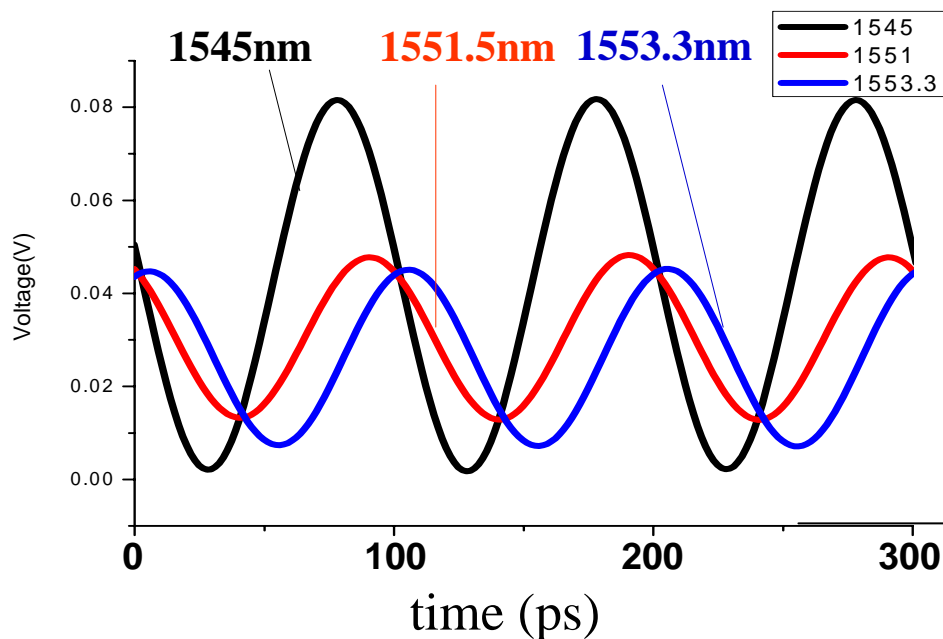
# 光子晶体波导慢光的重要应用— 微波信号可调真延时的实验论证

## 实验系统

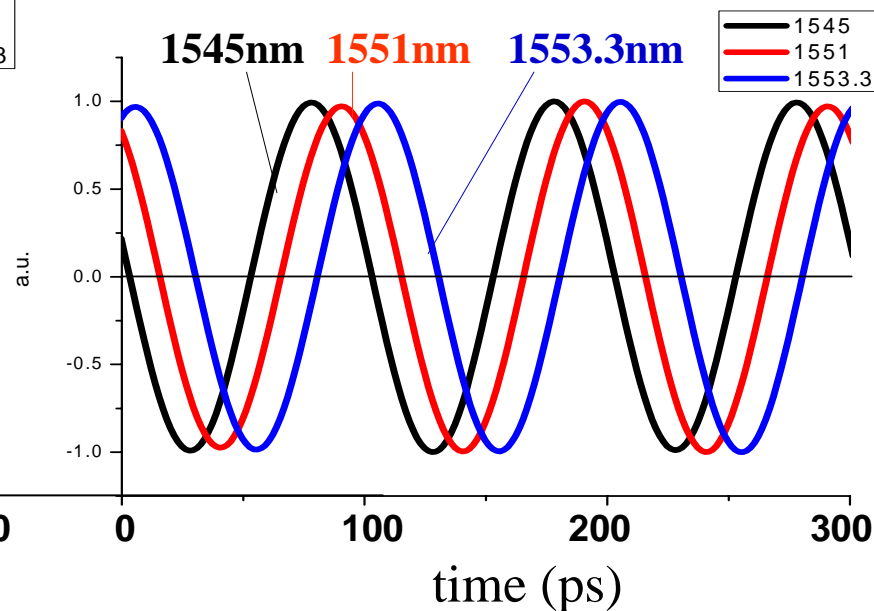


# 光子晶体波导慢光的重要应用— 微波信号可调真延时的实验论证

## 实验测量的波形



## 强度归一化后的波形



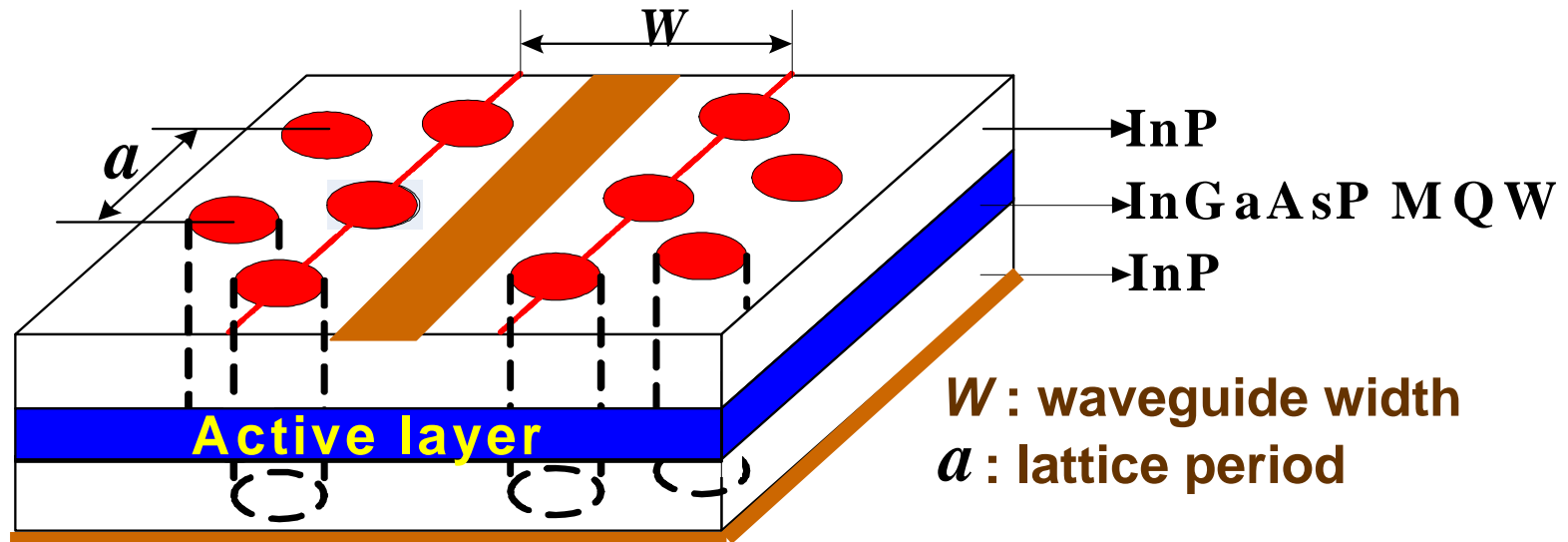
- 在单频激光上强度调制10GHz微波信号，观察不同激光波长下微波信号的延时
- 光子晶体波导长 $480\mu\text{m}$ ，测量得到最大延时差25ps，波形无明显畸变（对应 $n_g=15$ ）



# 有源慢光波导

(1) Abnormal  $v_g$  Controllable Gain?

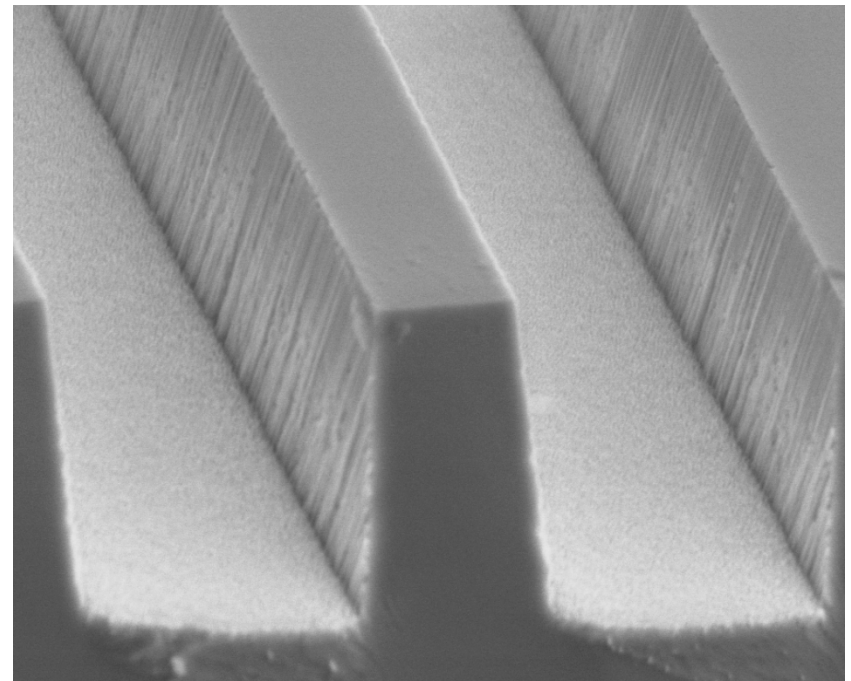
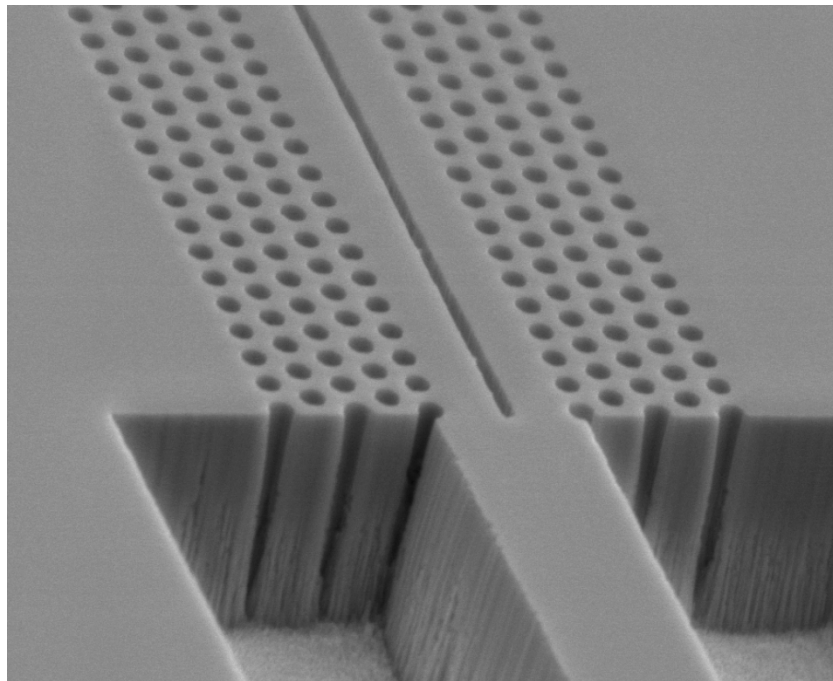
(2) Electrical injection can avoid the hole region



PC Waveguide - a line defect waveguide along  $\Gamma K$  direction

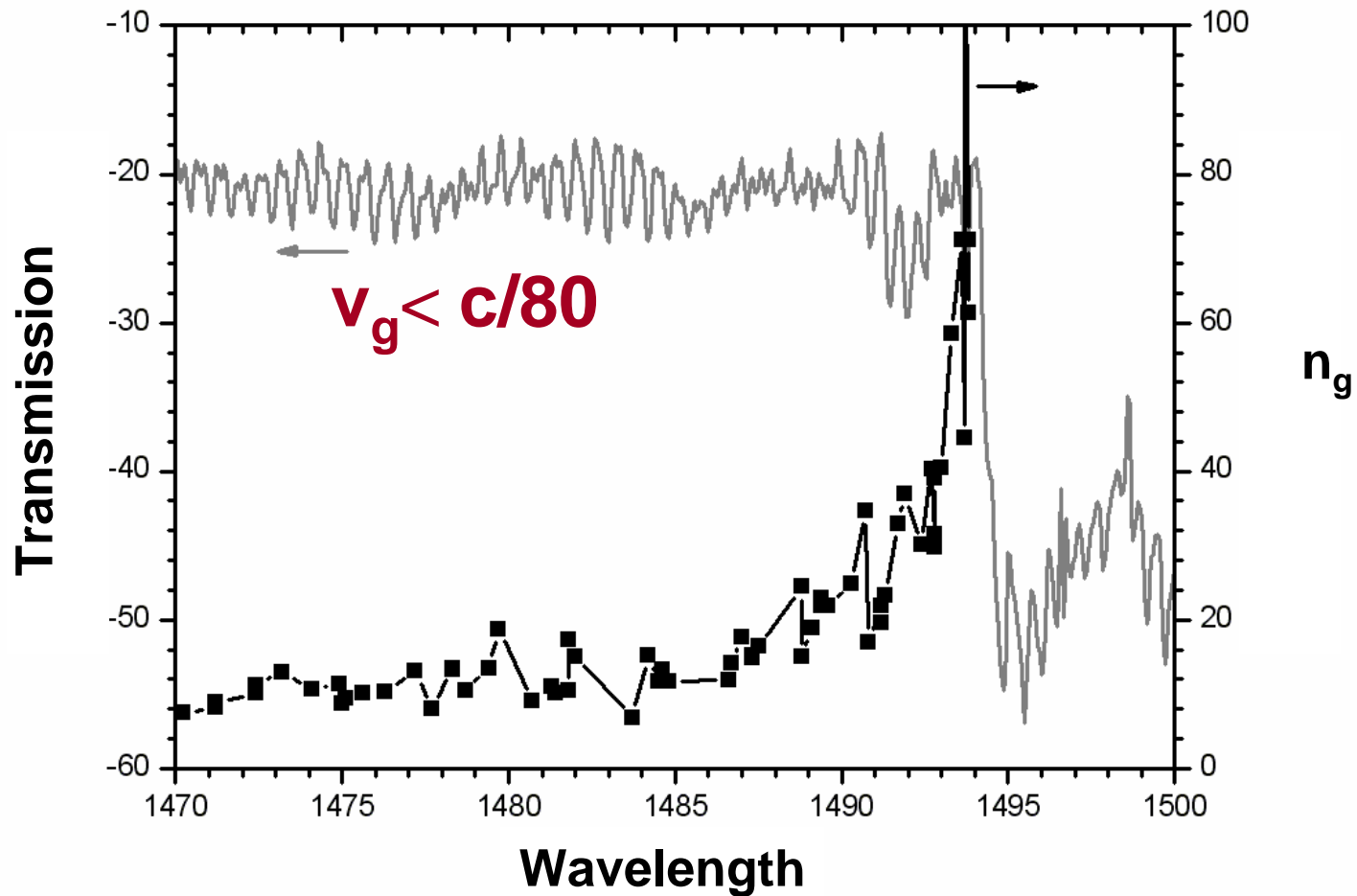
# InP基材料深刻蚀

◆ ICP/Bias=180W/200W Pressure=0.1Pa  
Cl<sub>2</sub>/SiCl<sub>4</sub>=1/3sccm Time=4min

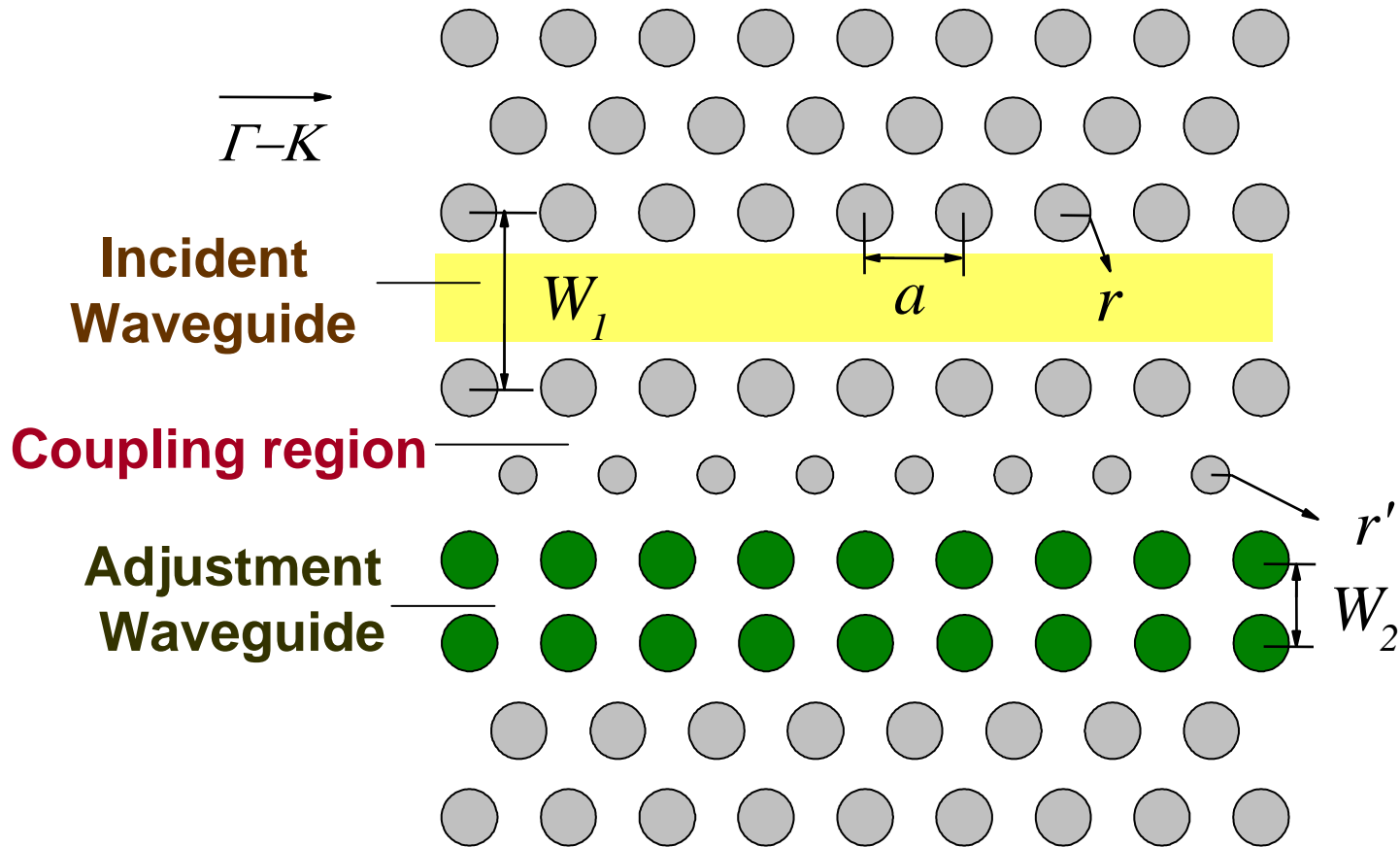


深宽比>10

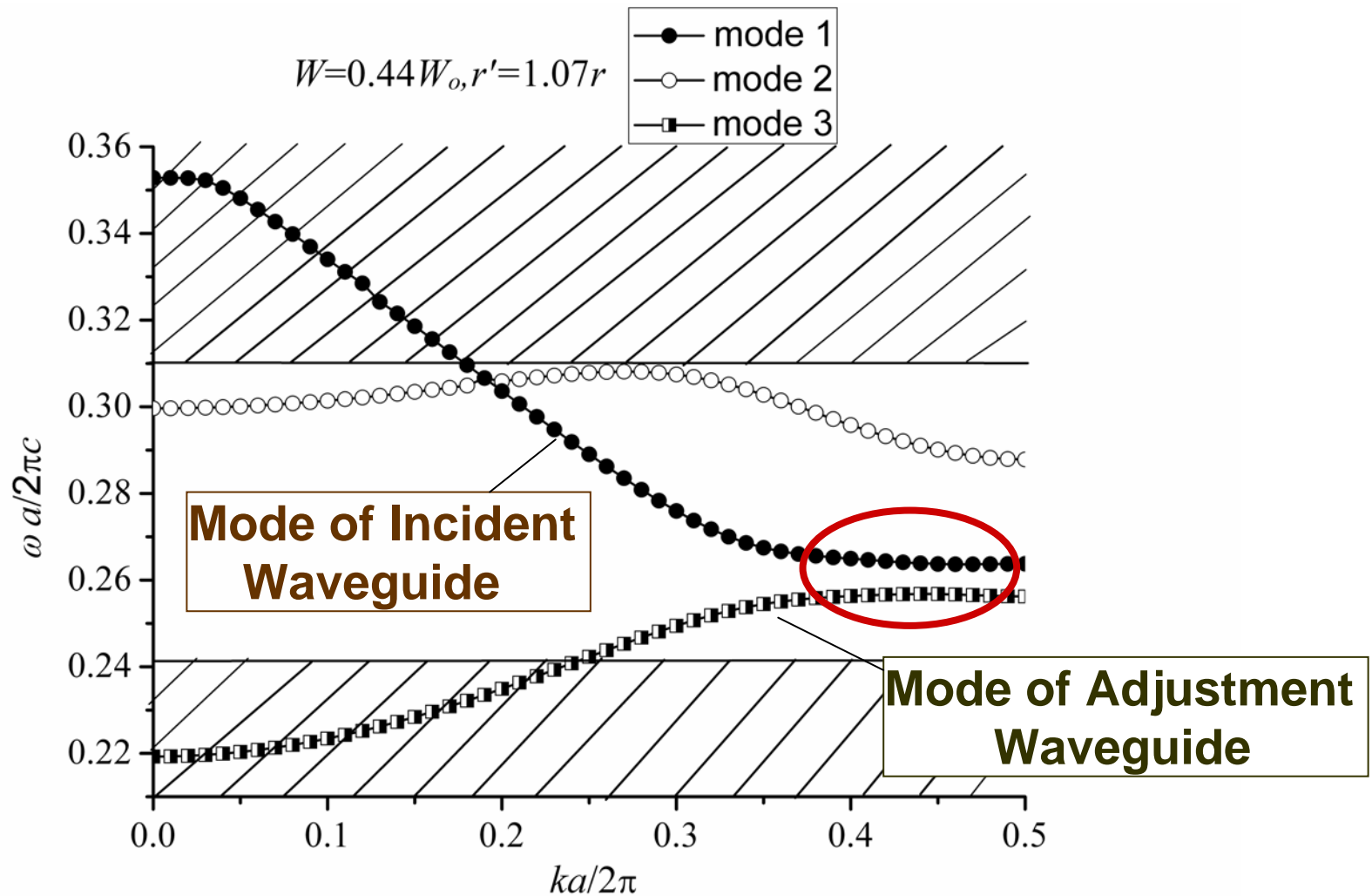
# 空气桥结构慢光波导测试结果



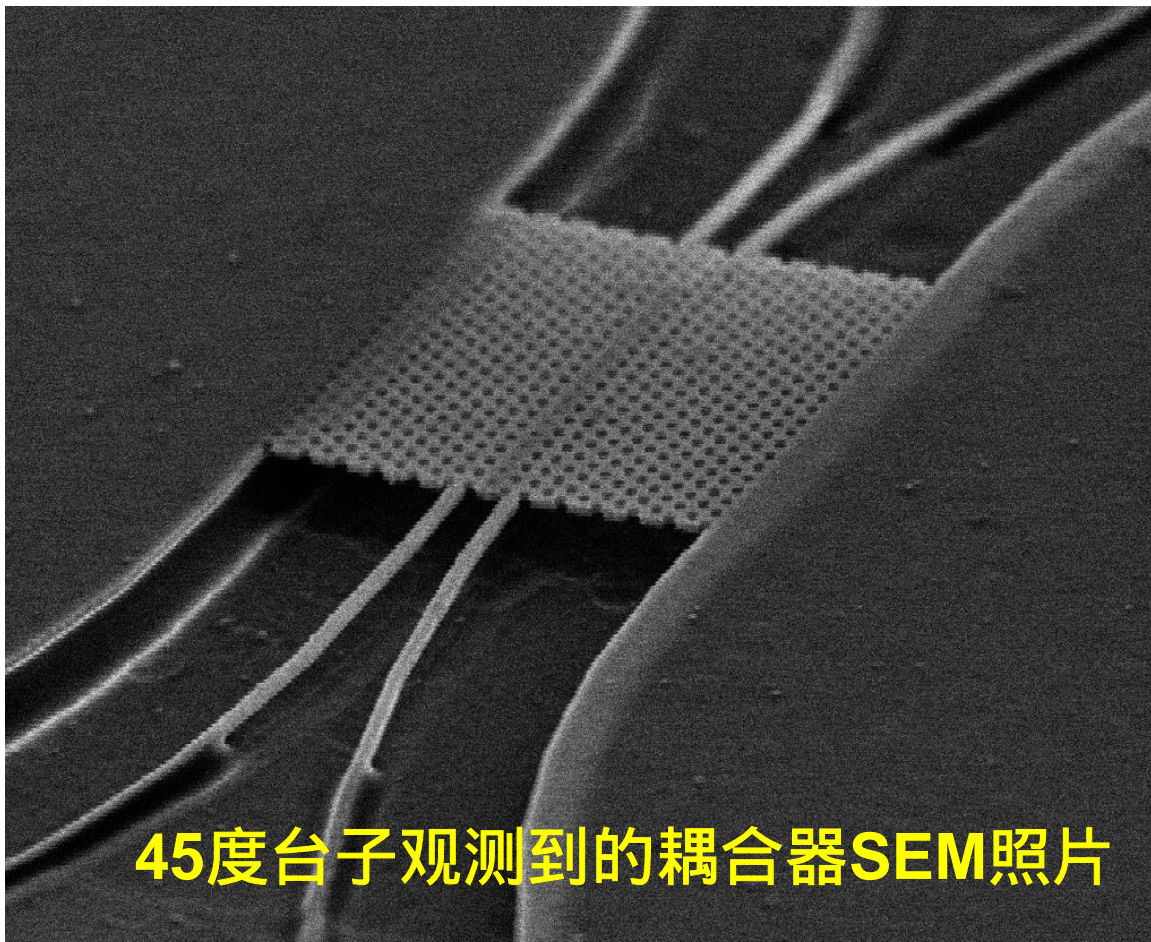
# Zero GVD Slow Light with Coupled PC WG



# Band Structure of the Coupled PC-WG



# 光子晶体波导耦合器



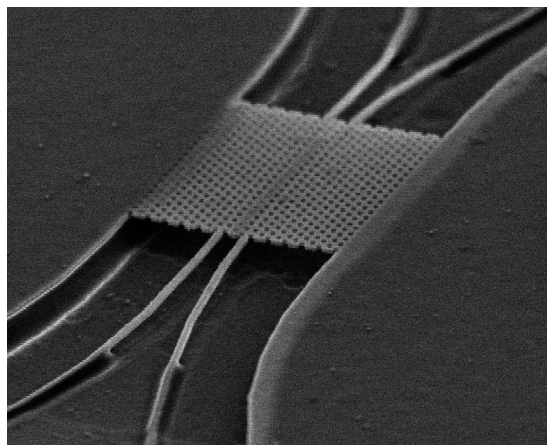
45度台子观测到的耦合器SEM照片

10 $\mu$ m

实验参数： $a=460\text{nm}$ ,  $r=130\text{nm}$ ,  $r'=90\text{nm}$ ，平板厚度为200nm

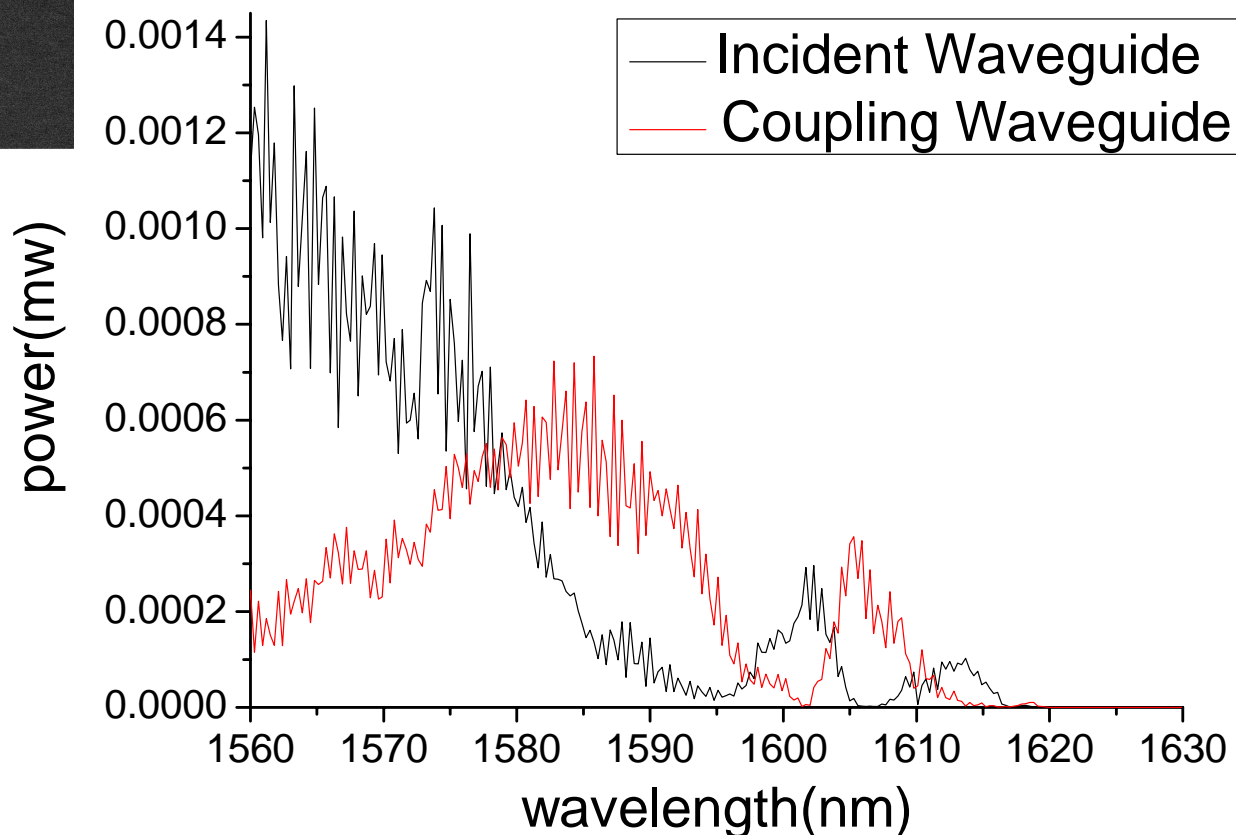


# 光子晶体波导耦合器



10 $\mu$ m

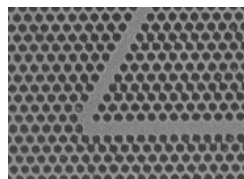
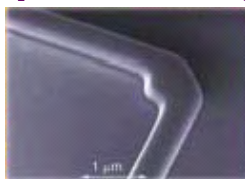
成功观测到了两个光子晶体波导间的  
能量耦合现象



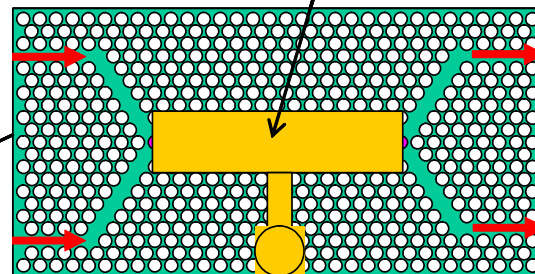
# 光子晶体

展示出一系列新的物理现象和独特的光学特性，为下一代光电子功能器件的发展提供了崭新的创造空间，也为光子集成的实现带来了新的希望

Optical waveguide/interconnection

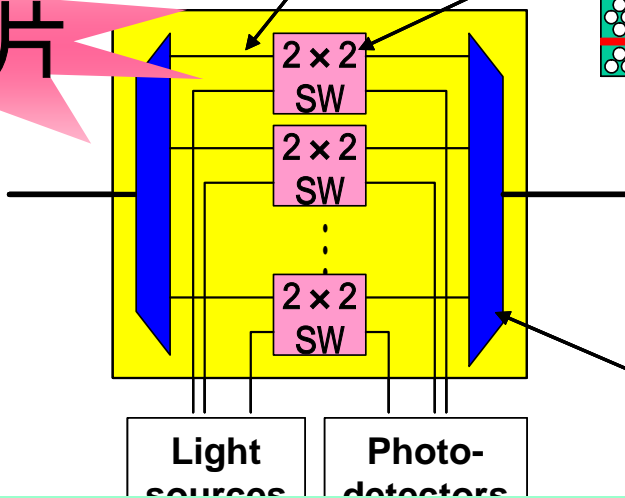


Electrode

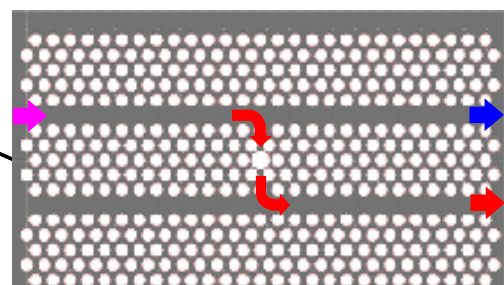


2 x 2 optical switch

光子集成芯片



ADM



WDM demultiplexer



# 微纳结构与物理

## 芯片

## 光纤

光子集成  
光延迟  
光子微腔...

光子晶体  
材料与器件

超低电压调制器  
传感器...

芯片光互连  
光量子器件...

量子通信  
可预测单光子源...

表面等离子体  
物理与器件

纳结构硅基光电子

光子晶体光纤  
及其应用

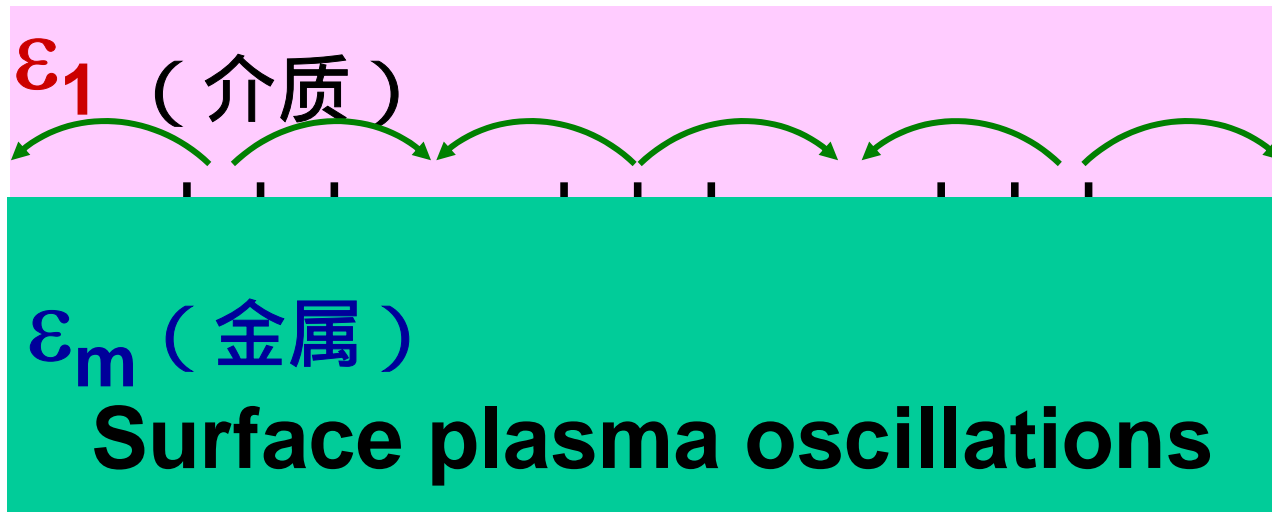
传统有源无源器件  
(LD,LED,SOA,耦合器,光开关等)

EDFA

光通信、光信号处理、光传感、光存储.....

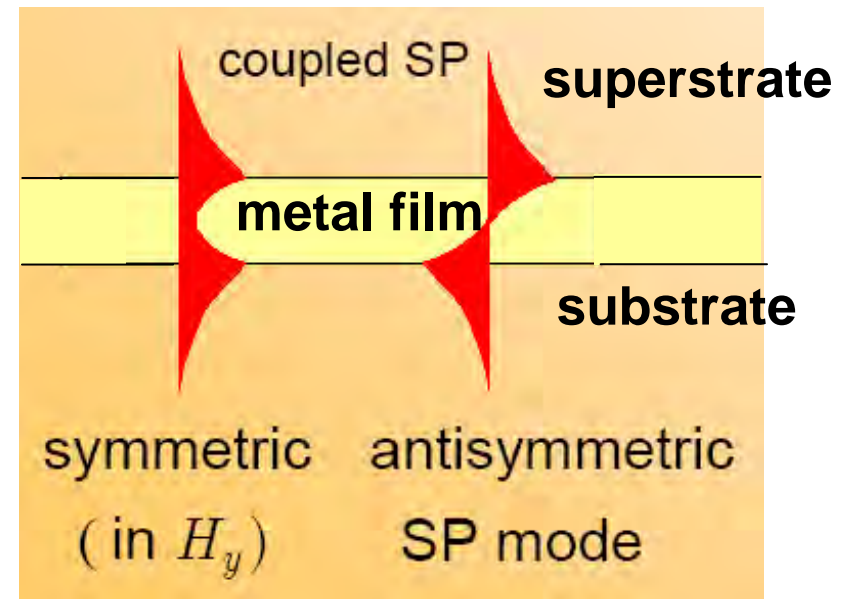
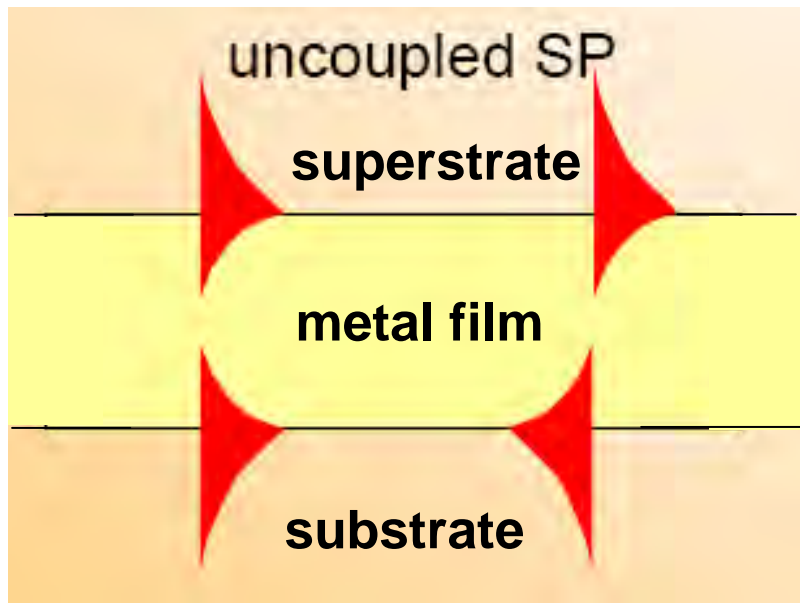
# 表面等离子波

金属表面电子浓度的起伏形成表面等离子振荡



损耗非常大，只能传输数十微米

# Long Range SPP: LR-SPP

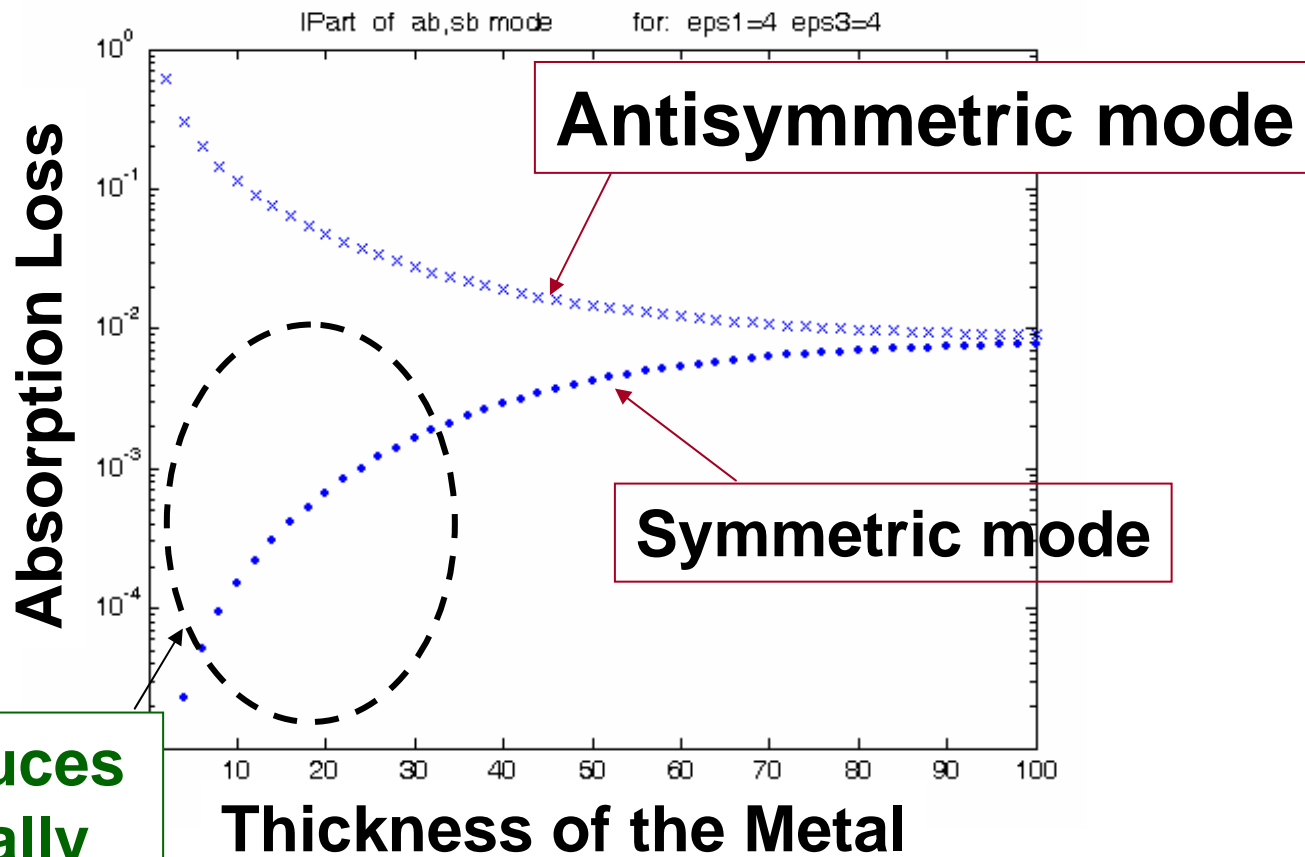


When the metal film is thin enough

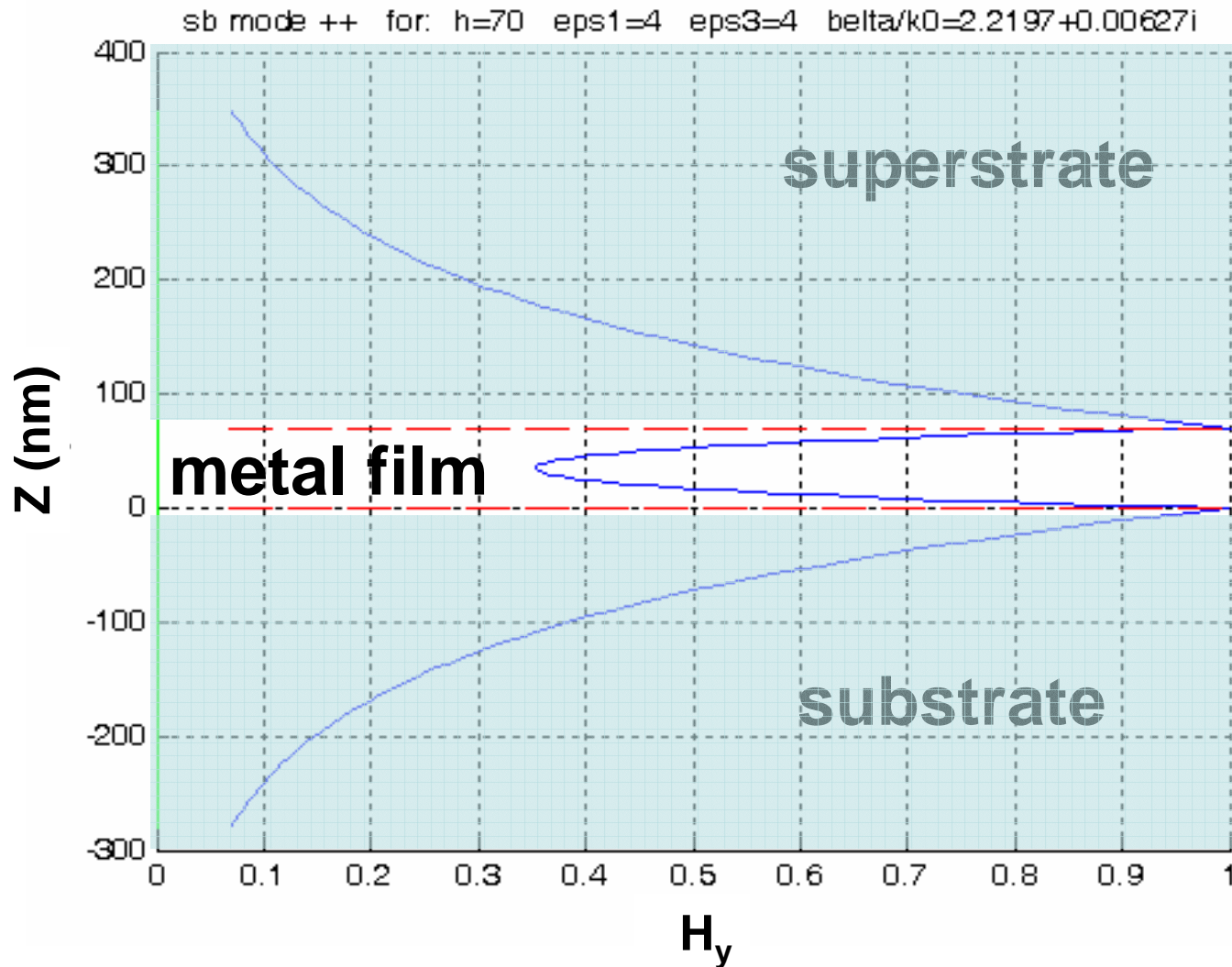


**SPPs on the two interfaces couple and form 2 types of different modes**

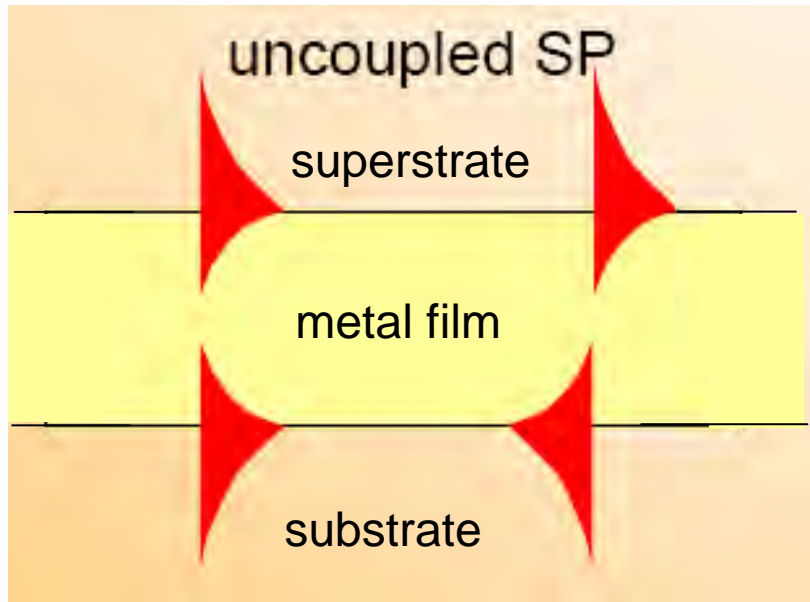
# Loss Characteristics



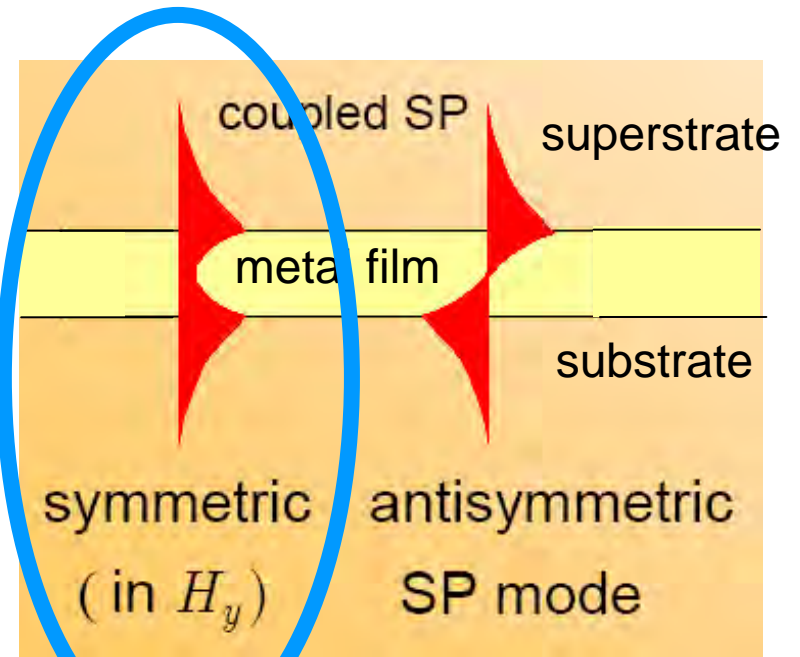
# Long Range SPP: LR-SPP



# Long Range SPP: LR-SPP



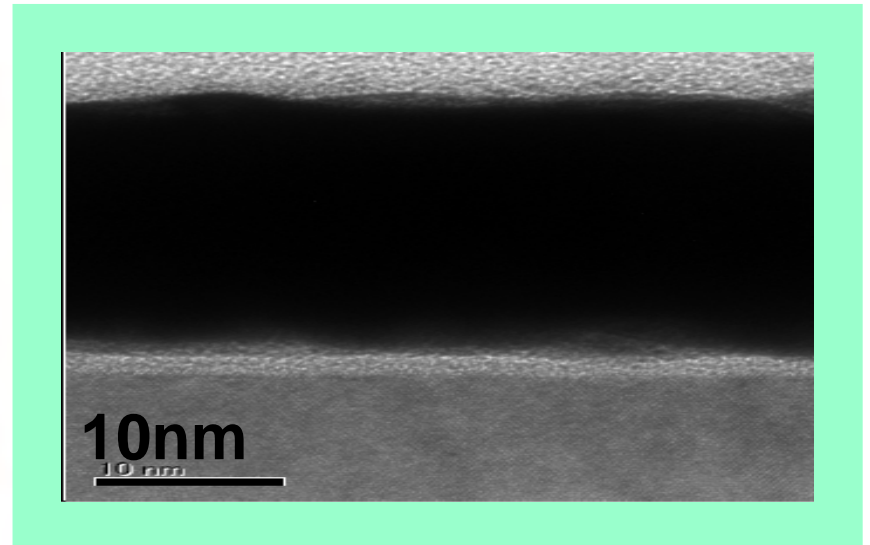
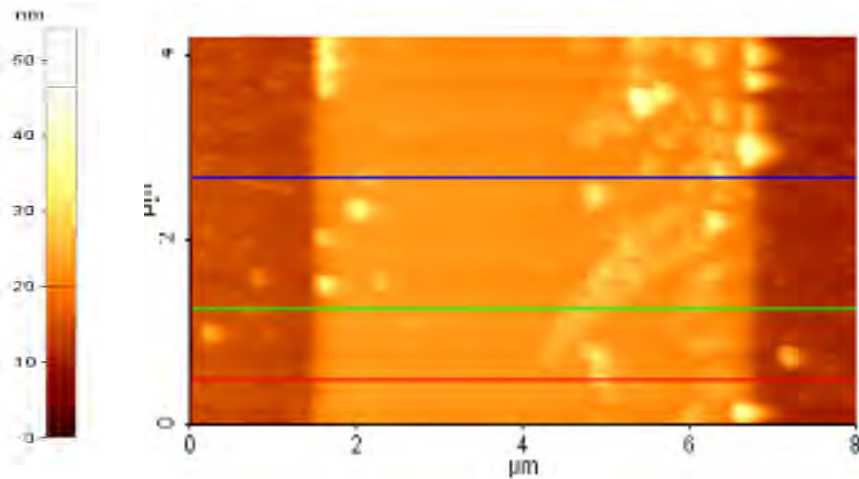
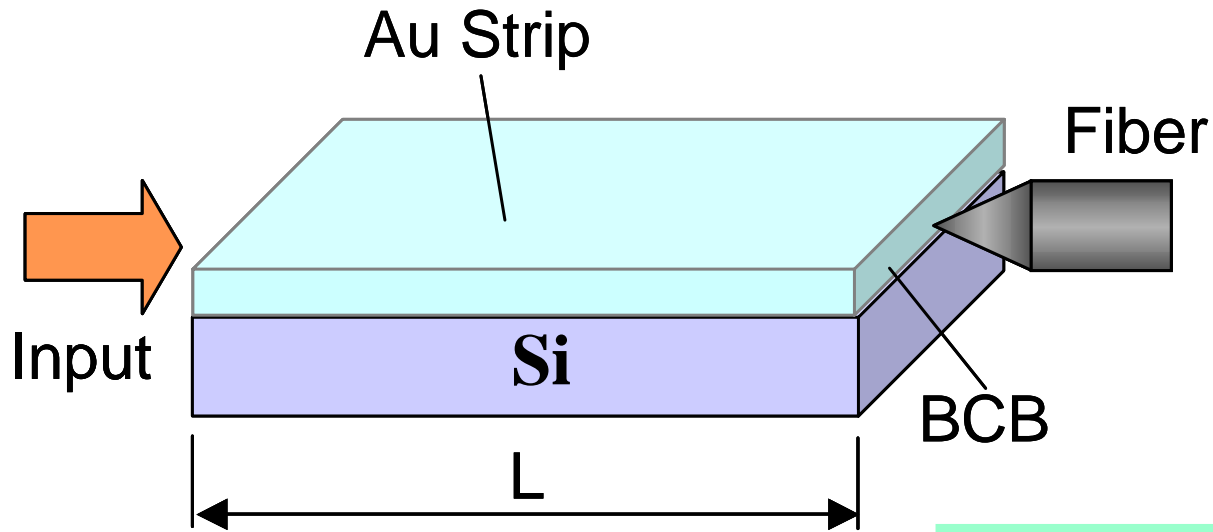
(a)



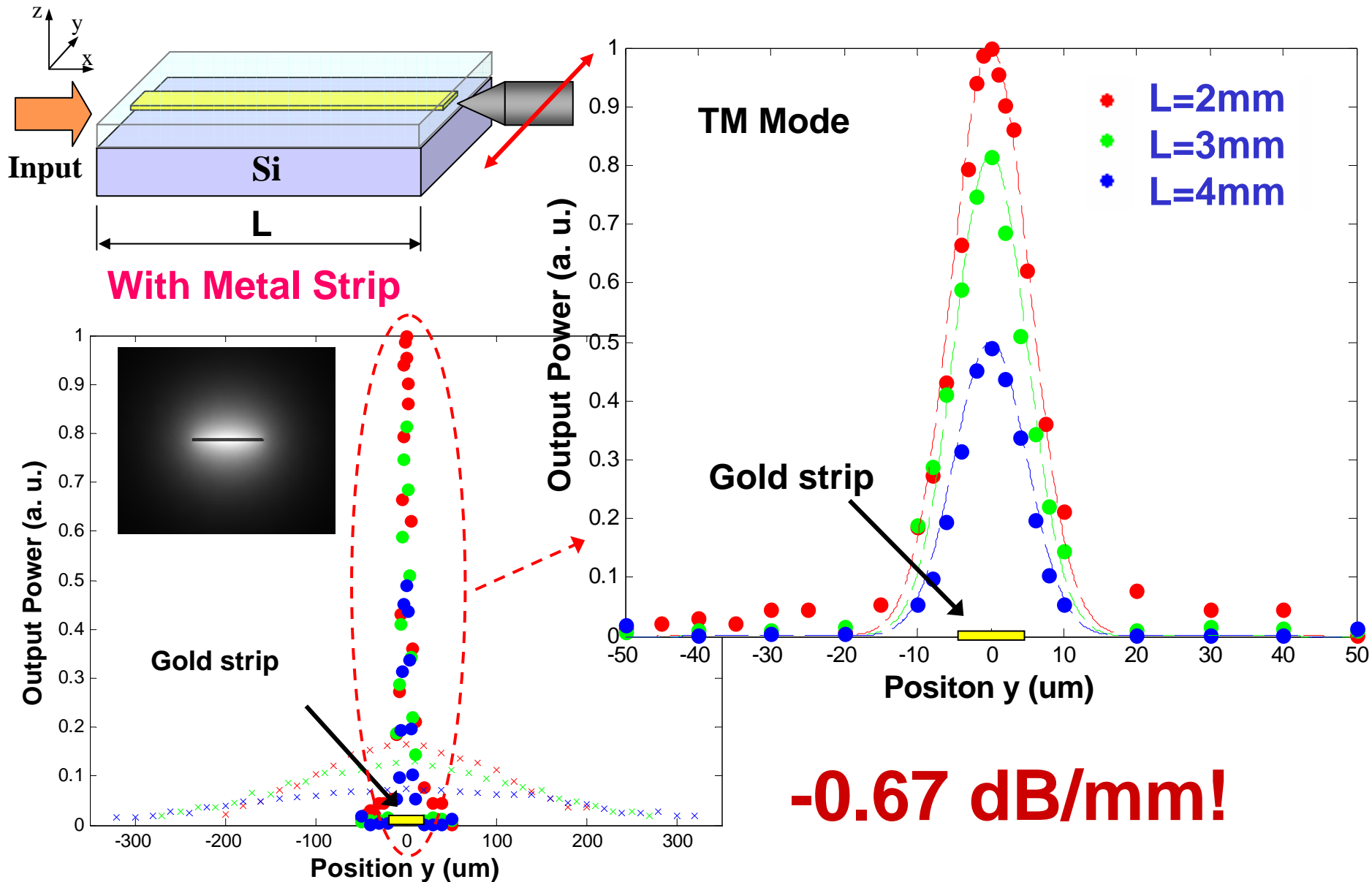
(b)

**LR-SPP**

# Fabrication of LR-SPP WG

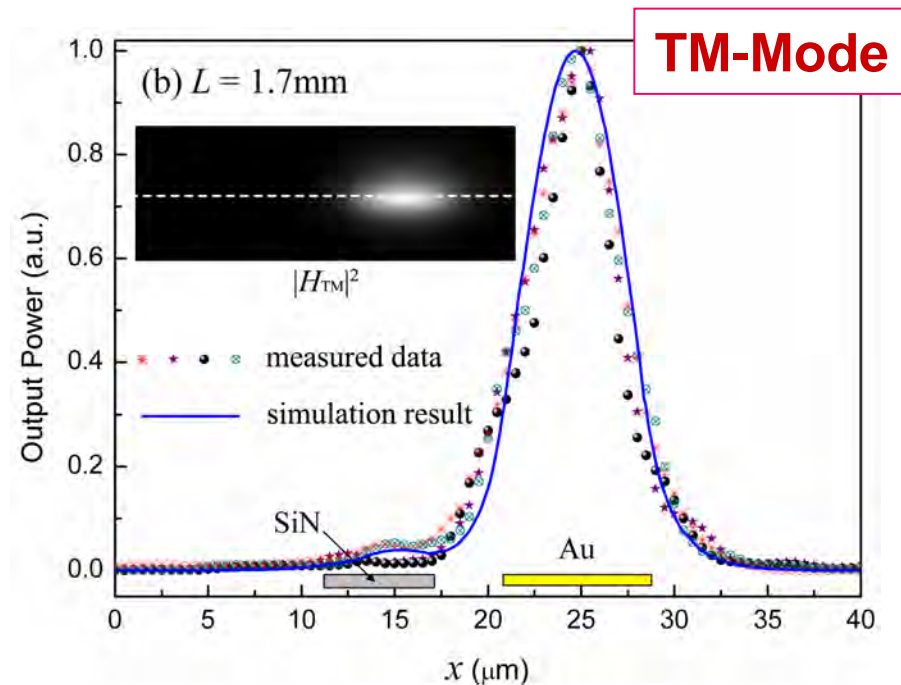
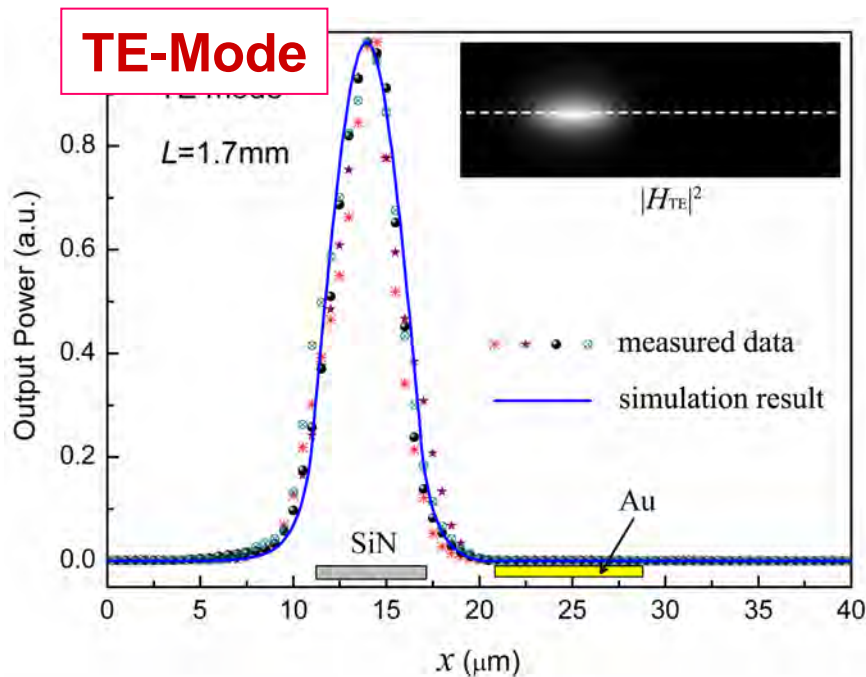
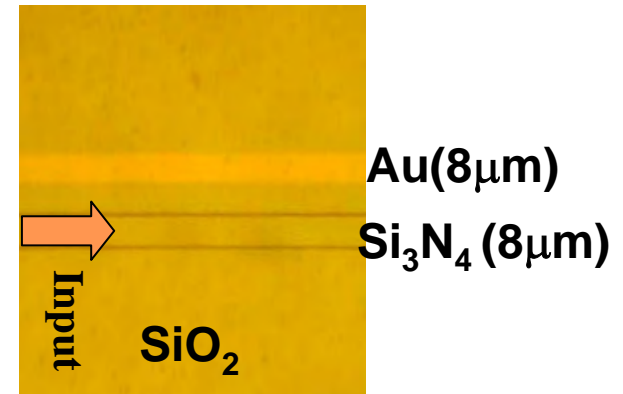
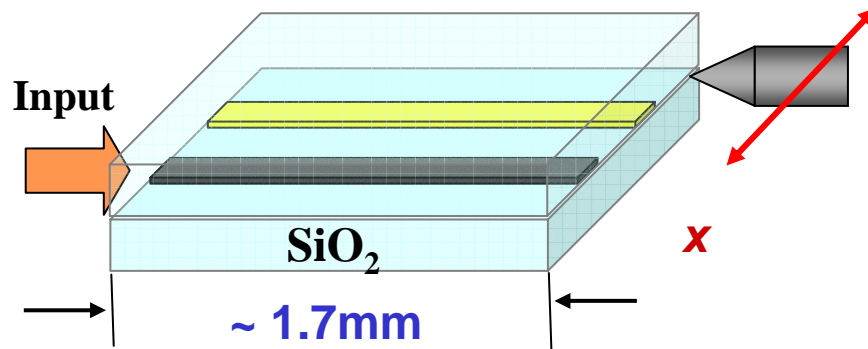


# Measurement Results

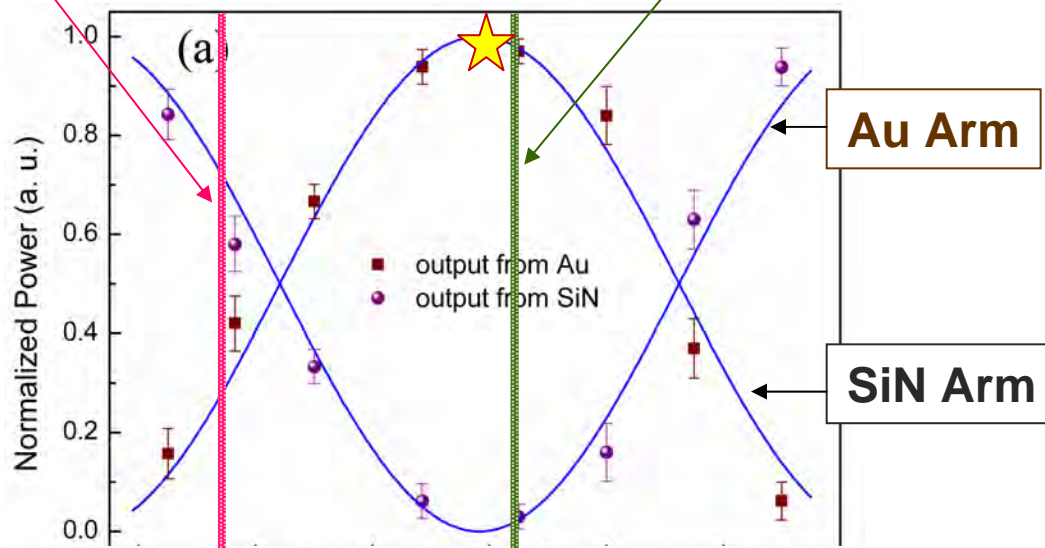
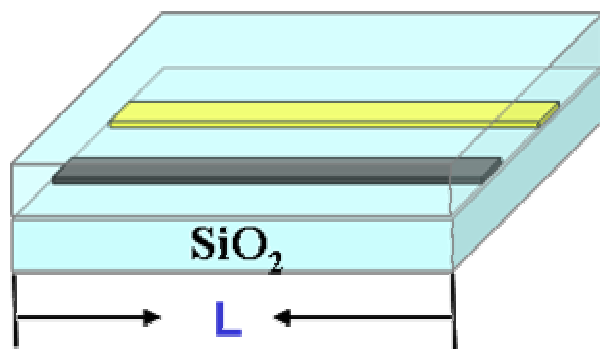
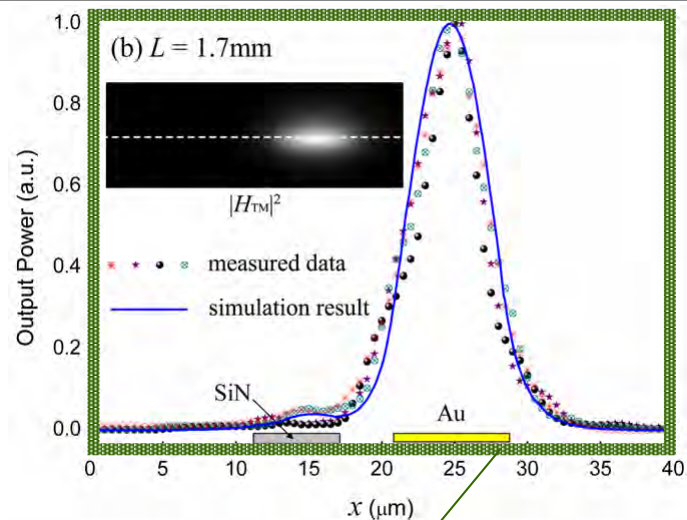
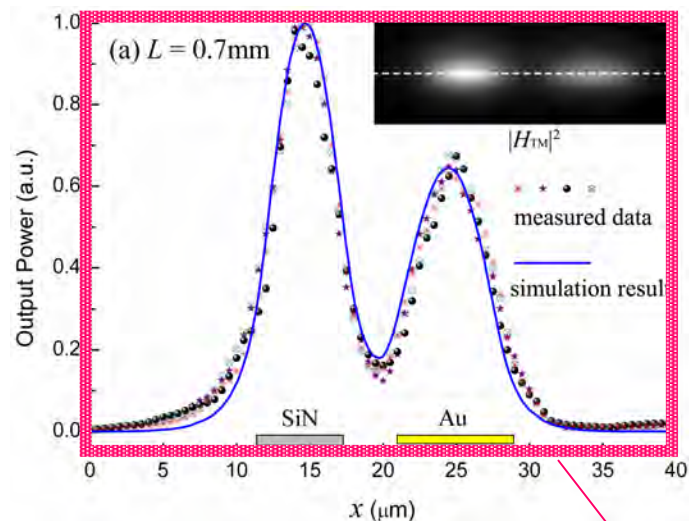




# Experimental Results for Hybrid Coupler

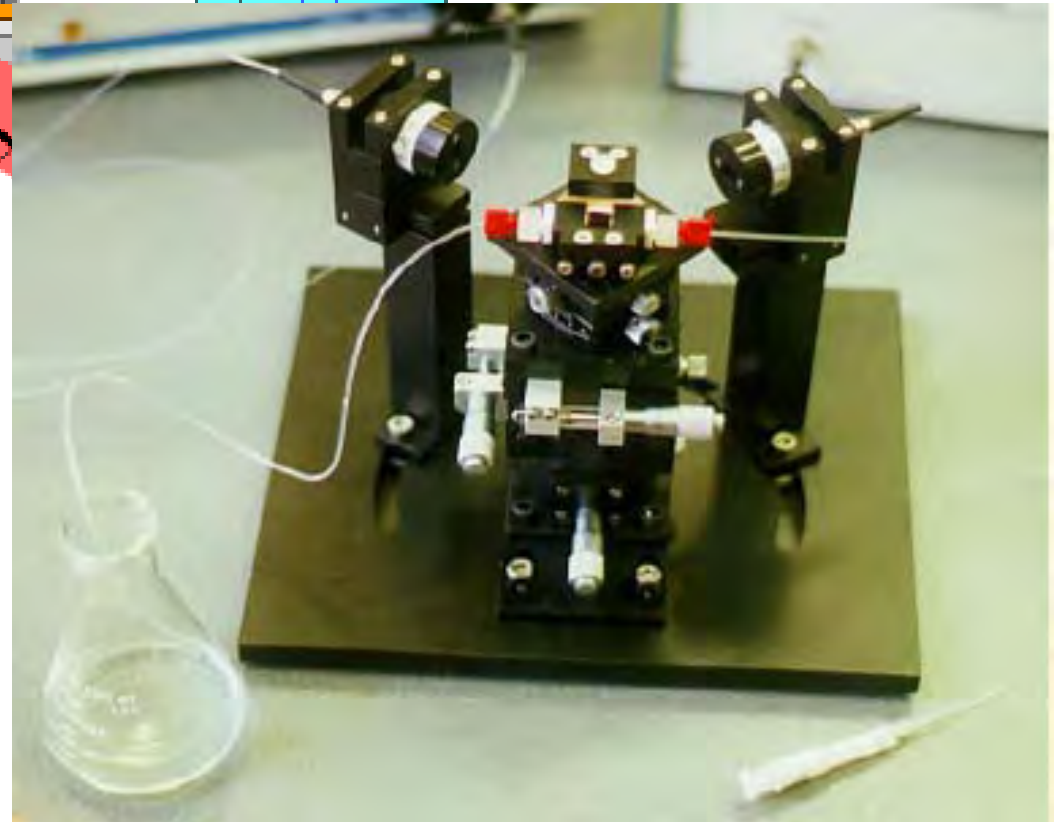
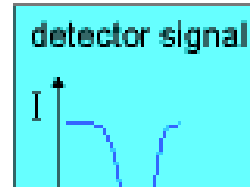
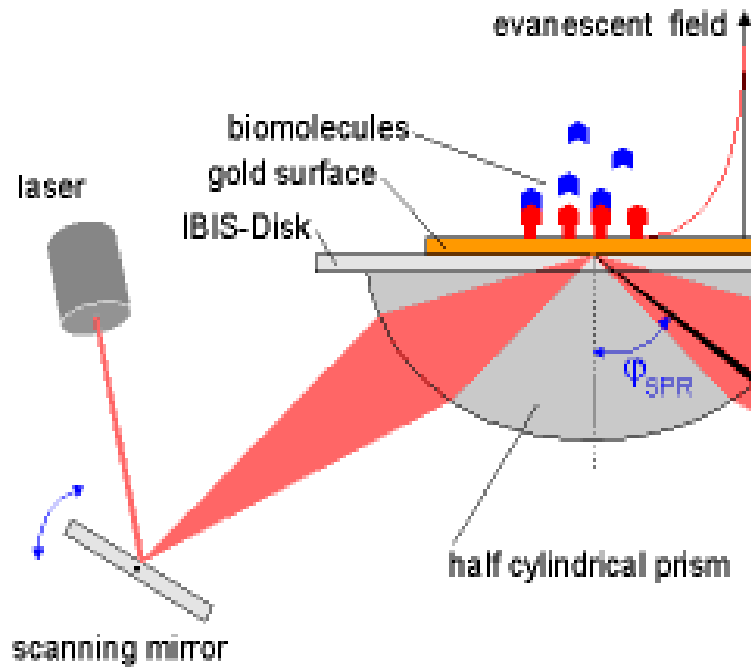


# Experimental Results for Hybrid Coupler

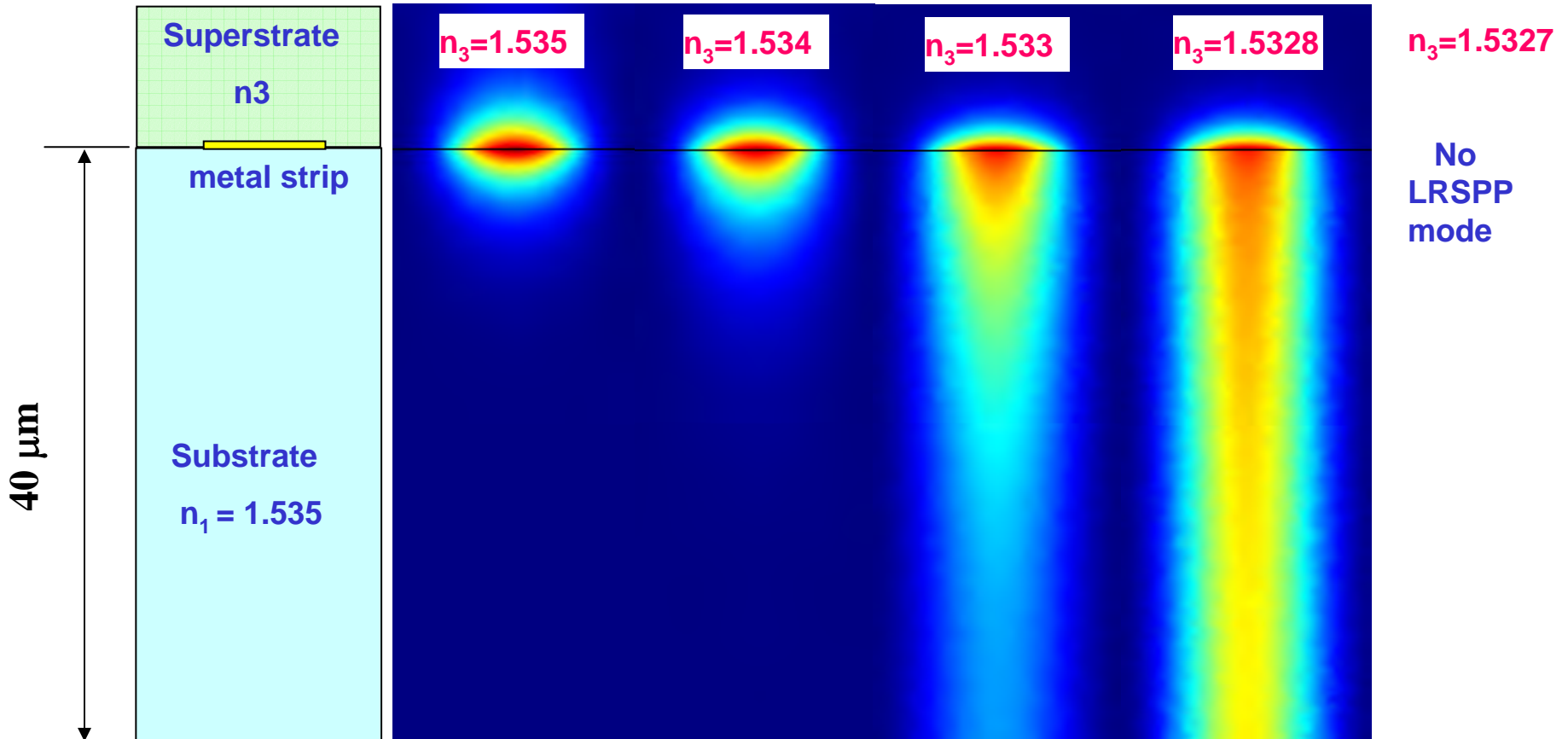


**extremely high coupling efficiency >99% !!**

# Conventional SPP Sensor



# LRSPP Supported by Metal Strip

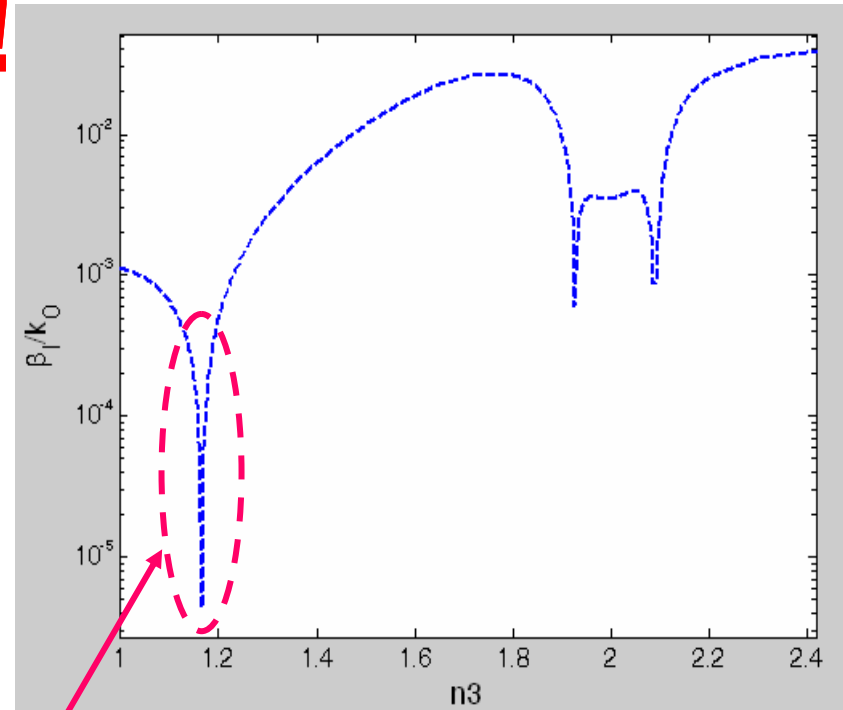
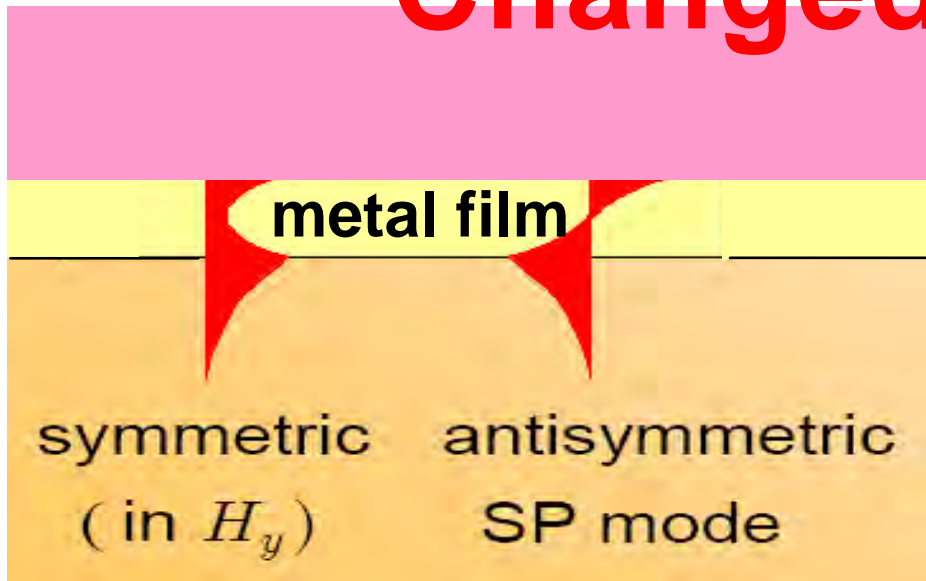


**Very Sensitive to  $n_3$ !**

# Sensor with LR-SPP Waveguide

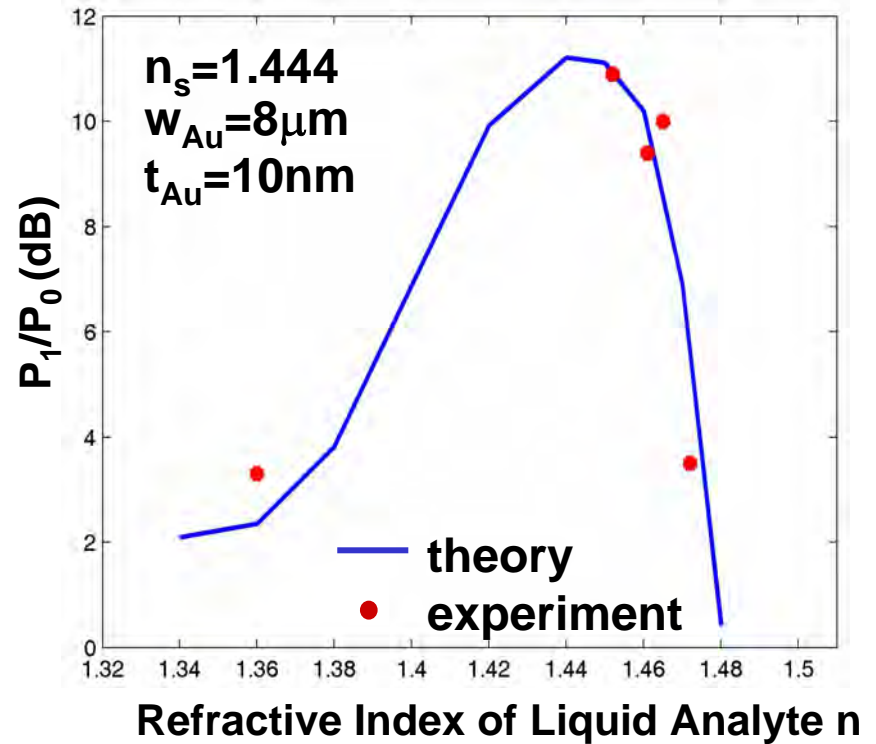
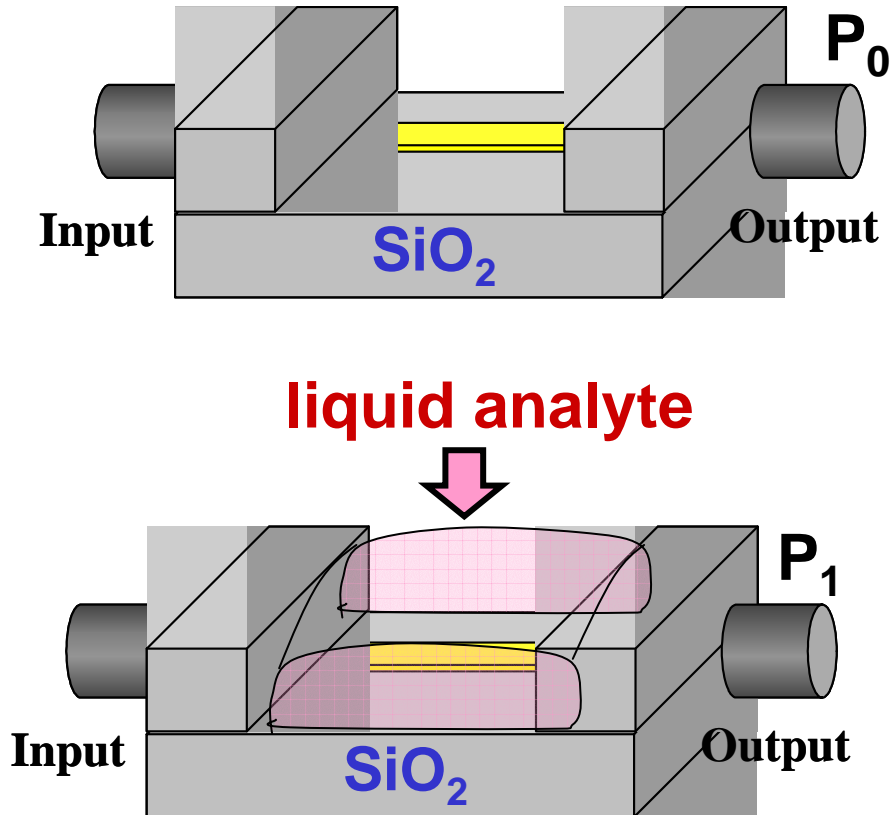
## Integrated Refractivity Sensor

**Changed!**



**Transmission Dip**

# Measurement Results



high sensitivity of  $10^{-4}$



# Reported by Nature CHINA

## as Research Highlight

The image is a screenshot of the Nature CHINA website. At the top, the "natureCHINA" logo is displayed in white on a red background. Below the logo, there is a search bar and a navigation menu. The main content area features a "Research Highlights" section with a red header. The highlighted article is titled "Plasmonics: Hybrid gives a boost" by Rachel Won, published online on 22 April 2009. The article abstract discusses an integrable excitation method based on a hybrid coupler structure. To the left of the main content is a sidebar with a "latest research highlights" section, listing various articles with "OPEN" tags. Below this is a "NPG Journals" section with links to different subject areas. To the right of the main content is a "Toolbox" section with various utility links like "Previous", "Recommend a paper", and "Export citation". At the bottom right, there is a small image of a hybrid coupler structure with the copyright notice "© (2009) ASP".

natureCHINA

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latest research highlights

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Cancer biology: Brain stopper OPEN

Cancer biology: Survival run

Biophysics: Water aid

Nonlinear dynamics: Spiralling heartbeats

Plasmonics: Hybrid gives a boost

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**Research Highlights**

Subject Category: **Physics**

Published online: 22 April 2009 | doi:10.1038/nchina.2009.84

**Plasmonics: Hybrid gives a boost**  
Rachel Won

An integrable excitation method based on a hybrid coupler structure may well make short-range surface plasmon polaritons an enabling technology for future highly compact functional devices

Original article citation  
Wan, R., Liu, F., Tang, X., Huang, Y. & Feng, J. *Vertical coupling between short-range surface plasmon polariton mode and dielectric waveguide mode*. Appl. Phys. Lett. **94** 141104 (2009).

Surface plasmon polariton (SPP) — a propagating electromagnetic mode at the interface between a metal and a dielectric material — has been a subject of great importance in recent decades. The symmetric mode, also known as long-range SPP, has been well studied and is the basis of many optical devices. However, the asymmetric mode, also known as short-range SPP, is much less explored because of higher propagation loss and difficulty in excitation. Fang Liu and co-workers at Tsinghua University in Beijing<sup>1</sup> have numerically demonstrated a compact, integrable excitation method that might put short-range SPP to good use.

The method in question requires a vertical hybrid coupler structure consisting of two arms: a gold strip as the upper arm and a silicon nitride waveguide as the bottom arm. The two arms, separated by a few micrometres, have different widths and thicknesses to get similar effective indices.

This is the international version of Nature China, if you are based in China we offer a Chinese mirror site.

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# 微纳结构与物理

## 芯片

## 光纤

光子集成  
延迟线  
传感器...

光子晶体  
材料与器件

传感器...

表面等离子体  
物理与器件

电泵发光  
芯片光互连...

硅基光电子

量子通信  
可预测单光子源...

光子晶体光纤  
及其应用

传统有源无源器件  
(LD,LED,SOA,耦合器,光开关等)

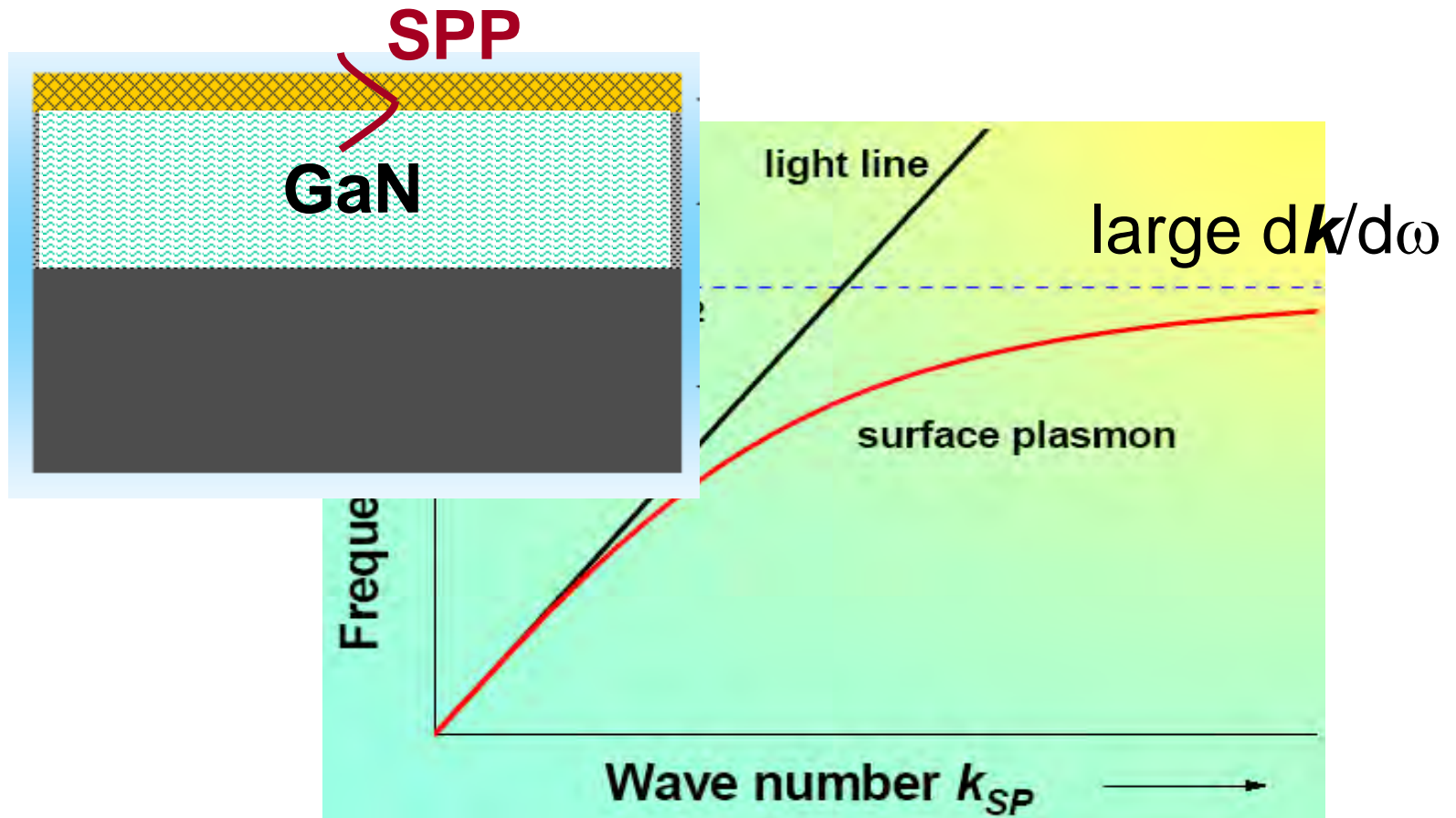
EDFA

光通信、光传感、光存储.....



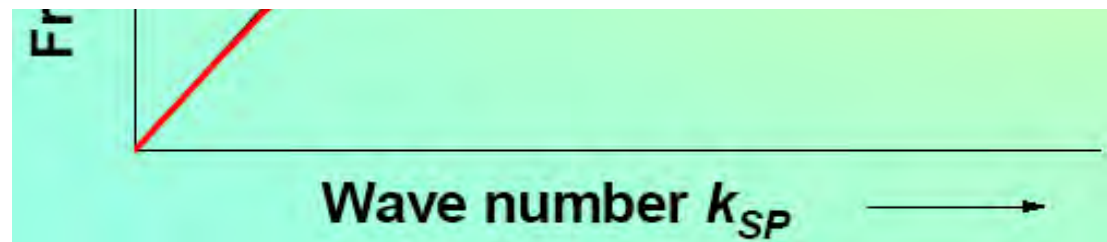
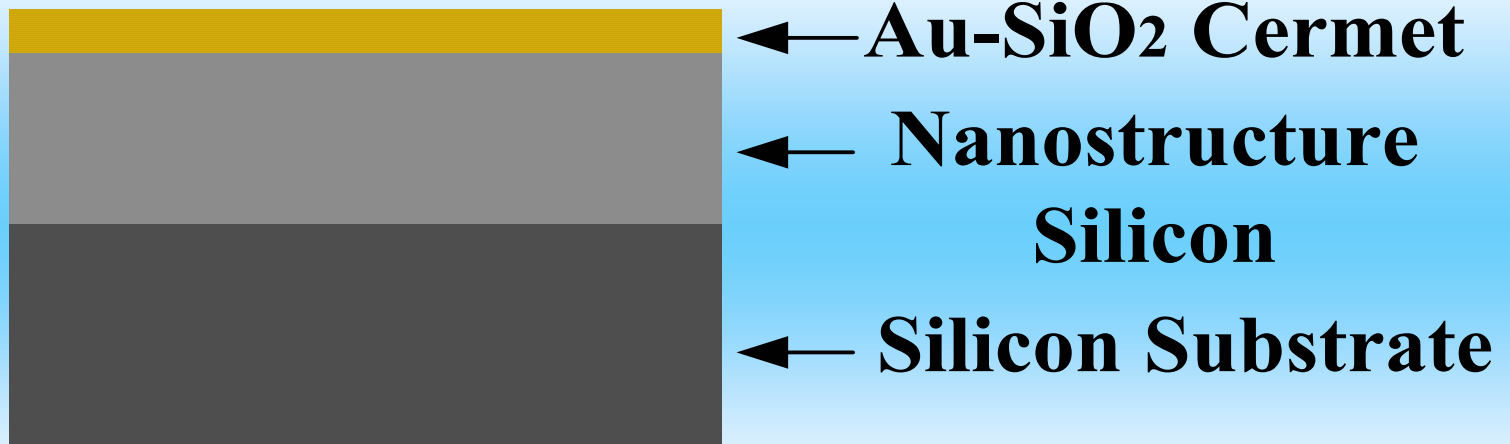
# Purcell Effect Associated with SPP

Enhanced Photoluminescence from Porous Silicon?



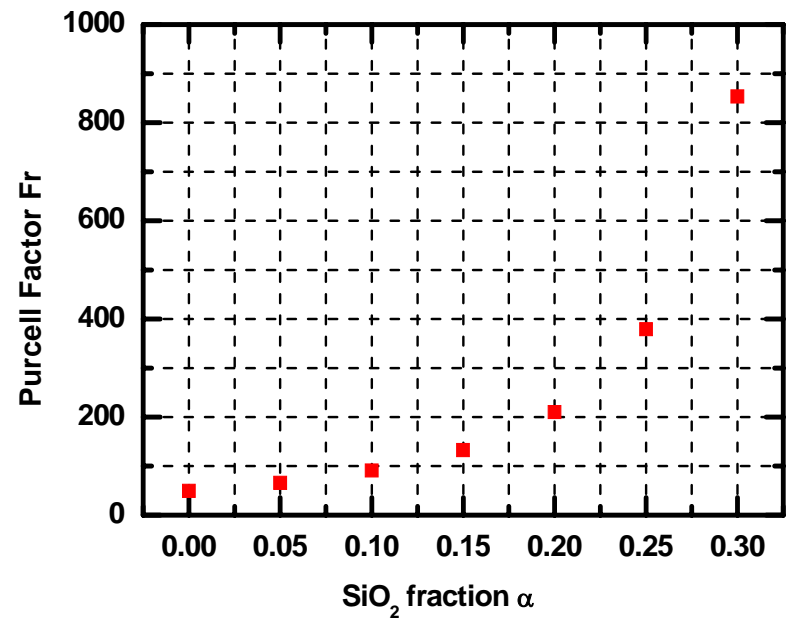
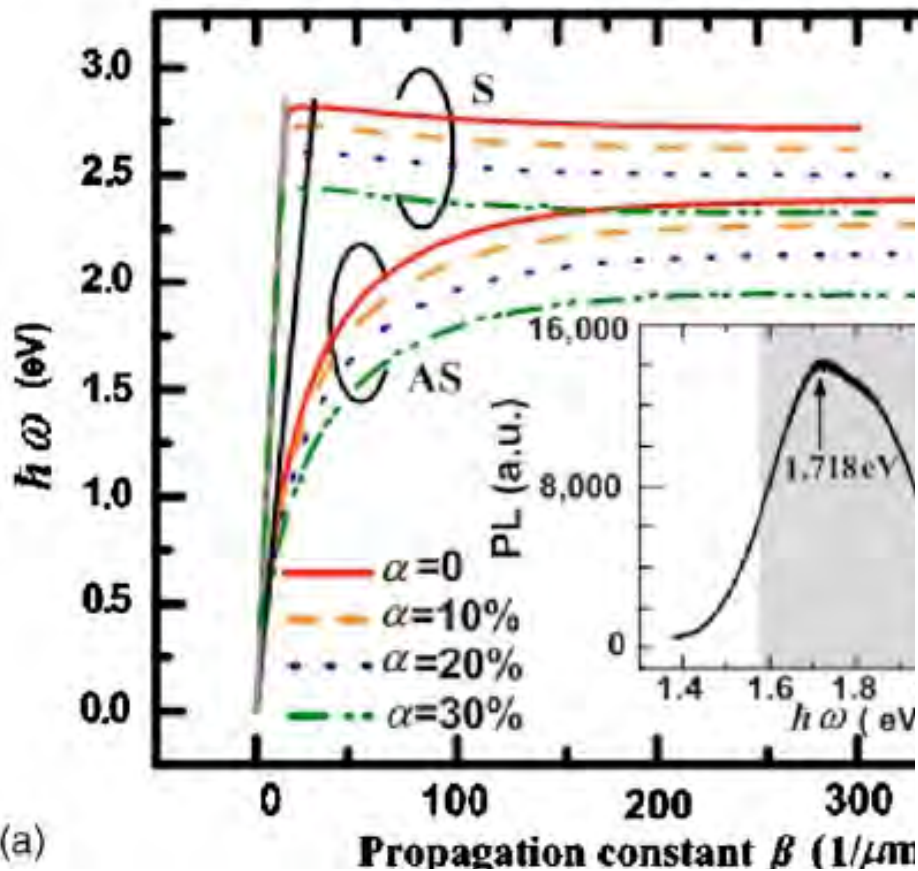
# Purcell Effect Associated with SPP

Enhanced Photoluminescence from Porous Silicon?



# Purcell Effect Associated with SPP

## Enhanced Photoluminescence from Porous Silicon



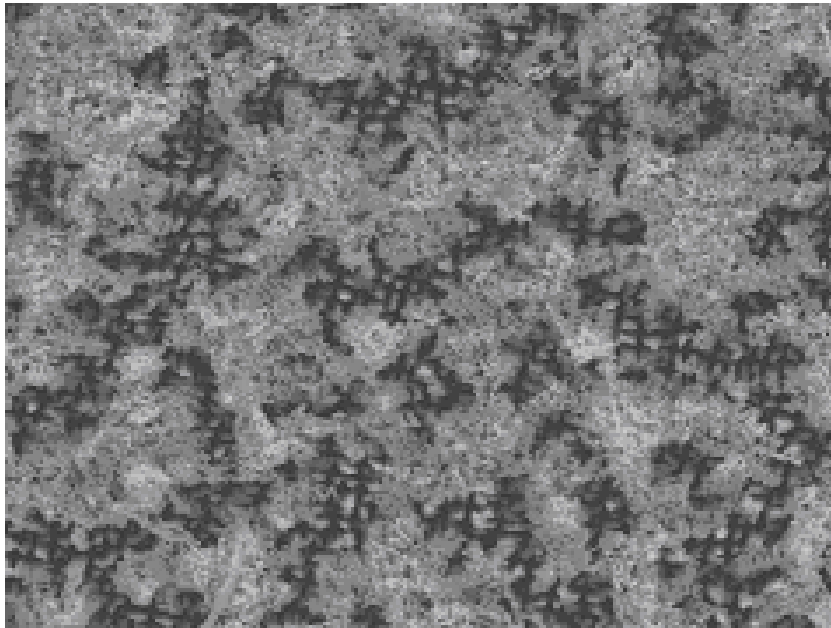
*Appl. Phys. Lett. vol. 89, no. 081112, 2006*

*Appl. Phys. Lett. vol. 92, no. 251116, 2008*

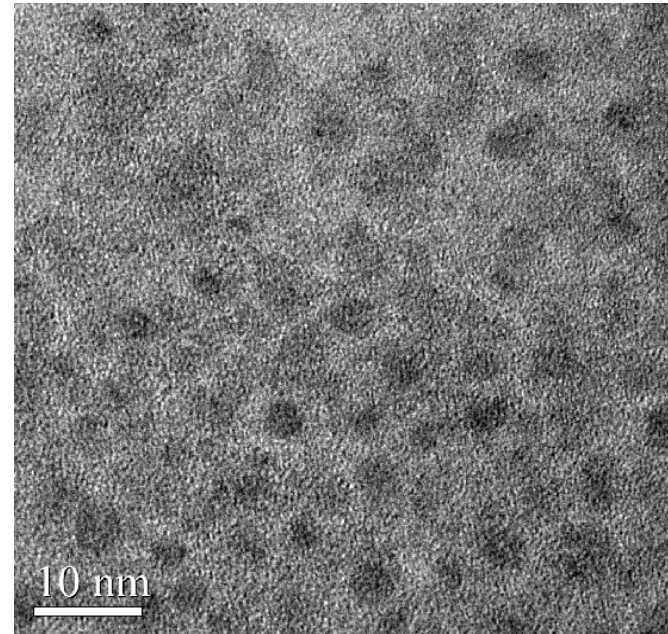
# Nano-Structure Silicon

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Porous Silicon



SiN<sub>x</sub> Nanocrystal

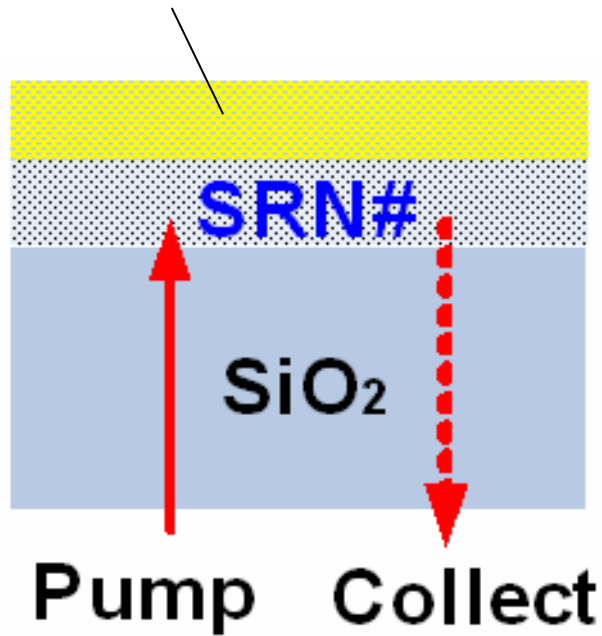


**Surface Plasmon Waveguide**

# Experimental Results

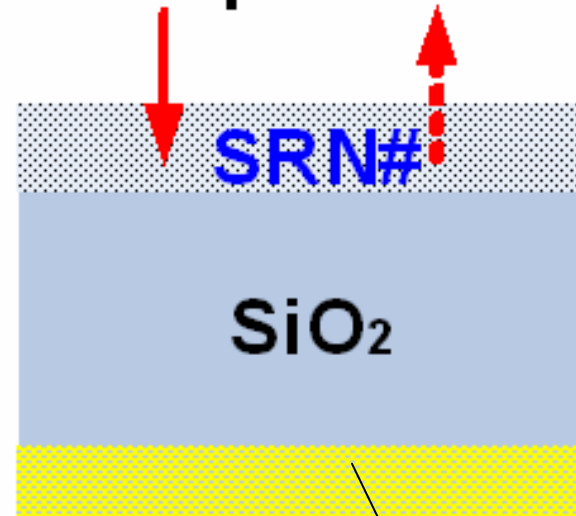
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Au-SiO<sub>2</sub> Cermet



(A)

Pump Collect

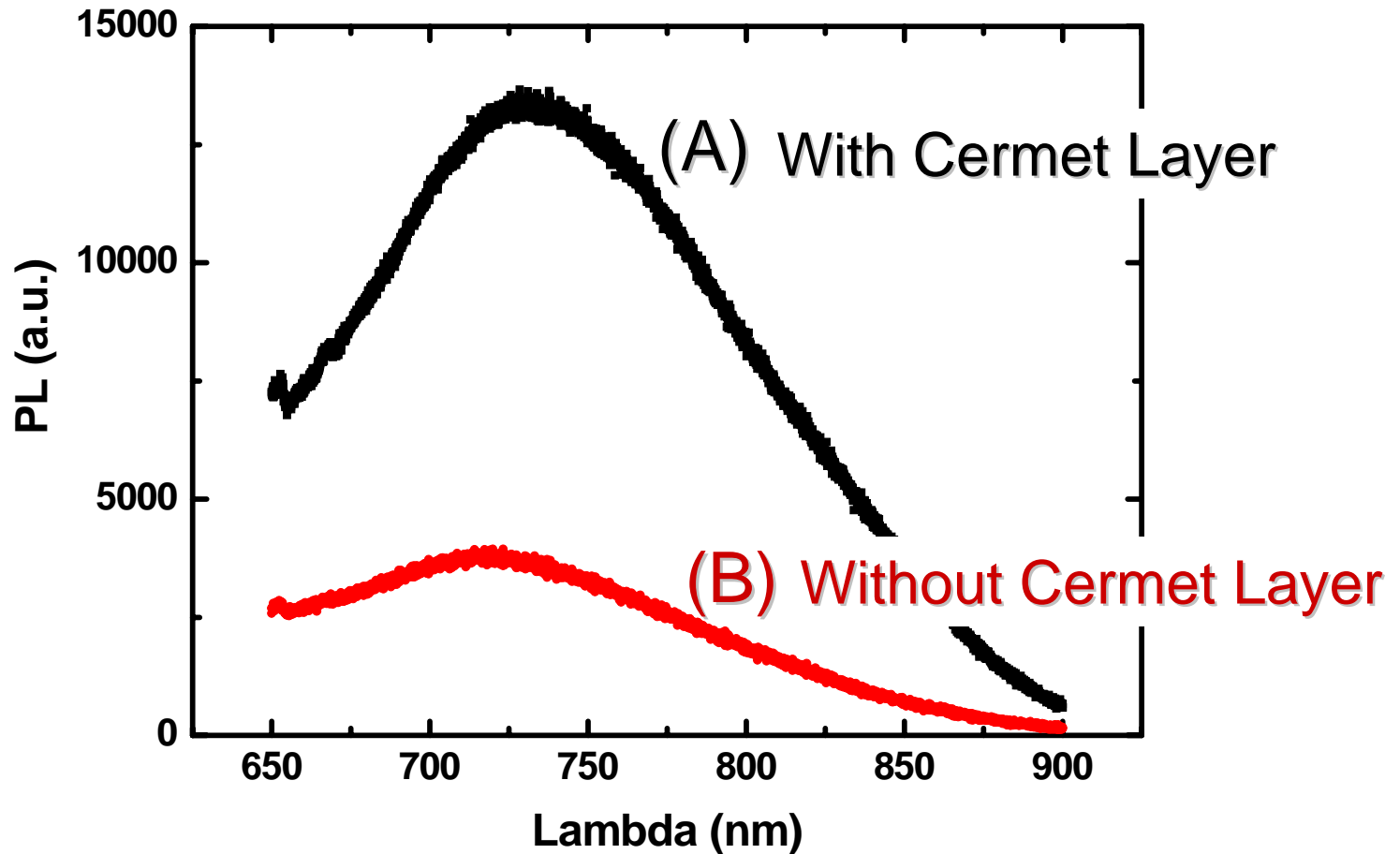


Au-SiO<sub>2</sub> Cermet

(B)

# Experimental Results

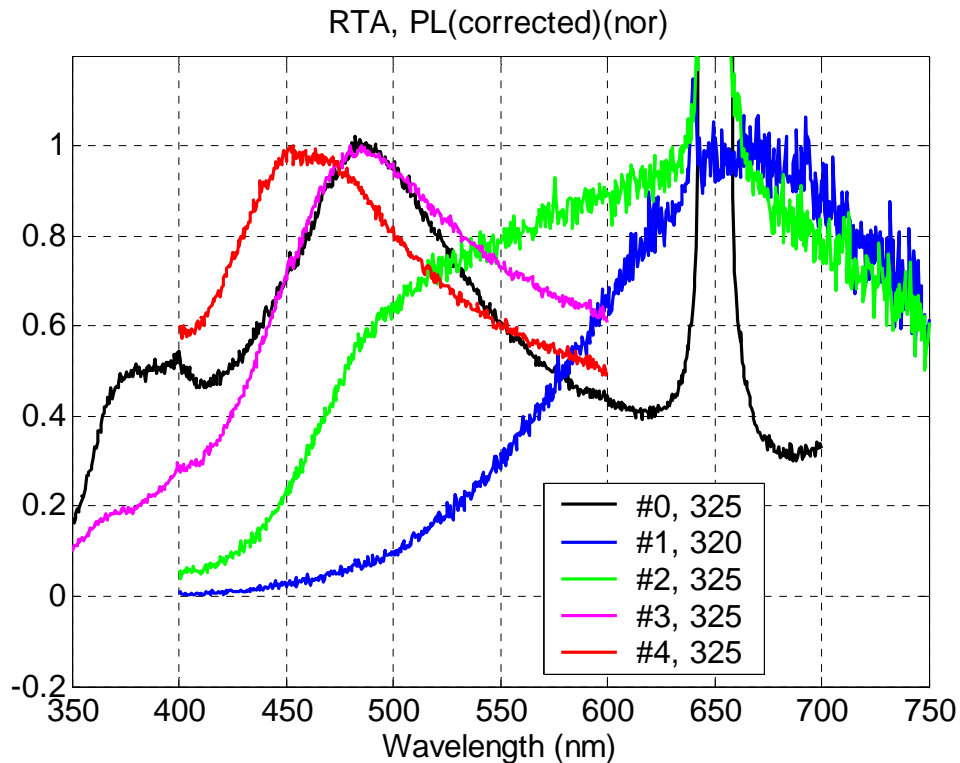
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# Photoluminescence (PL)



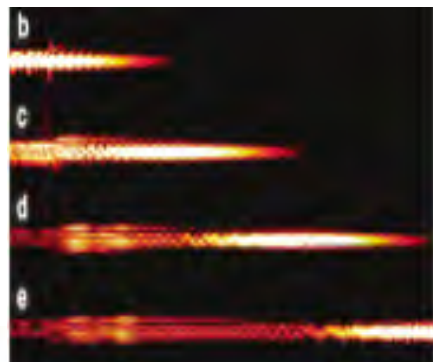
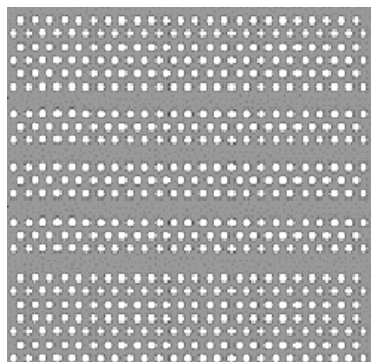
Excited by 325nm  
laser ( $0.5\text{mW}/\text{mm}^2$ )



**~1% of III-V  
semiconductor**



# 光子晶体慢光波导 光学真延迟结构设计

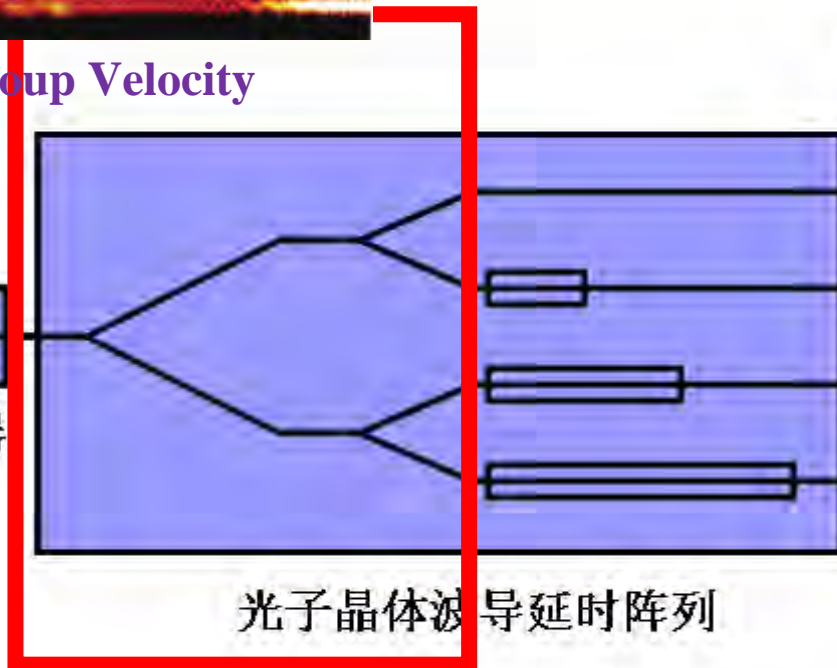


Controllable Light Group Velocity

波长可调激光器



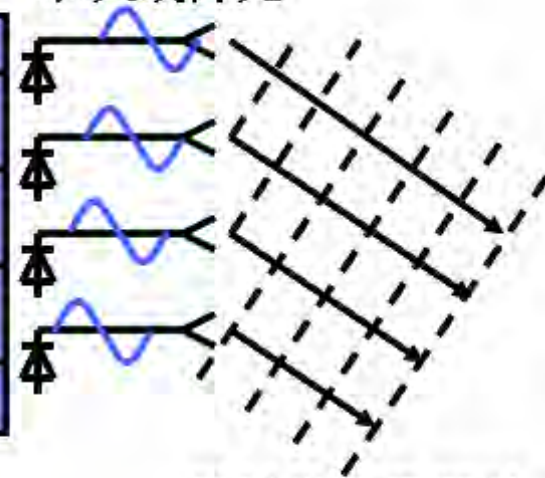
光调制器



光子晶体波导延时阵列

Y分支光波导

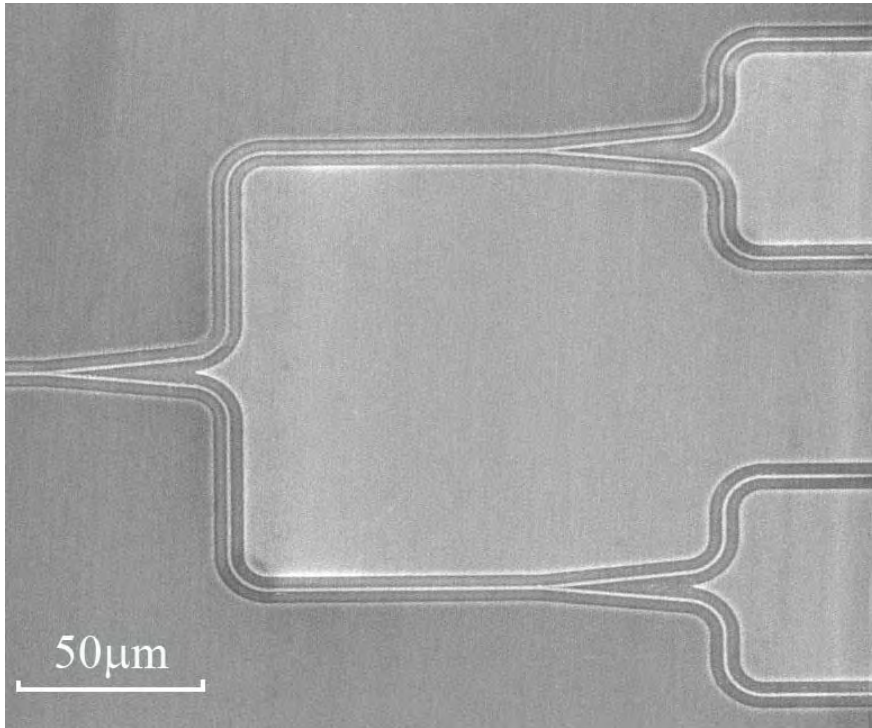
光电探测器和天线阵元



通过光学真延时  
实现波束偏转



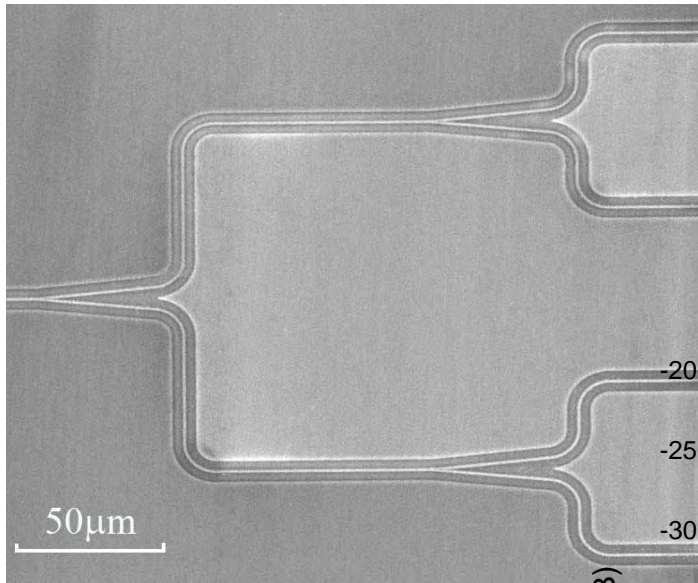
# Si 纳米线 Y 分支光波导的制作



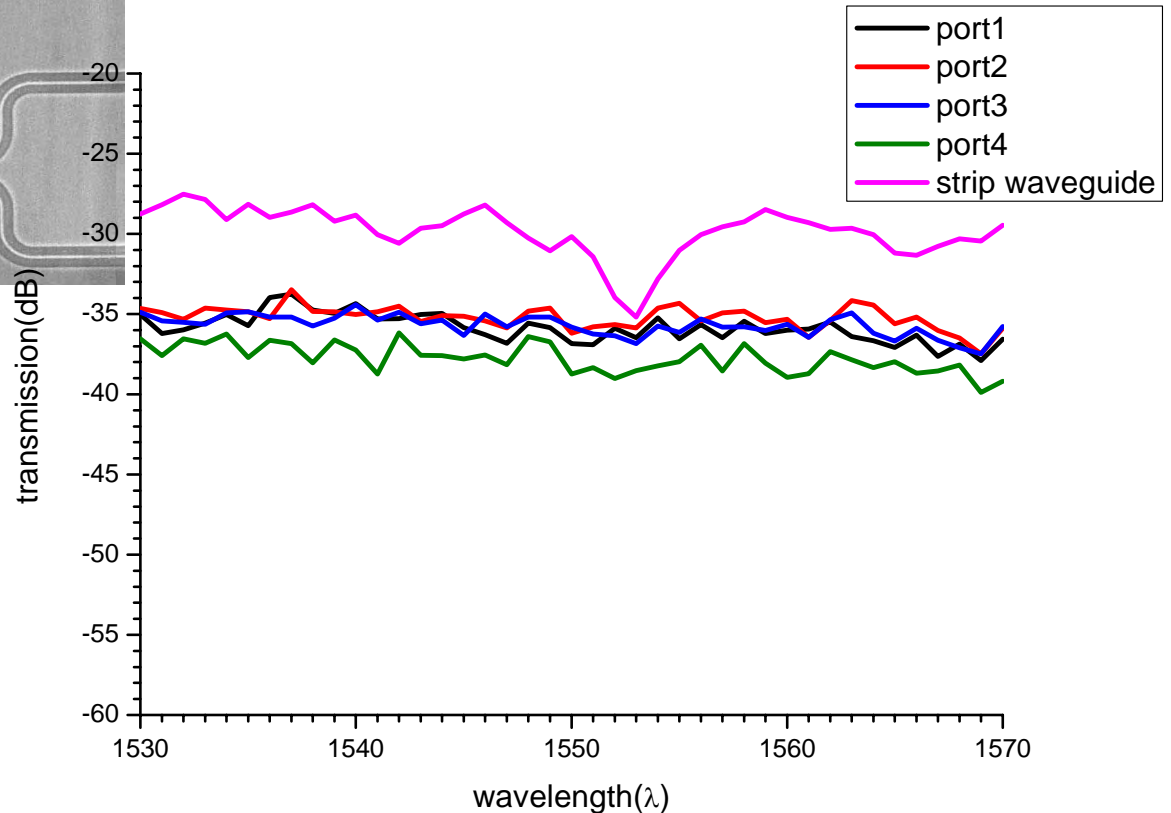
波导宽度=465nm 分支角度=12度 转弯半径=10 $\mu$ m

表面SiO<sub>2</sub>覆盖层：600nm

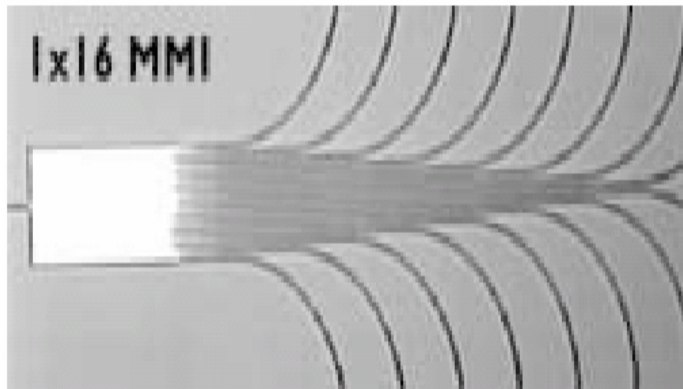
# Si 纳米线 Y 分支光波导的制作



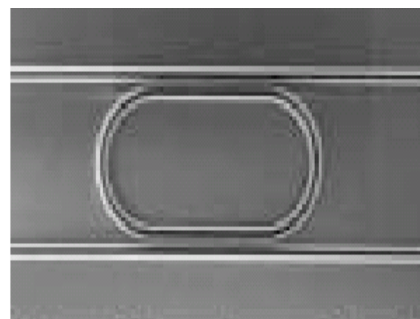
插入损耗：1-2dB



# 硅纳米线 Si-Nanowire Waveguide

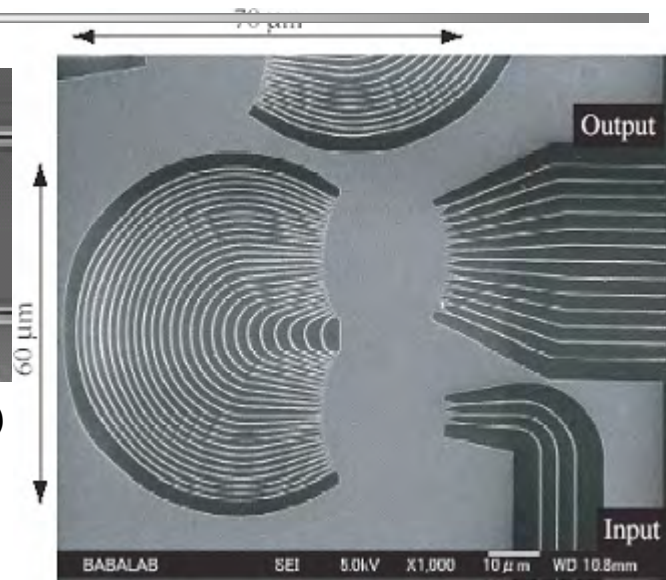


MMI coupler (MIT)

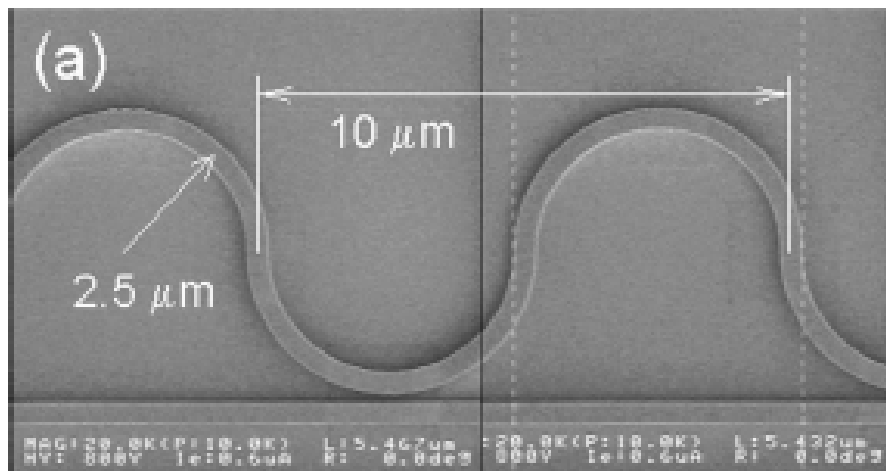


Ring resonator (MIT)

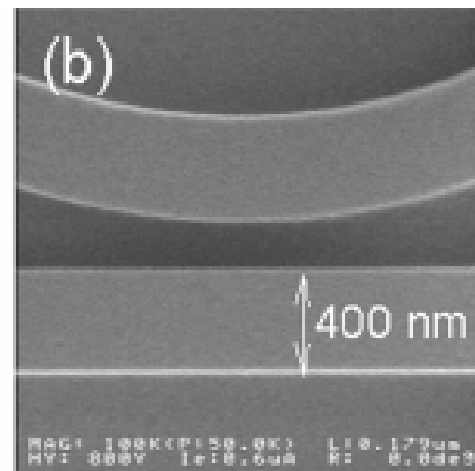
K. Sasaki, et al., IQEC &  
CLEO-PR 2005, CWE1-1  
(2005)



AWG (Yokohama National Univ.)



Lattice filter  
(NTT)



K. Yamada, et al., IEICE Trans.  
Electron. **87-C**, 351 (2004)

# 微纳结构与物理

## 芯片

## 光纤

光子集成  
延迟线  
传感器...

光子晶体  
材料与器件

传感器...

电泵发光  
芯片光互连...

量子通信  
可预测单光子源...

硅基光电子

光子晶体光纤  
及其应用

表面等离子体  
物理与器件

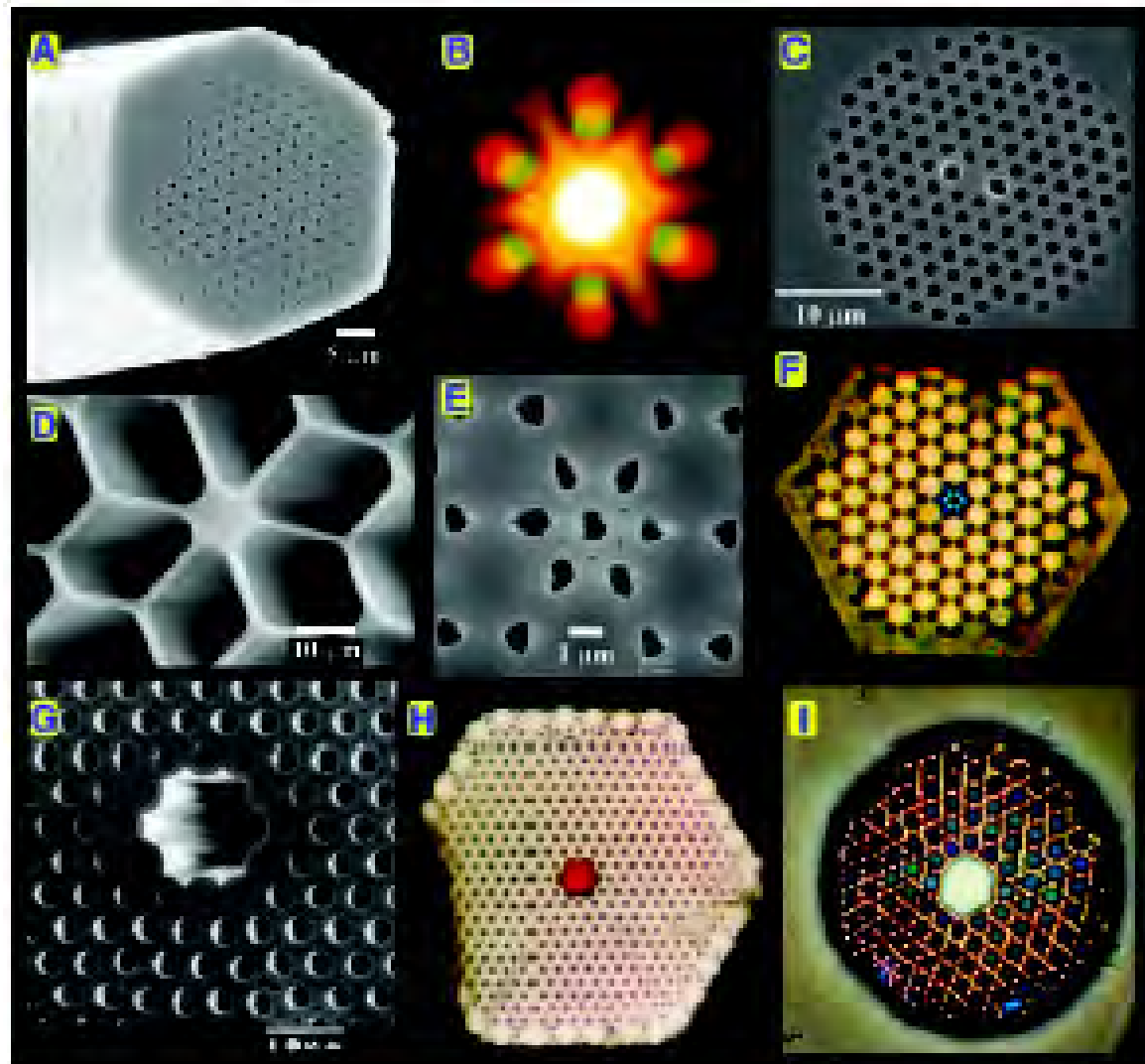
传统有源无源器件  
(LD,LED,SOA,耦合器,光开关等)

EDFA

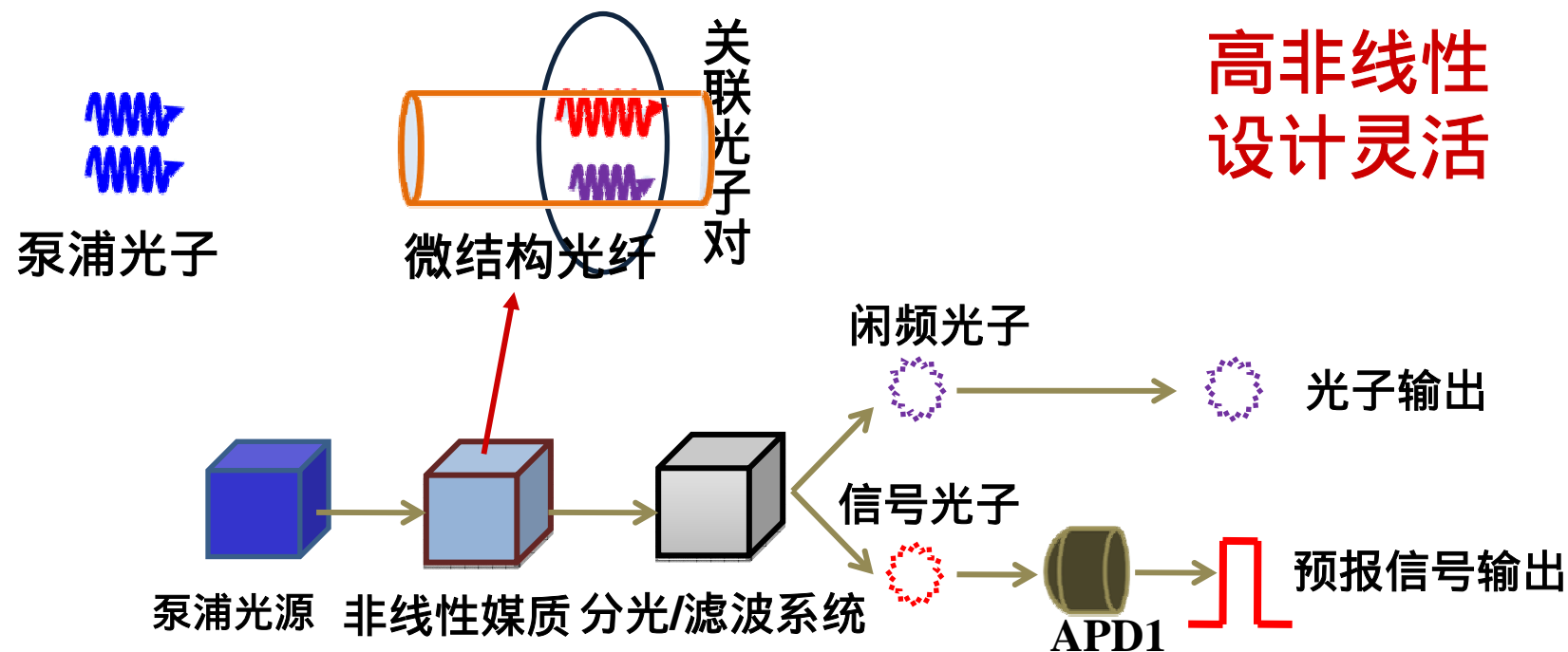
光通信、光传感、光存储.....

# 微结构光纤 (MSF)

- 一种芯轴四周排布许多气孔的石英纤维



# 可预报单光子源



➤ 非线性光学过程产生具有**时间关联性的两路光子**

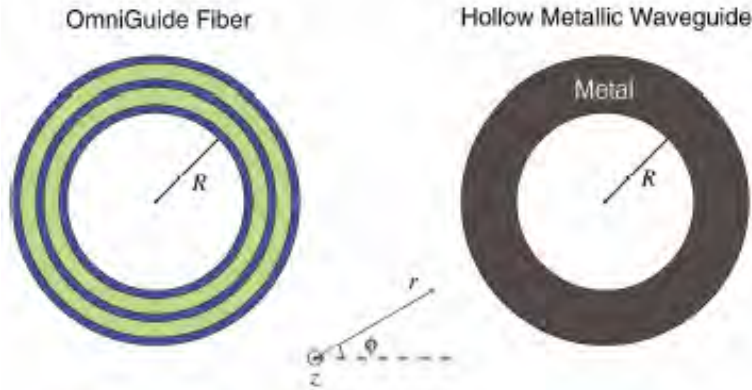
——**关联光子对**

➤ 探测其中一路光子，预报另一路**1.5微米波段单光子**的存在

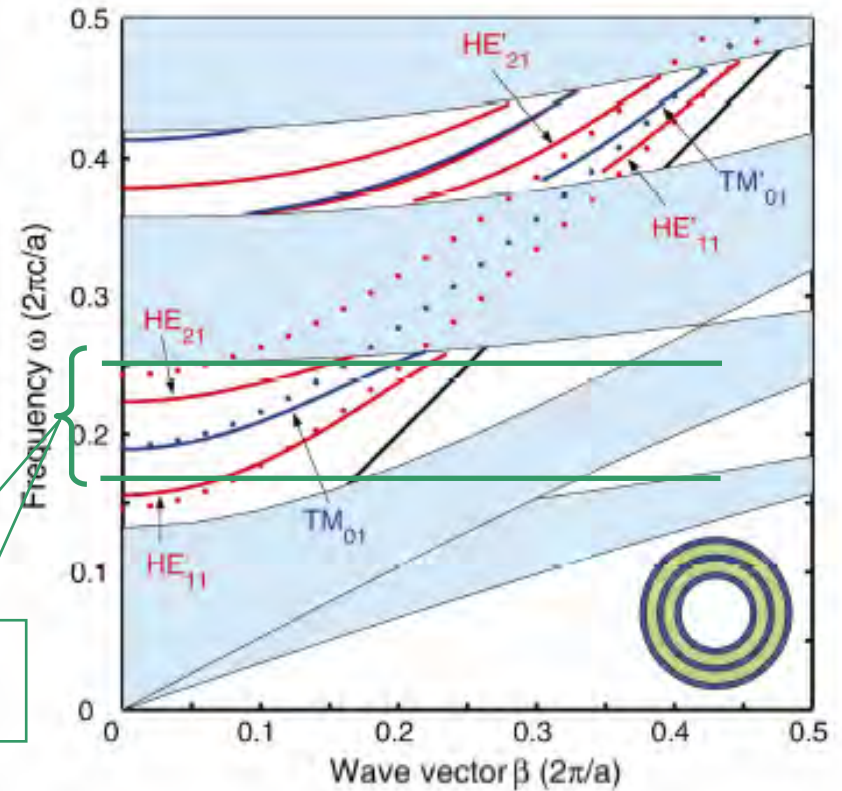
**能够在保证单光子输出的基础上，有效避免空脉冲！**

# 半导体聚合物基全向反射导引Bragg光纤

- 导光机制：圆筒状全向反射膜层  $\rightarrow$  1D PC 全向反射
  - 高反射纤维
  - 全介质空心波导



模式特性与金属波导接近 **Omni-directional reflection band**

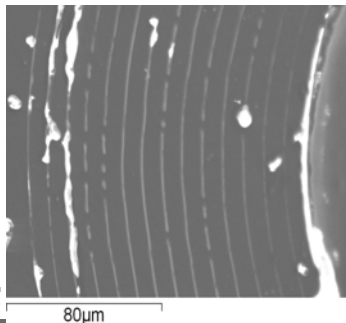




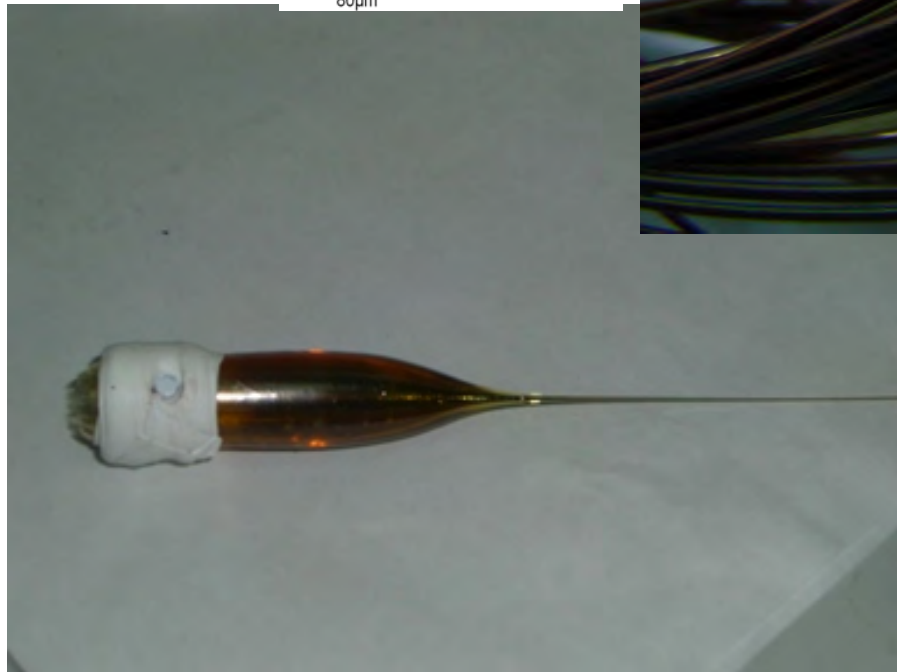
# 半导体/聚合物Bragg光纤的制备工艺和测试研究

- 半导体/聚合物Bragg光纤制备工艺平台的建立和工艺可行性的实验论证

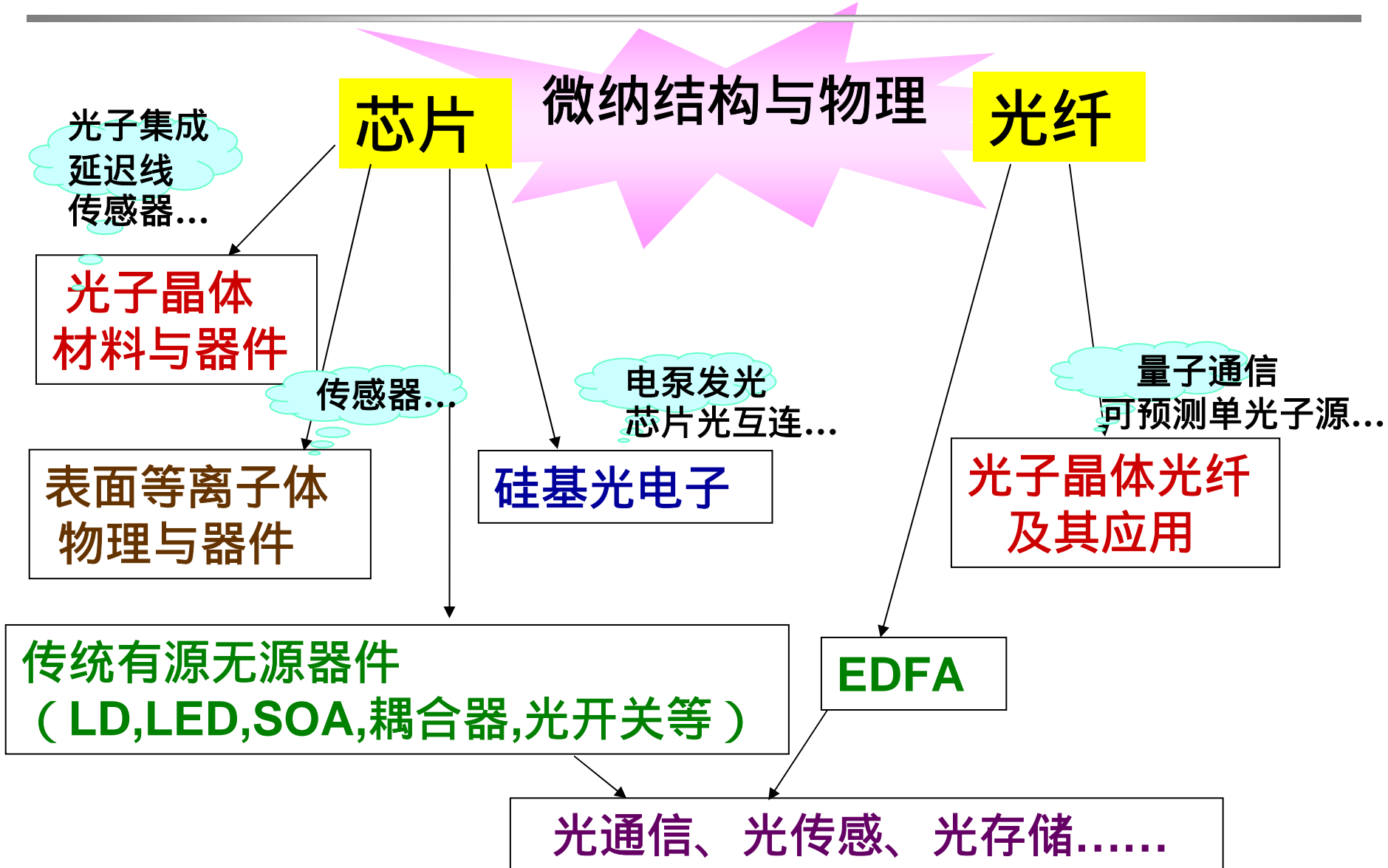
预制棒丝头



半导体聚合物Bragg光纤样品



# 纳结构光电子器件



谢谢!

