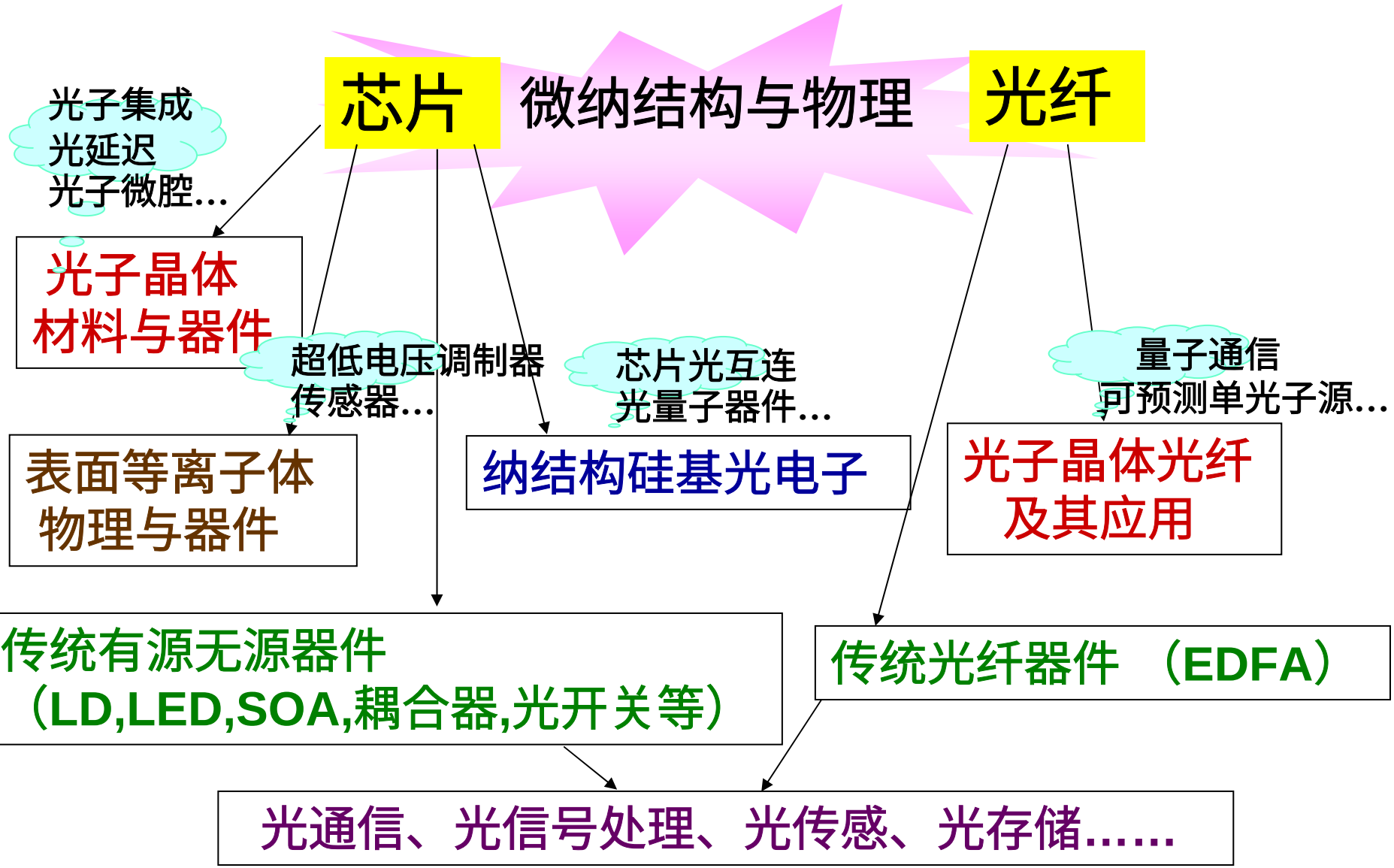
纳结构光电子器件

Research on Nano-Optoelectronics

清华大学 电子工程系 黄 翊 东

纳结构光电子器件

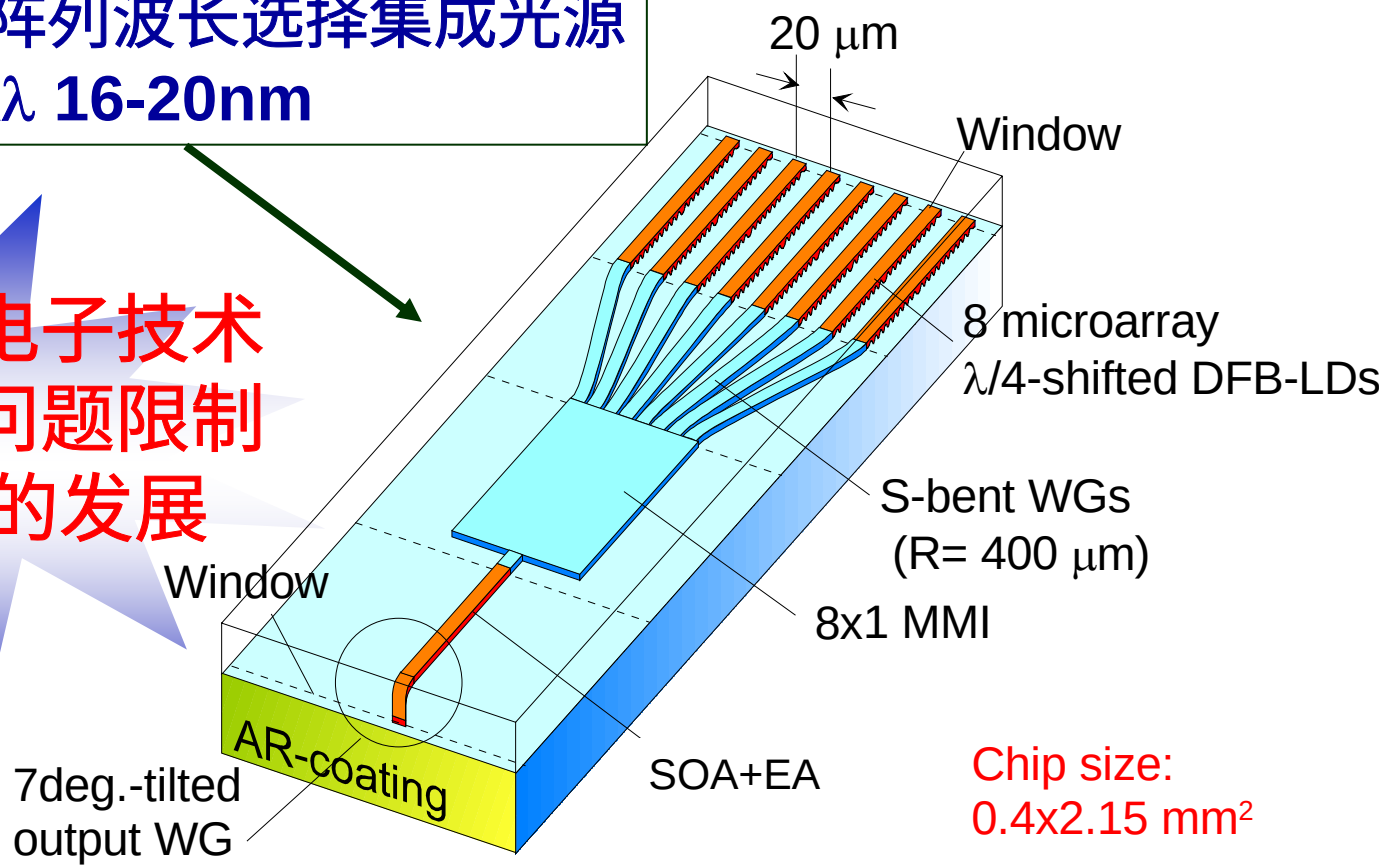

芯片
微纳结构与物理
光纤
光子集成
光延迟
光子微腔…
光子晶体
材料与器件
超低电压调制器
传感器…
芯片光互连
光量子器件…
量子通信
可预测单光子源…
表面等离子体
物理与器件
纳结构硅基光电子
光子晶体光纤
及其应用
传统有源无源器件
（LD,LED,SOA,耦合器,光开关等）
传统光纤器件 （EDFA）
光通信、光信号处理、光传感、光存储……

光电子器件技术突破期待着

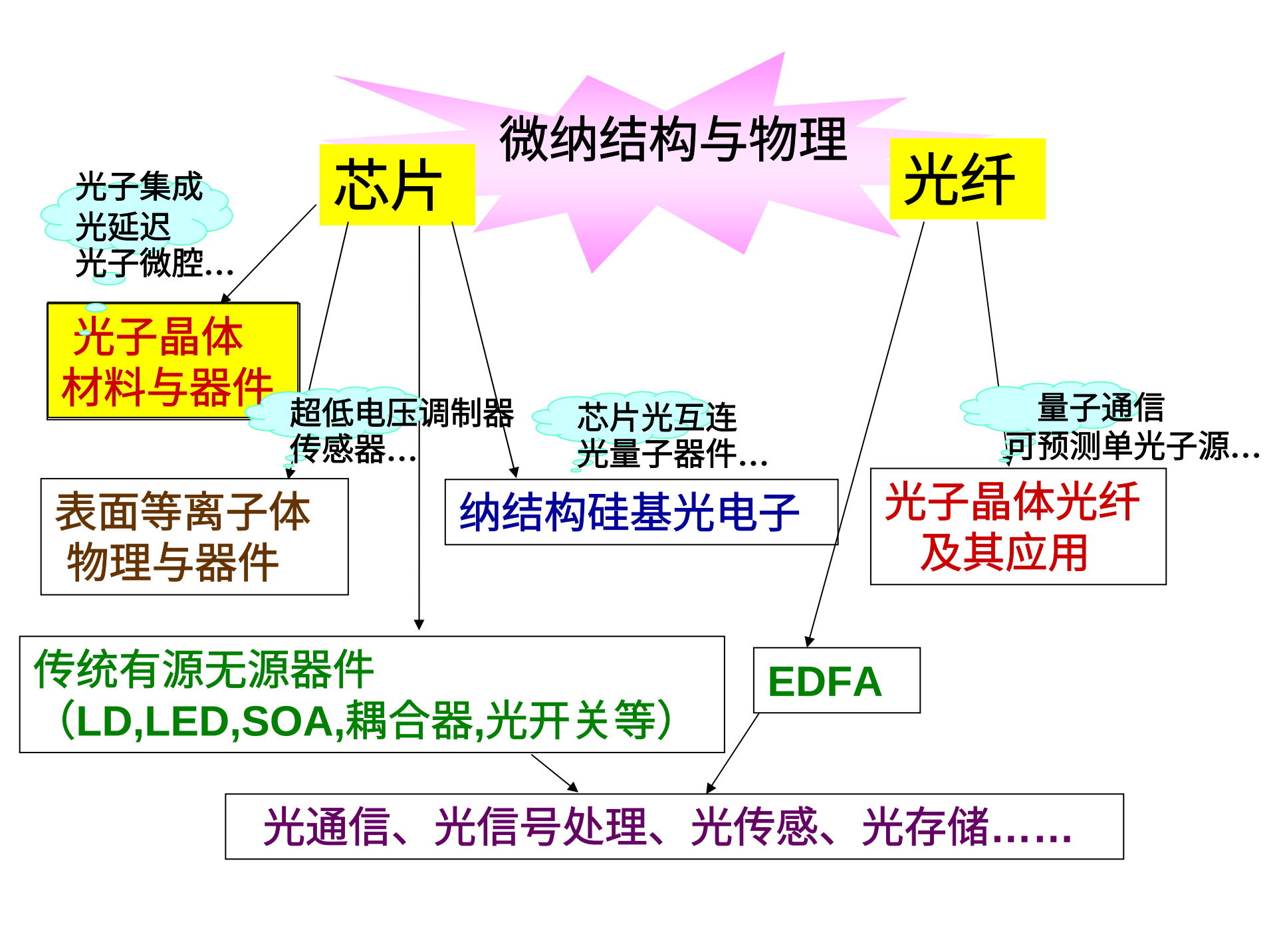
新材料、新原理、新技术的出现

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



Chip size:
0.4x2.15 mm^2


微纳结构与物理
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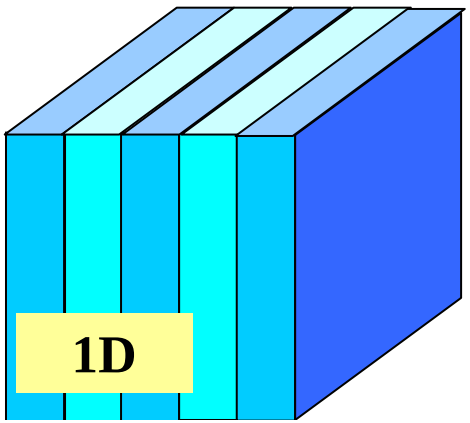
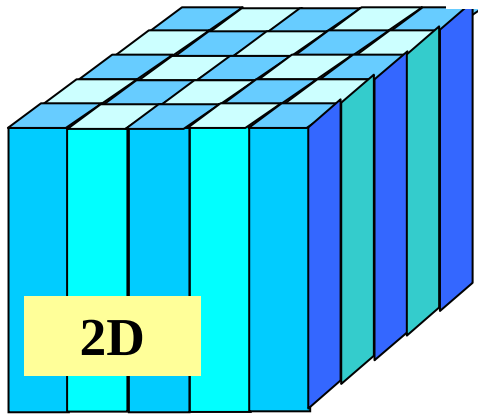
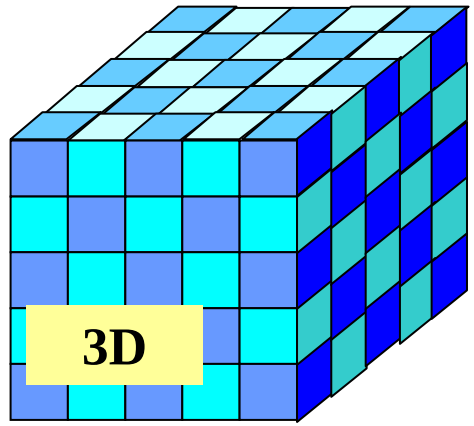
（LD,LED,SOA,耦合器,光开关等）
EDFA
光通信、光信号处理、光传感、光存储……

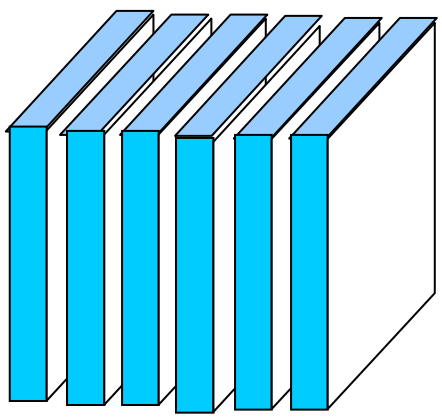
光 子 晶 体

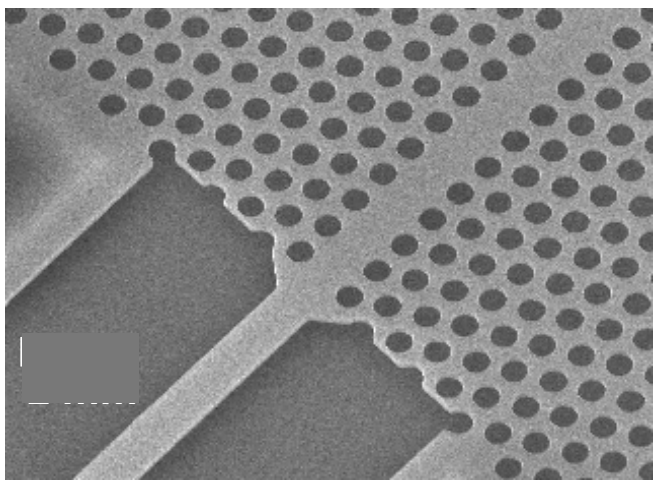
- 由介电常数不同的介质材料在空间周期性排列而构成, 变化周期为波长量级

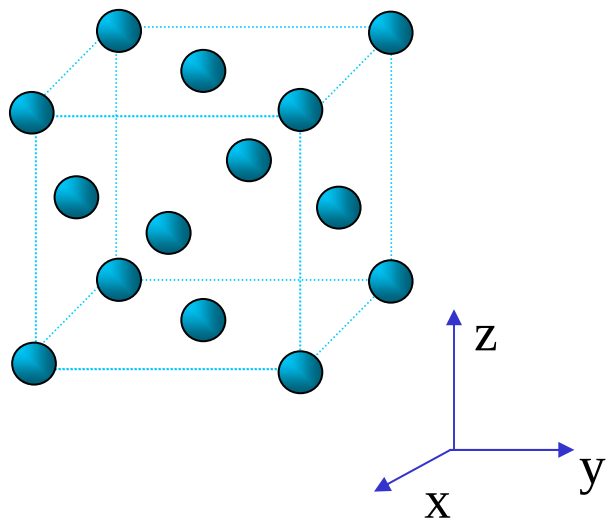




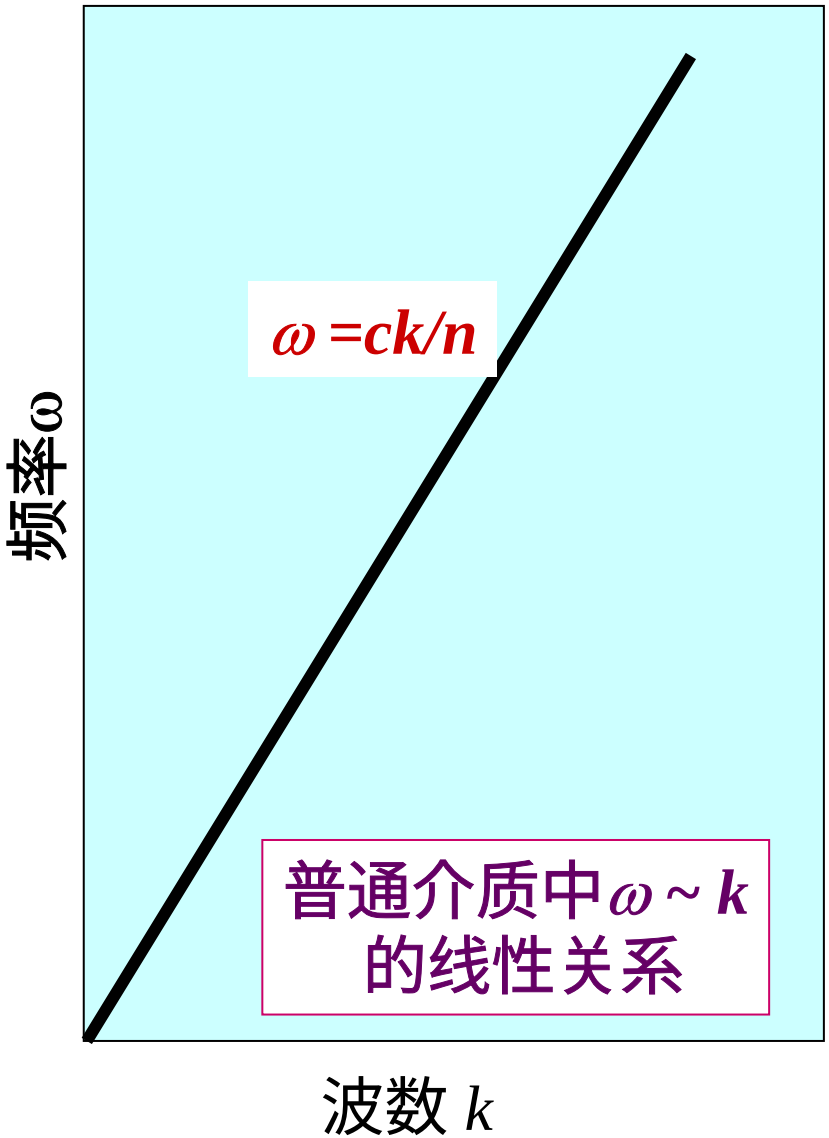


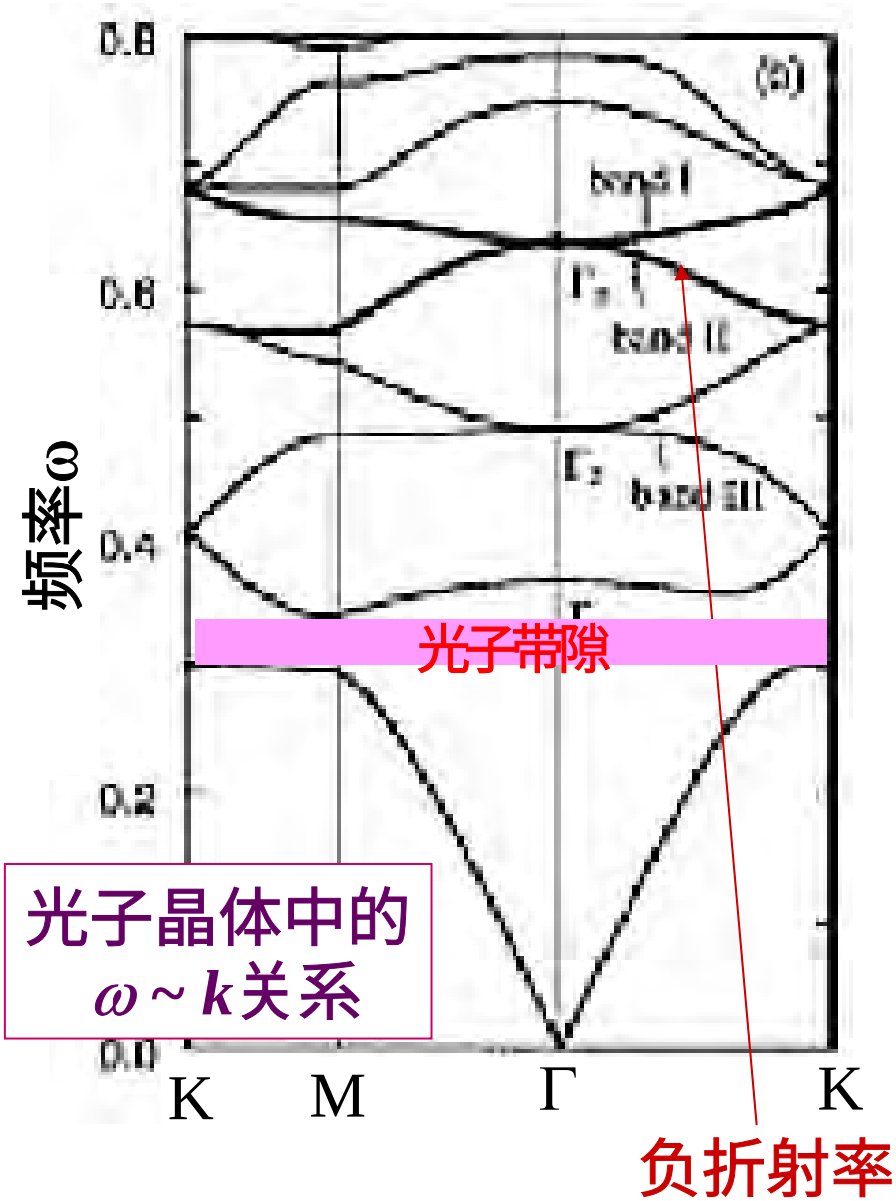






光子晶体的光带结构图

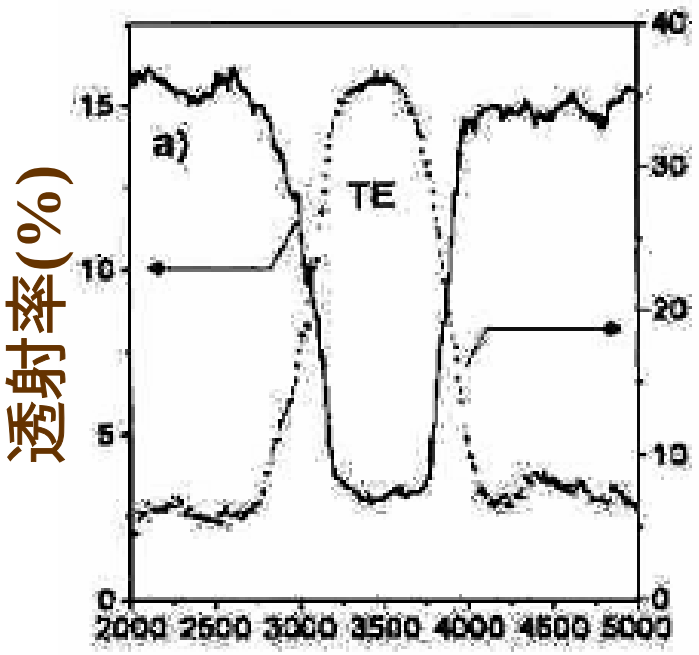

频率ω
ω =ck/n
普通介质中ω ~ k
的线性关系
波数 k

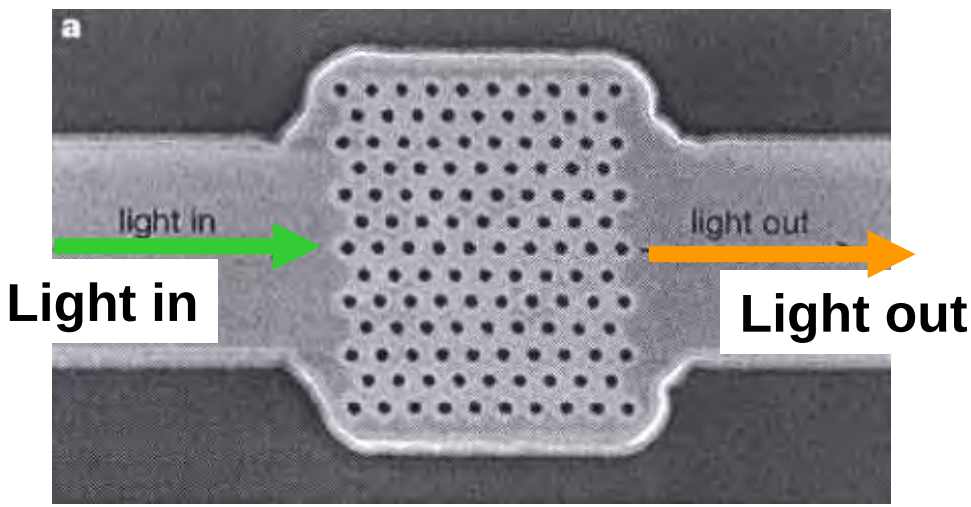

频率ω
0.8
0.6
0.4
0.2
0.0
(a)
band I
band II
band III
光子带隙
光子晶体中的
ω ~ k关系
K
M
Γ
K
负折射率

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

- 1987年 E.Yablonovitch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

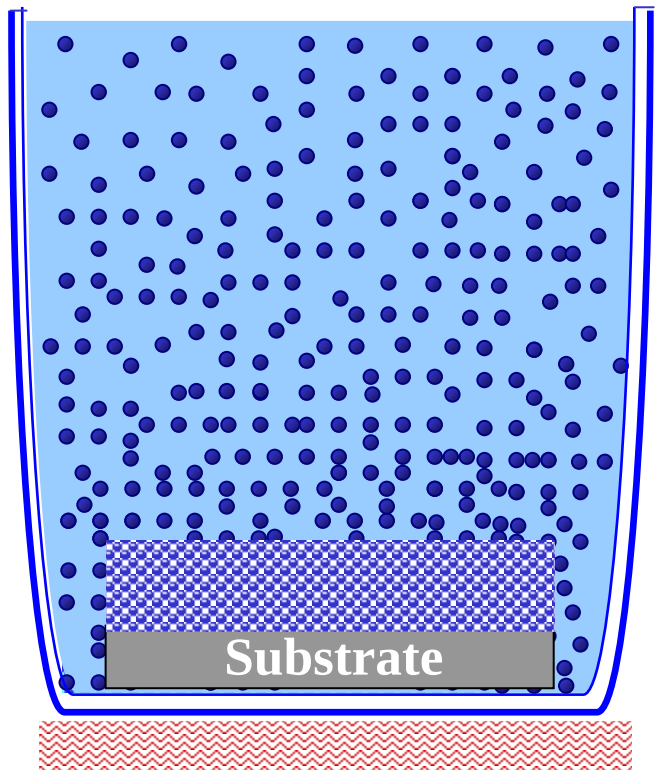
三维光子晶体的实验研制

自 组 装 法

●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。

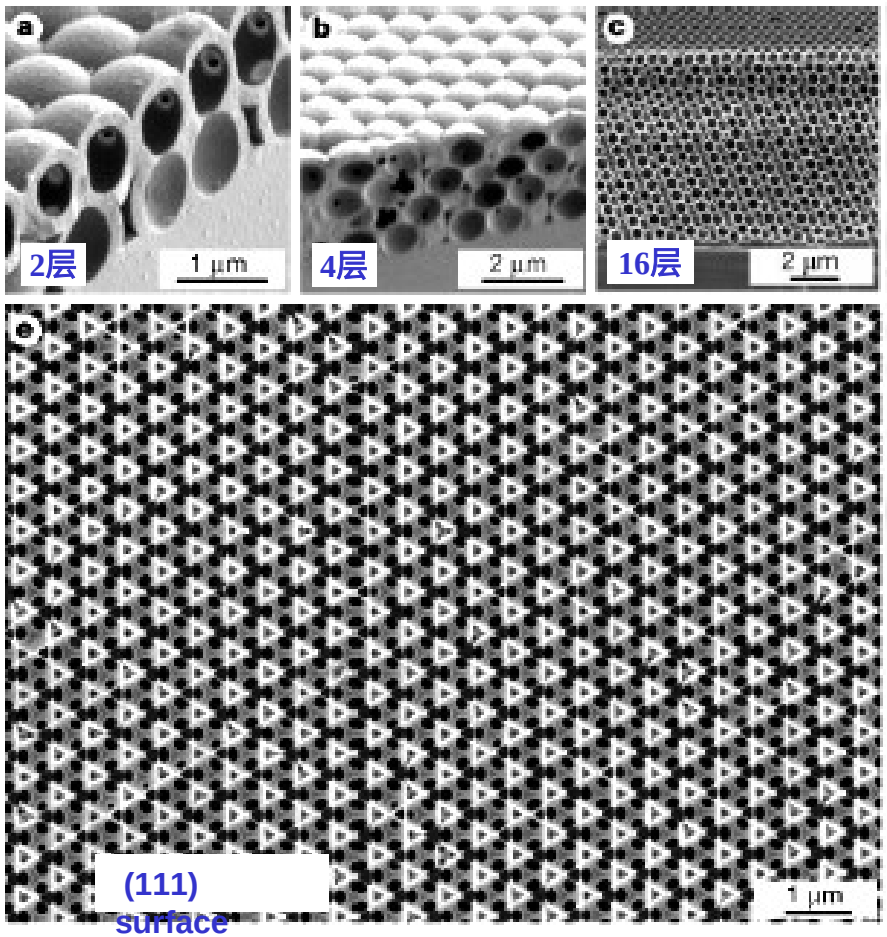


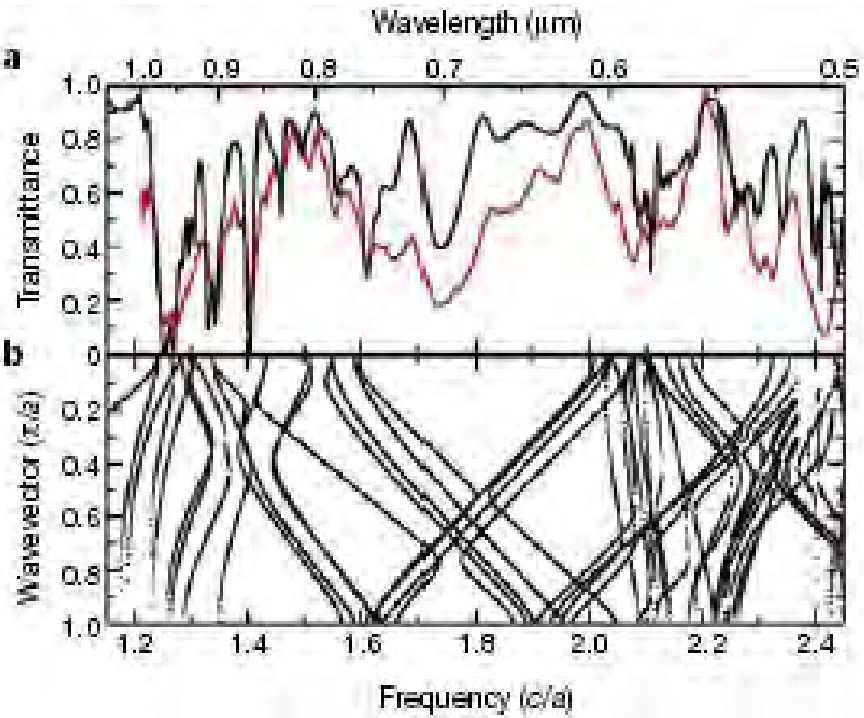
介电常数比较小而禁带窄小

H. Miguez, et.al.,“Photonic crystal properties of packed submicrometric 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): 1mm,
(c, e): 670nm

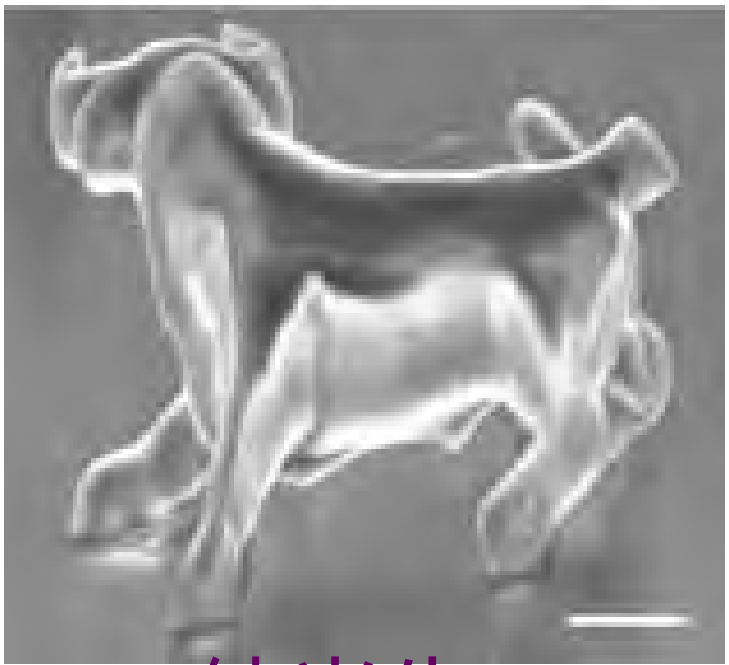
a. 透射谱：— 理论
— 实验

b. 理论计算的光子能带

三维光子晶体的实验研制

纳米激光加工

双光子吸收光聚合



纳米牛

(体长10μm)

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

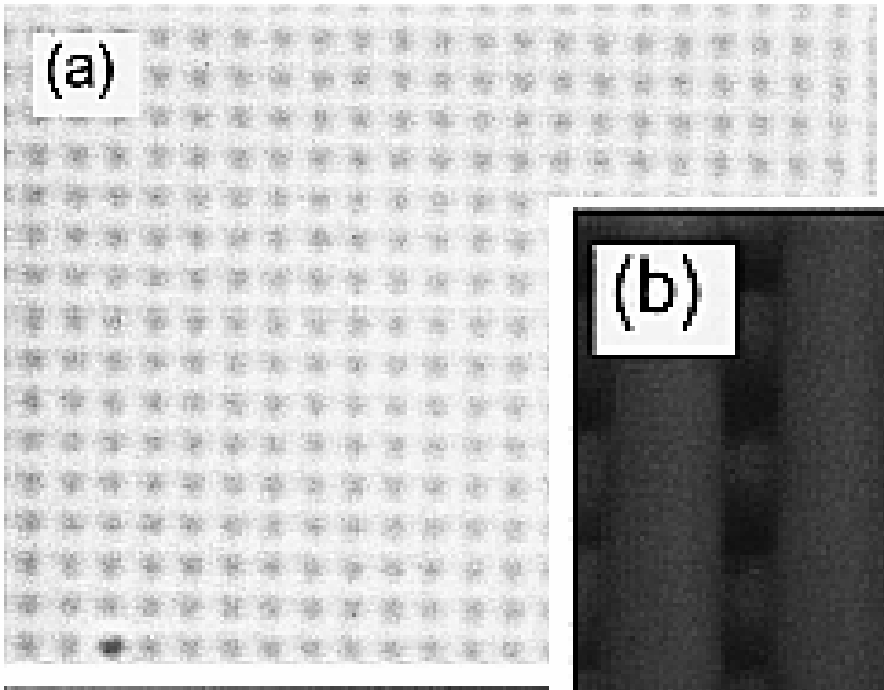
波长： 800→400nm

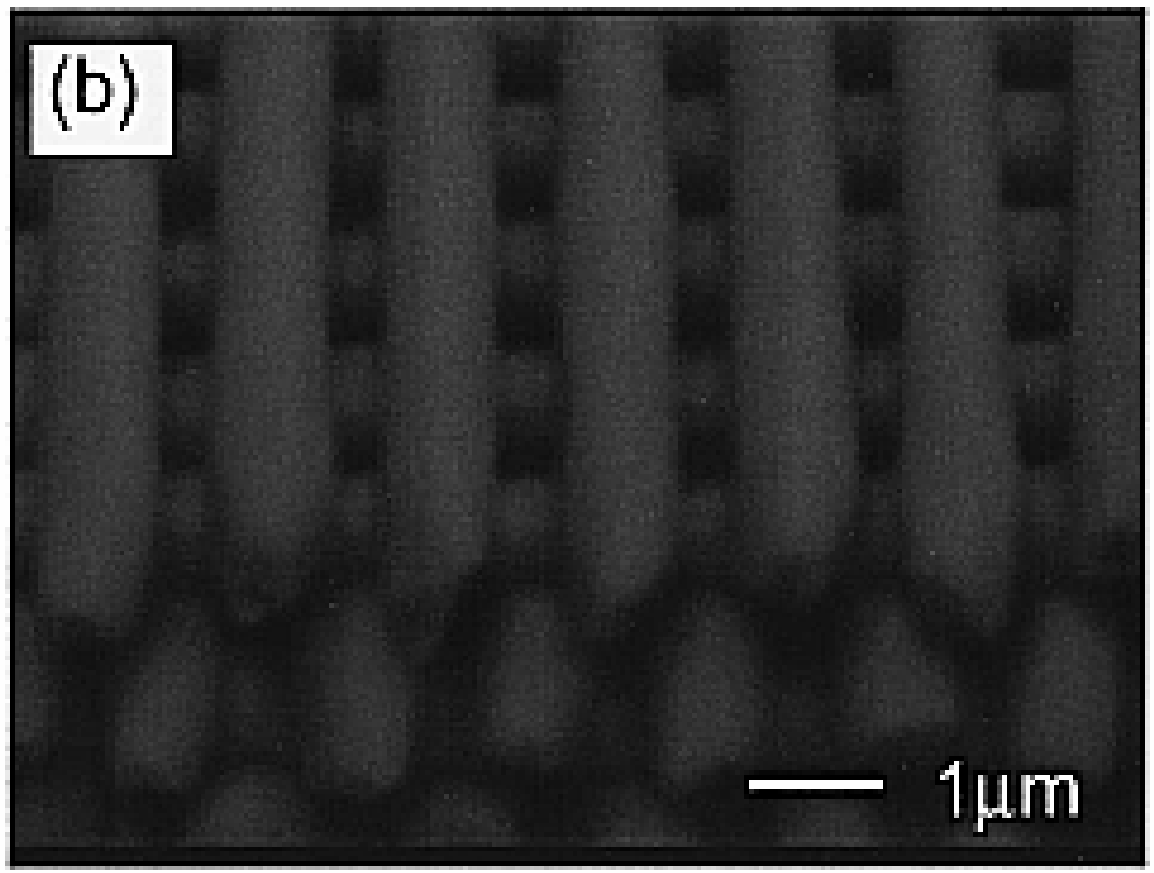
脉冲： 5KHz, 130fs

分辨率： 120nm

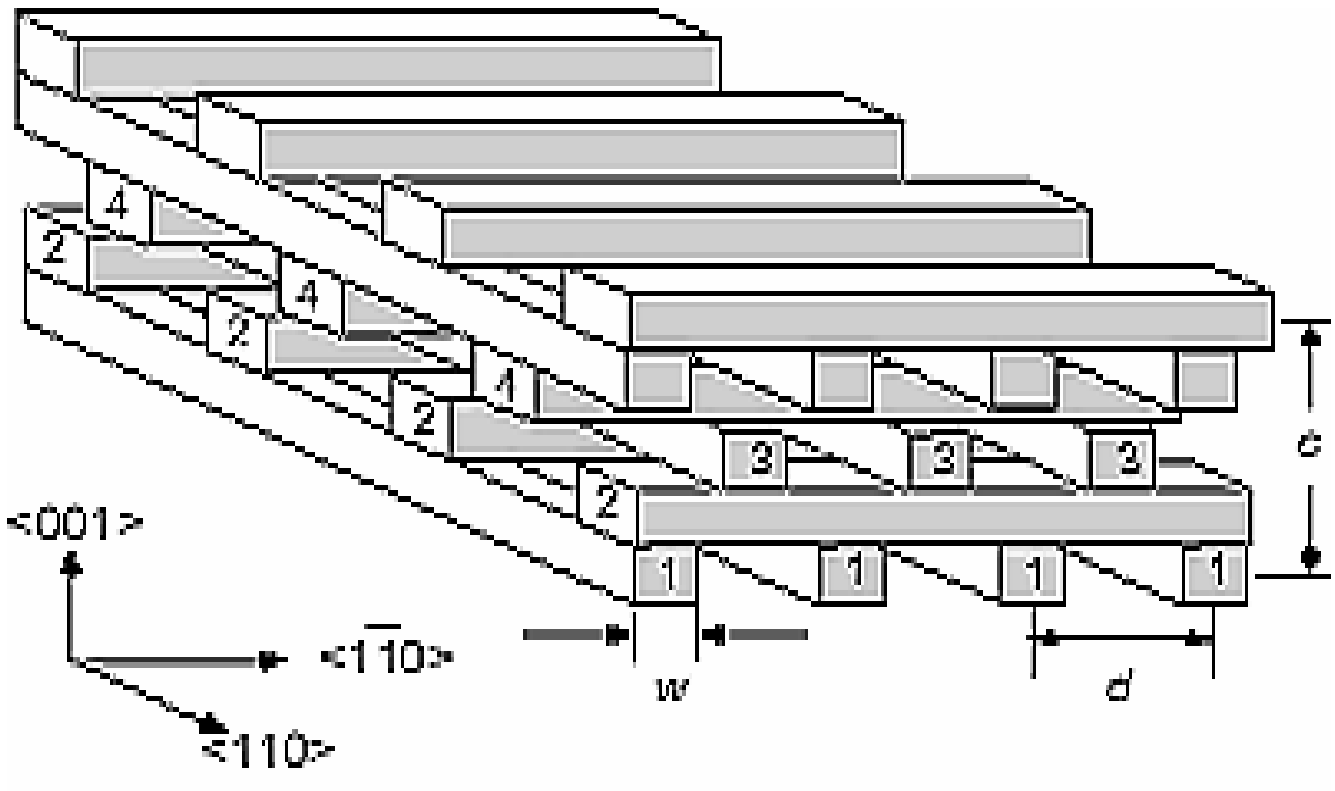
三维光子晶体的实验研制

纳米激光加工





3D PC 的基板融接制作法—积木法

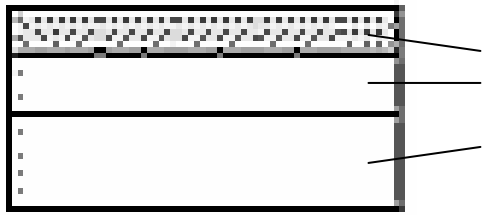


调整w,d,c,光子禁带从远红外至1.35-1.95μm.

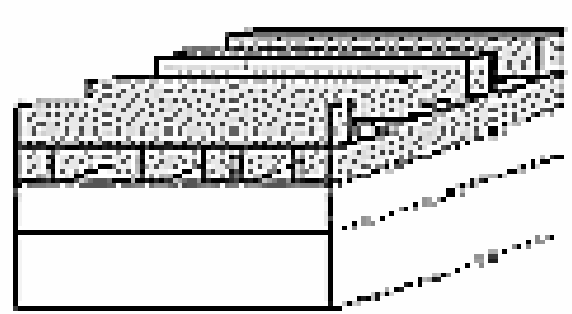
S. Y. Lin, et.al., "A three-dimensional photonic crystal operating at infrared wavelengths", *NATURE,* 1998, 394(16):251- 253

三维光子晶体的实验研制

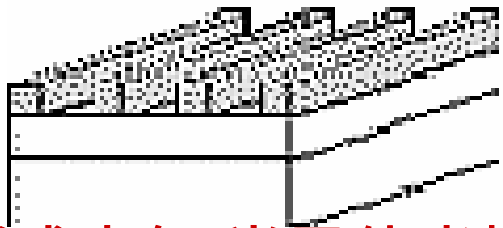
3D PC 的基板融接制作法



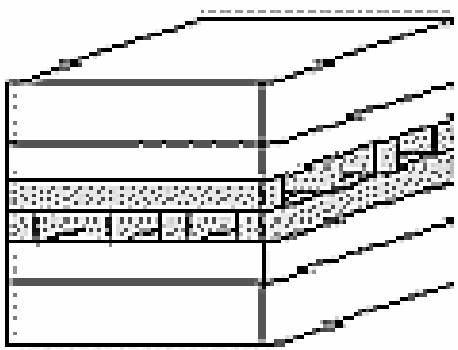
结晶生长



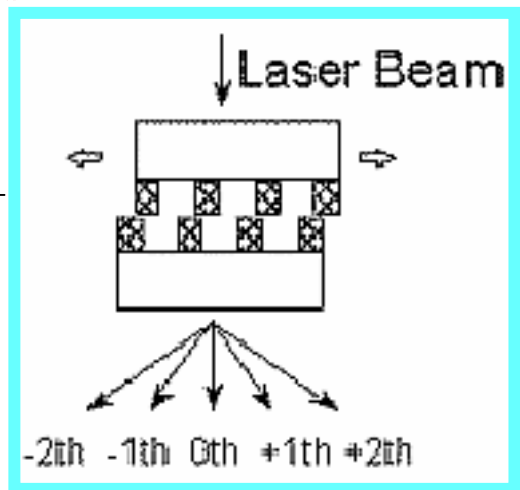
除去上层衬底

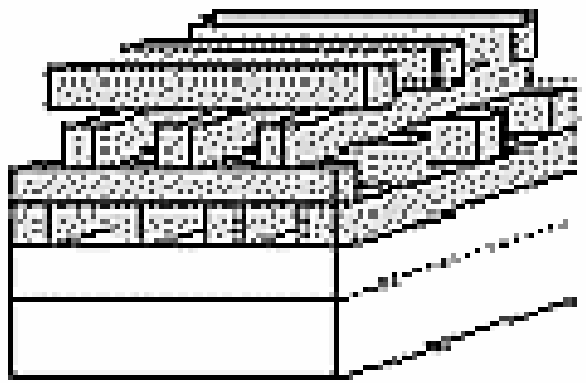


形成空气/半导体光栅



Wafer融接



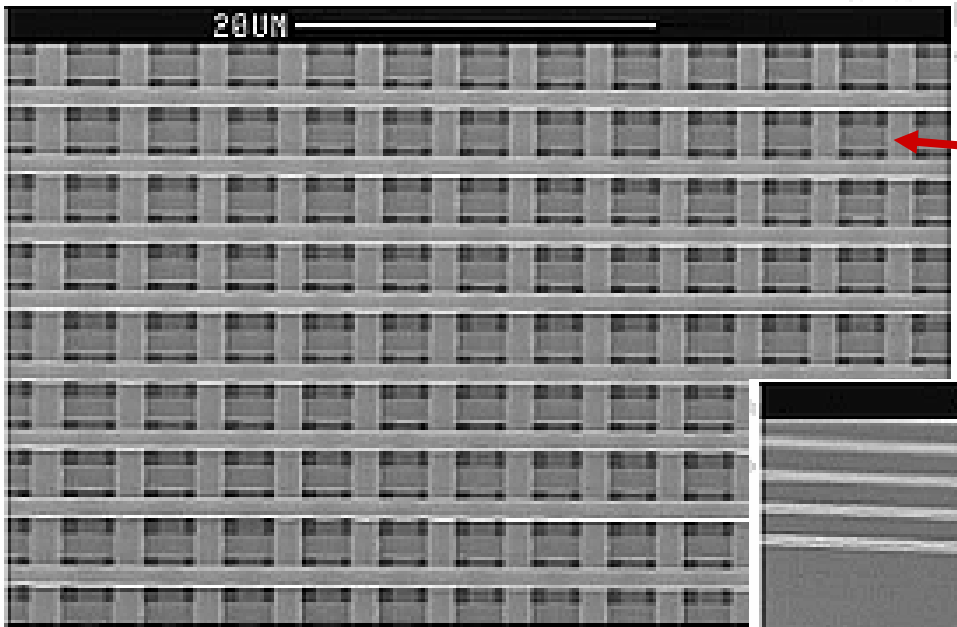


重复上述操作
实现积木结构

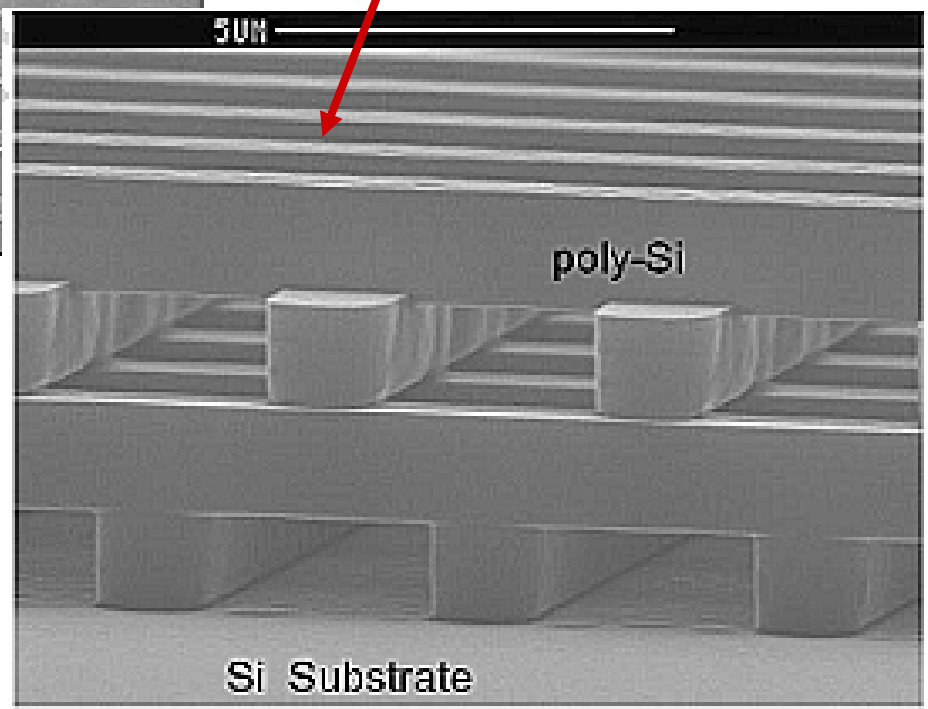
三维光子晶体的实验研制

3D PC 的基板融接制作法

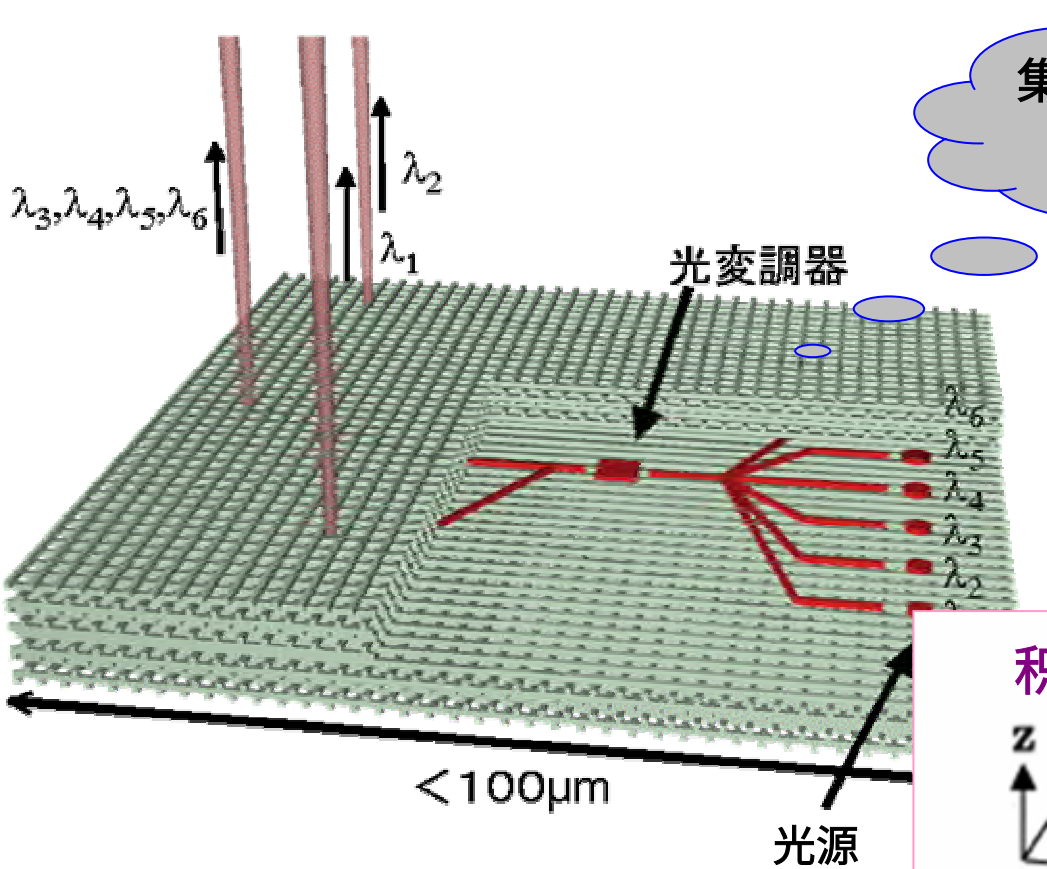
实际制作的三维光子晶体

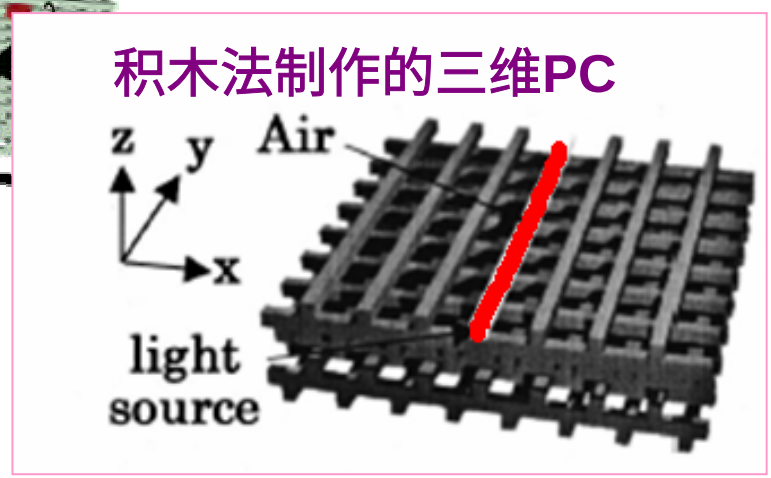


SEM写真



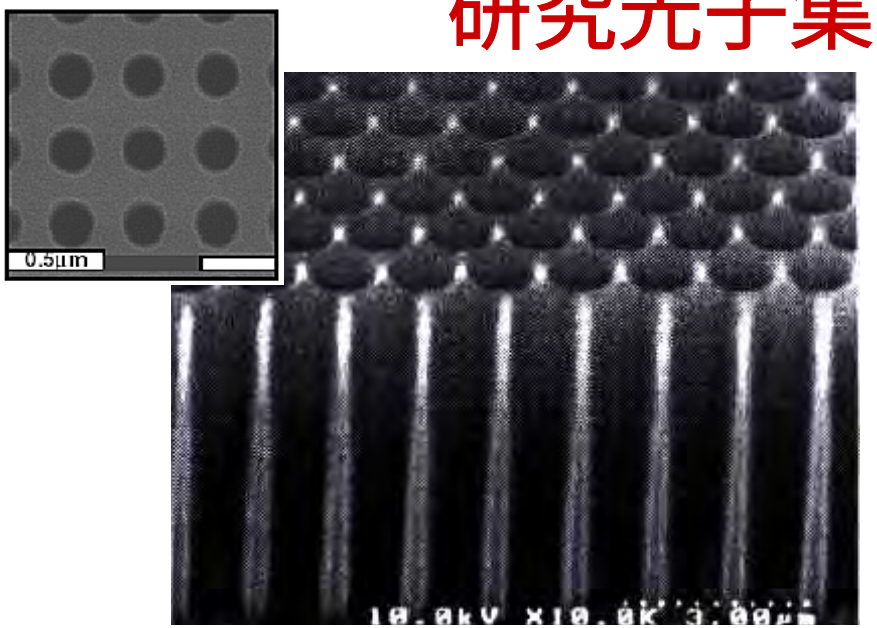
三维光子晶体集成光器件

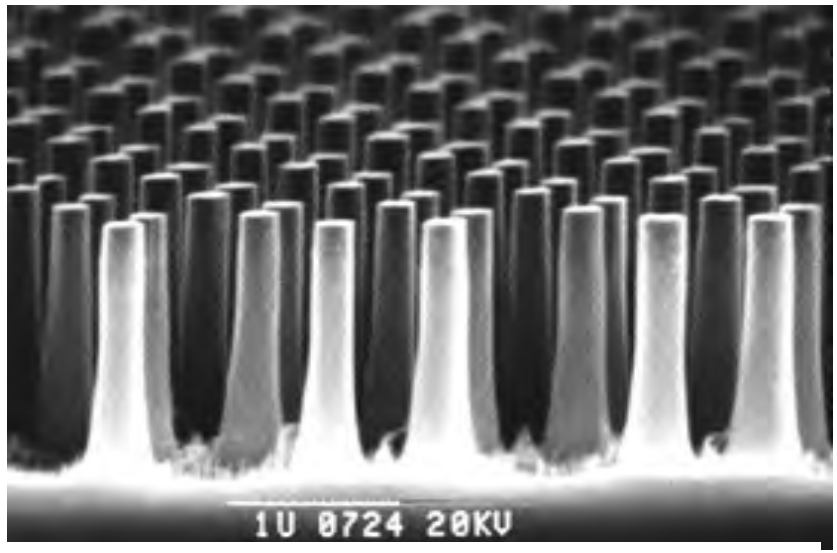




二维平板光子晶体

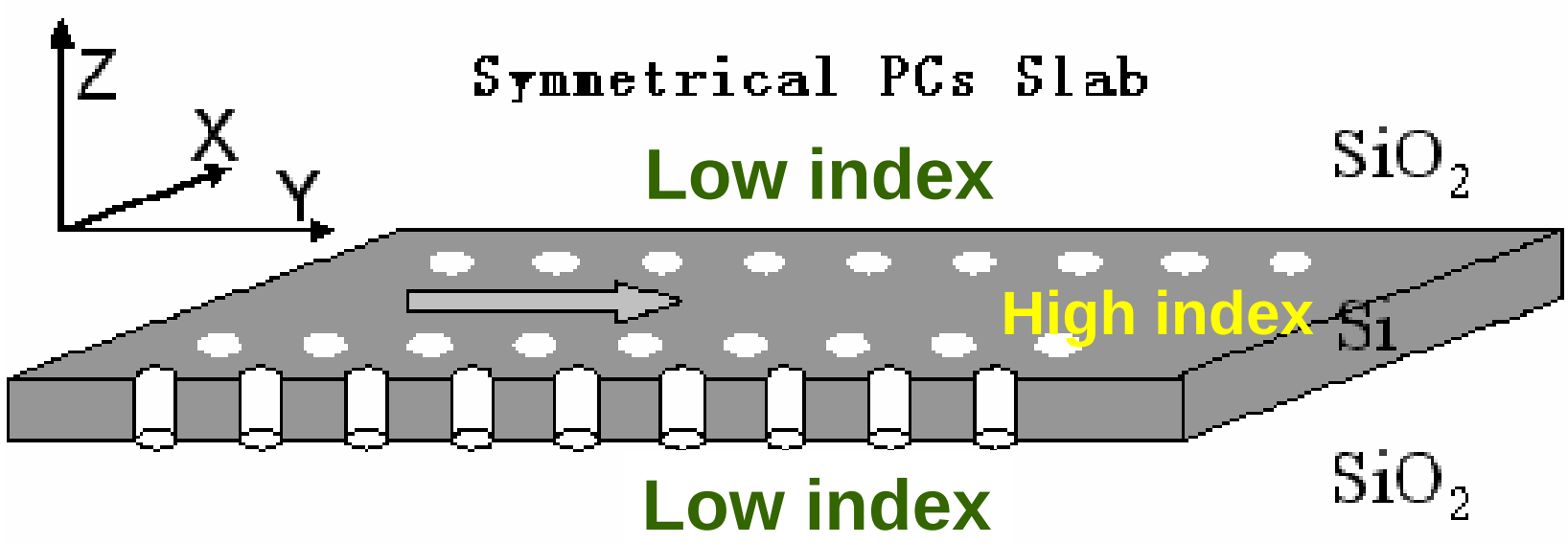
研究光子集成的材料平台





- 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



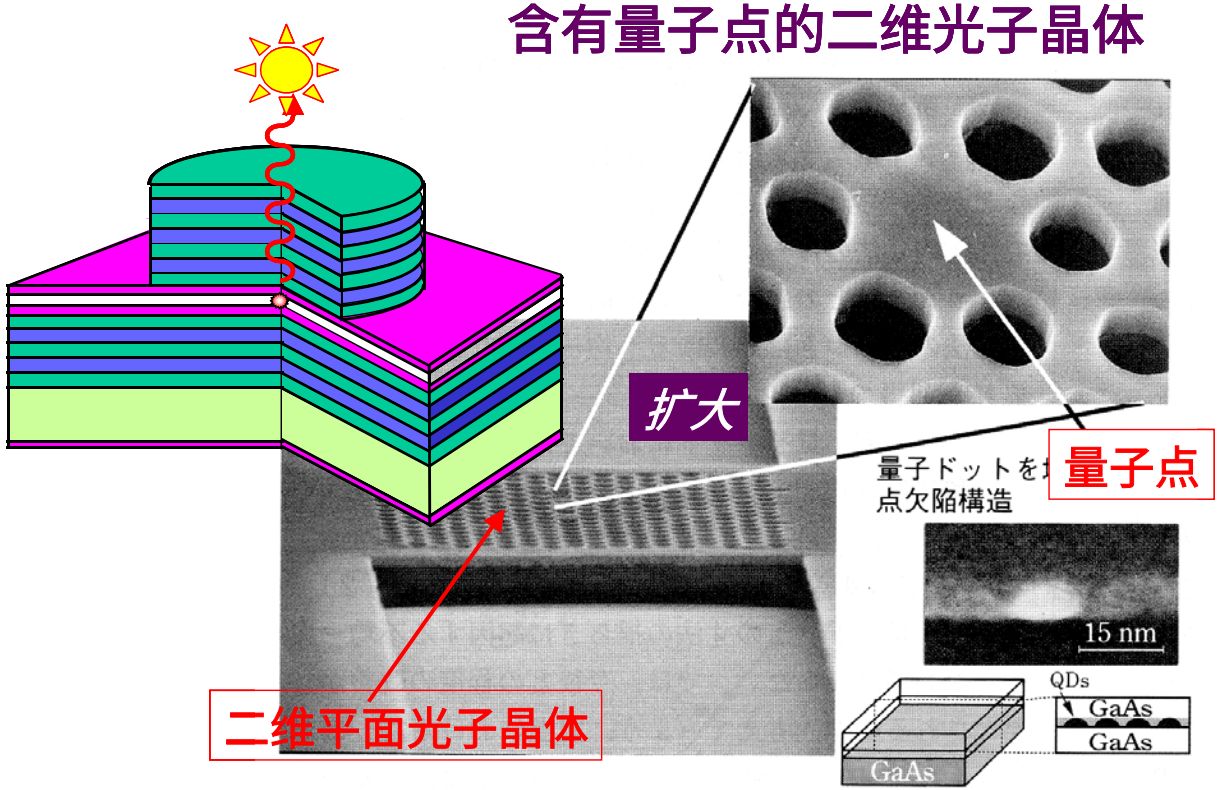
in-plane band-gaps provided by 2D PC also show their potential for applications

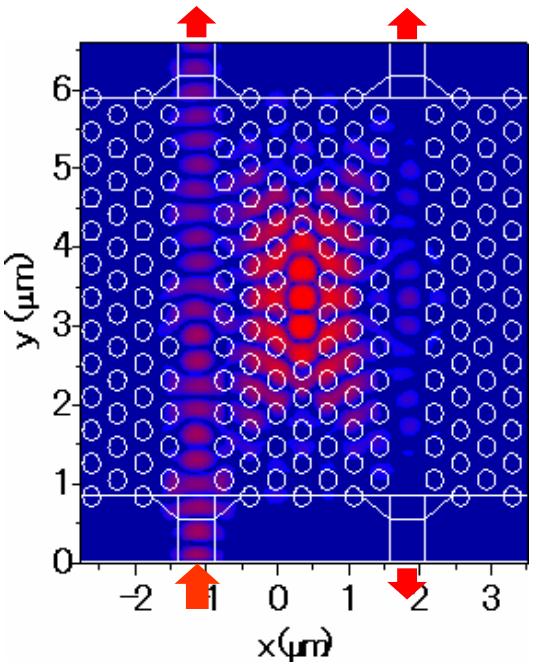
光子晶体材料与器件

光子微腔效应-单光子源

双光子纠缠对

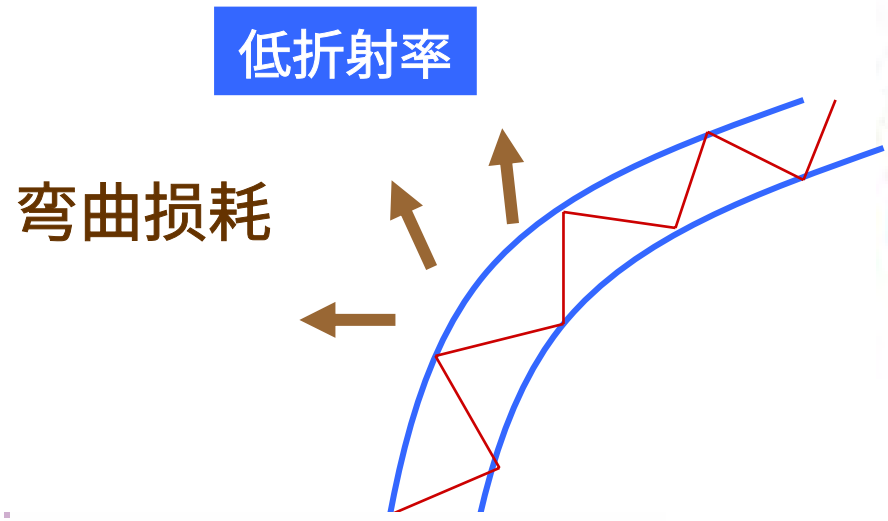
含有量子点的二维光子晶体

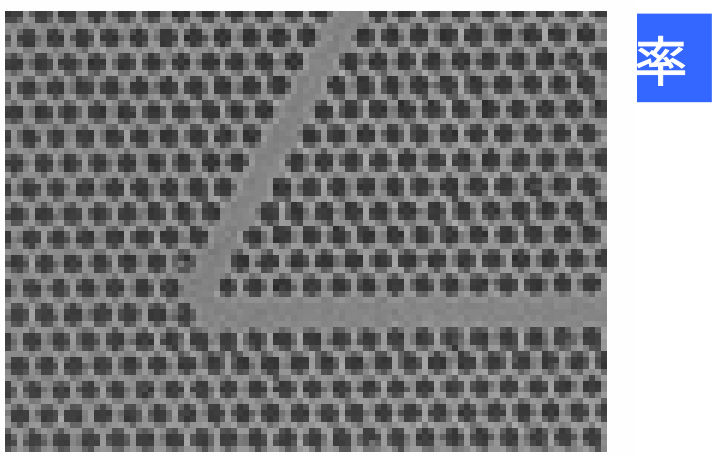


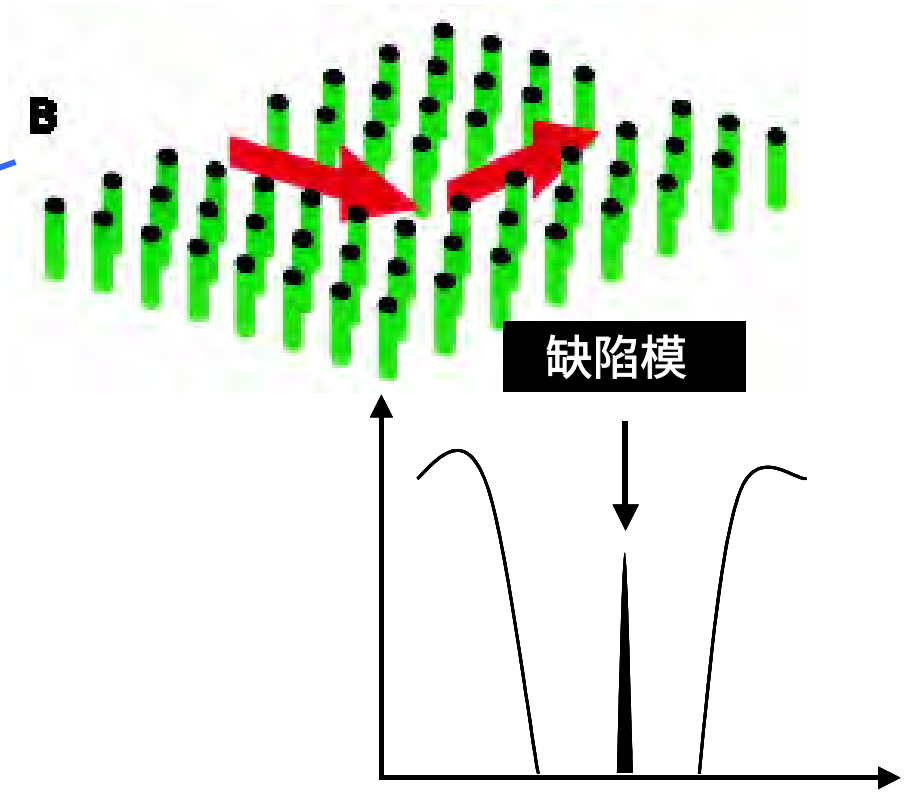


基于光子晶体材料的单体器件将具有新的功能及特性

光子晶体器件及其集成技术





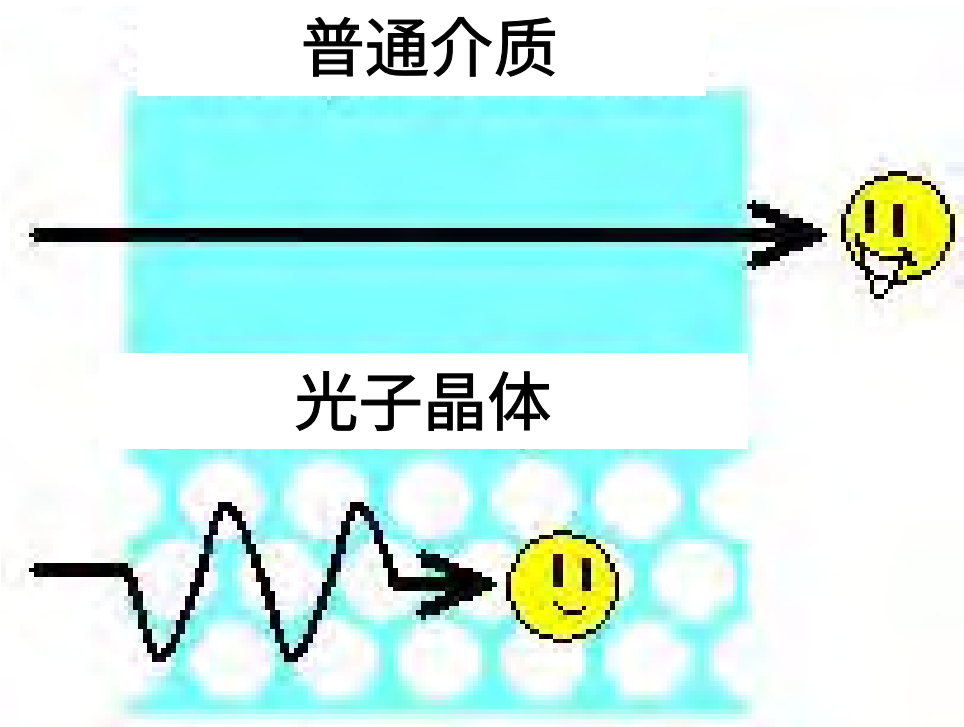


低损耗大角度弯曲波导

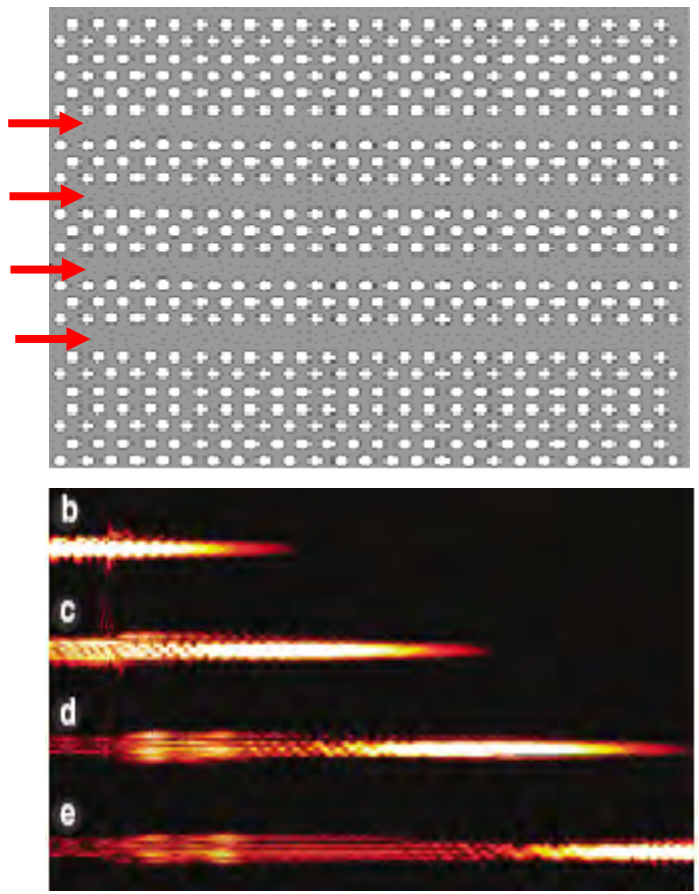
光子晶体材料集成器件将实现微纳尺度的超小型化

光子晶体材料与器件

光群速度调控



可集成光真时延迟器

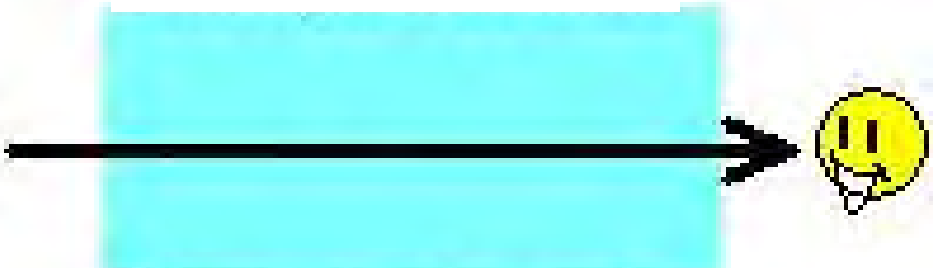


基于光子晶体材料的单体器件将具有新的功能及特性

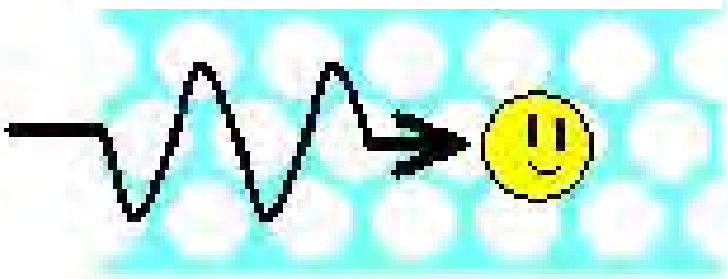
新型光电子器件

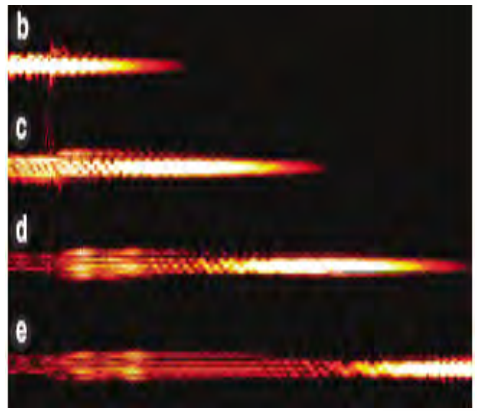
光群速度调控

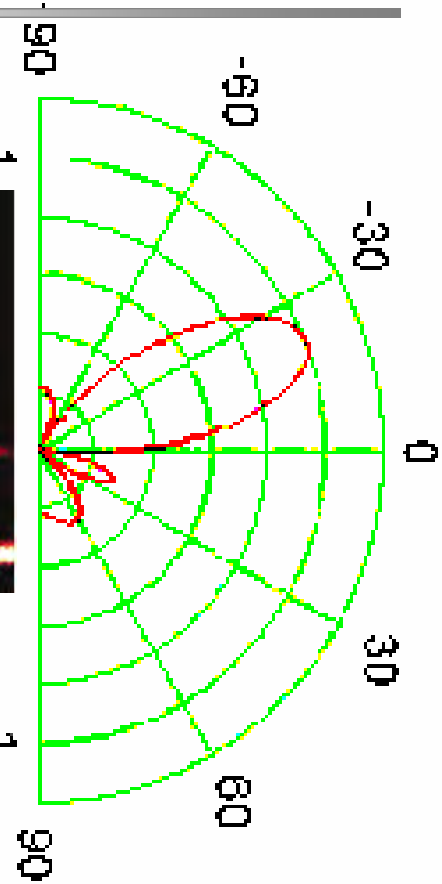
普通介质



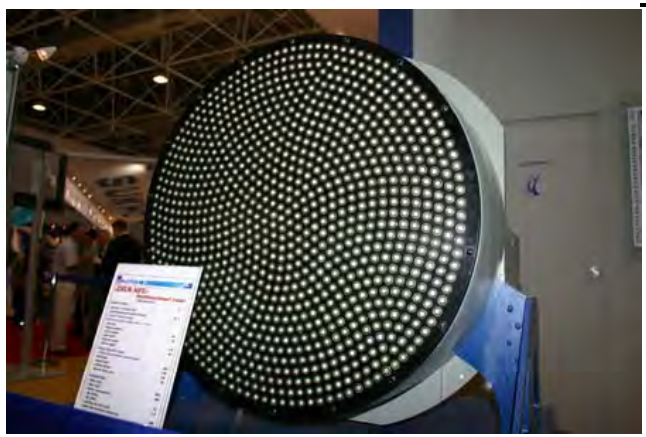
光子晶体



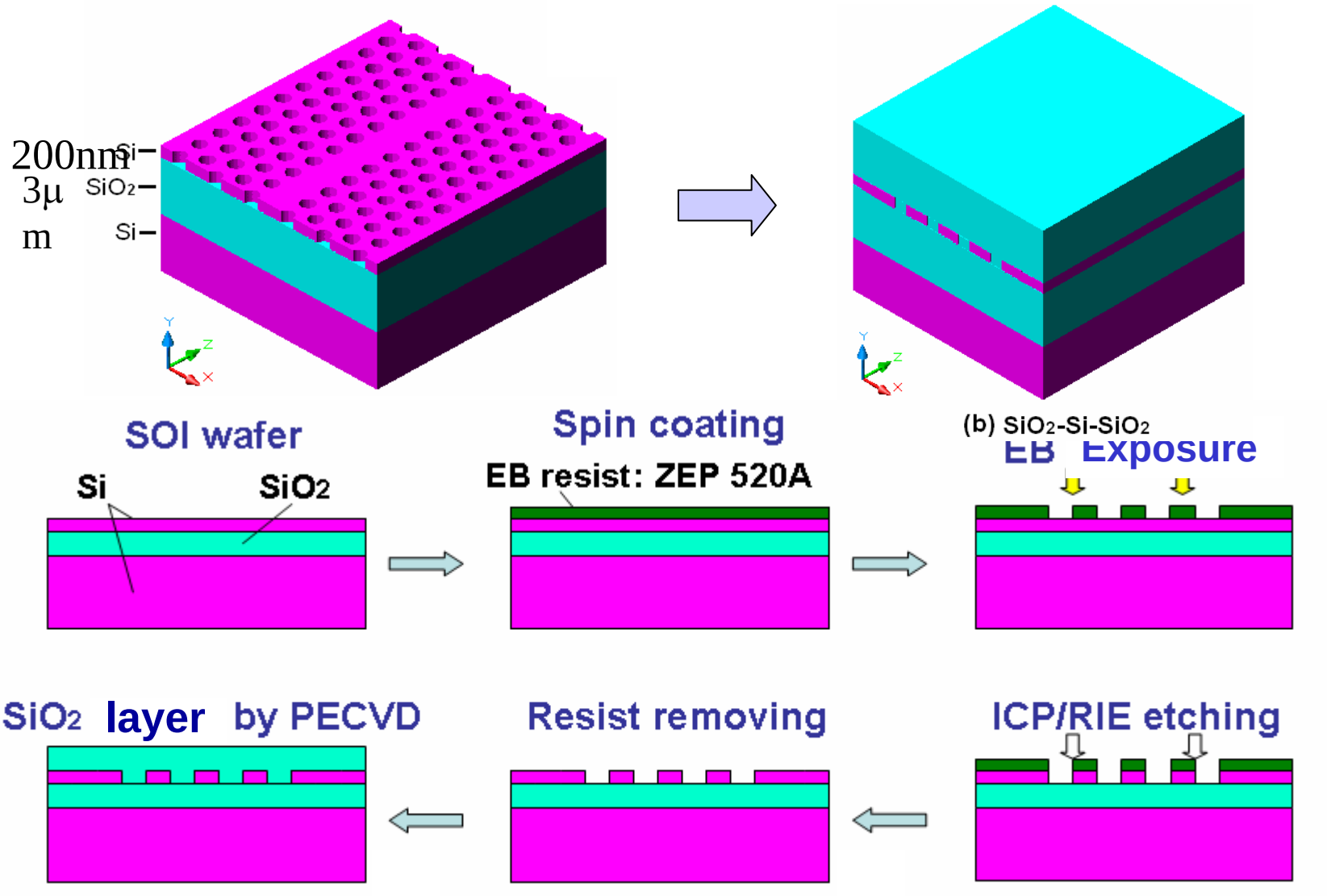




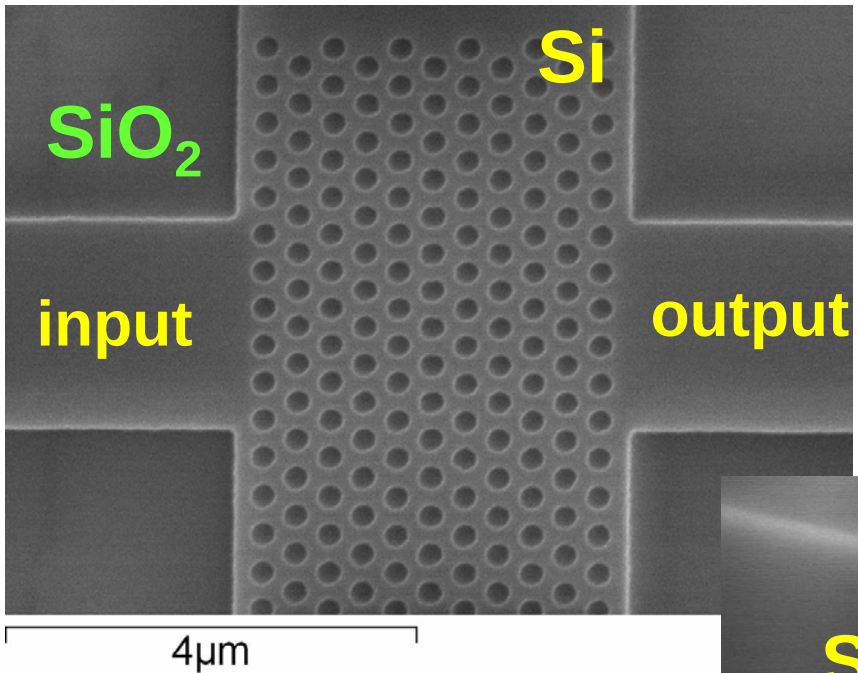
相控阵雷达



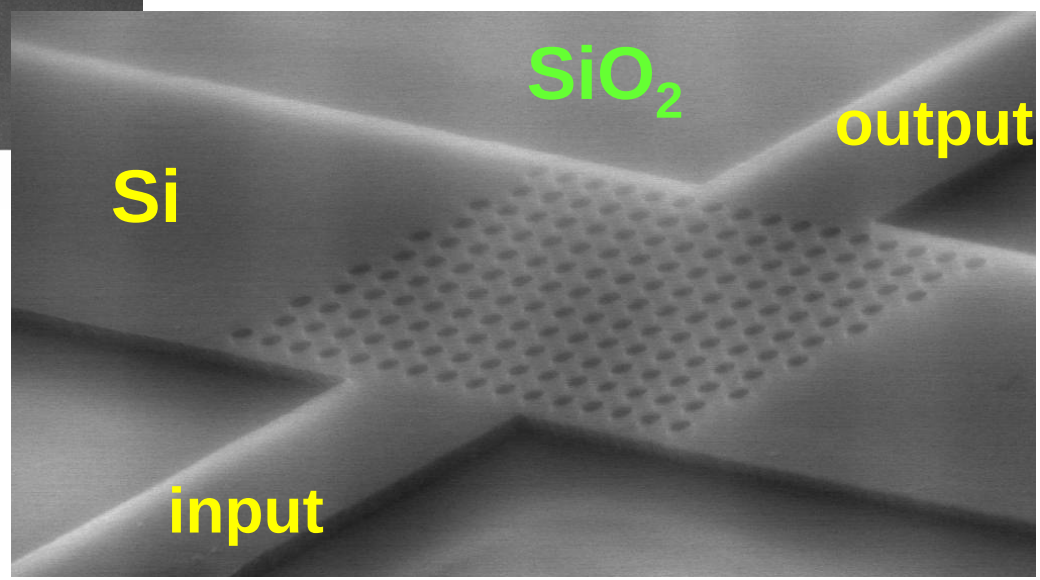
光子晶体慢光波导的制作



实现了二维平板光子晶体

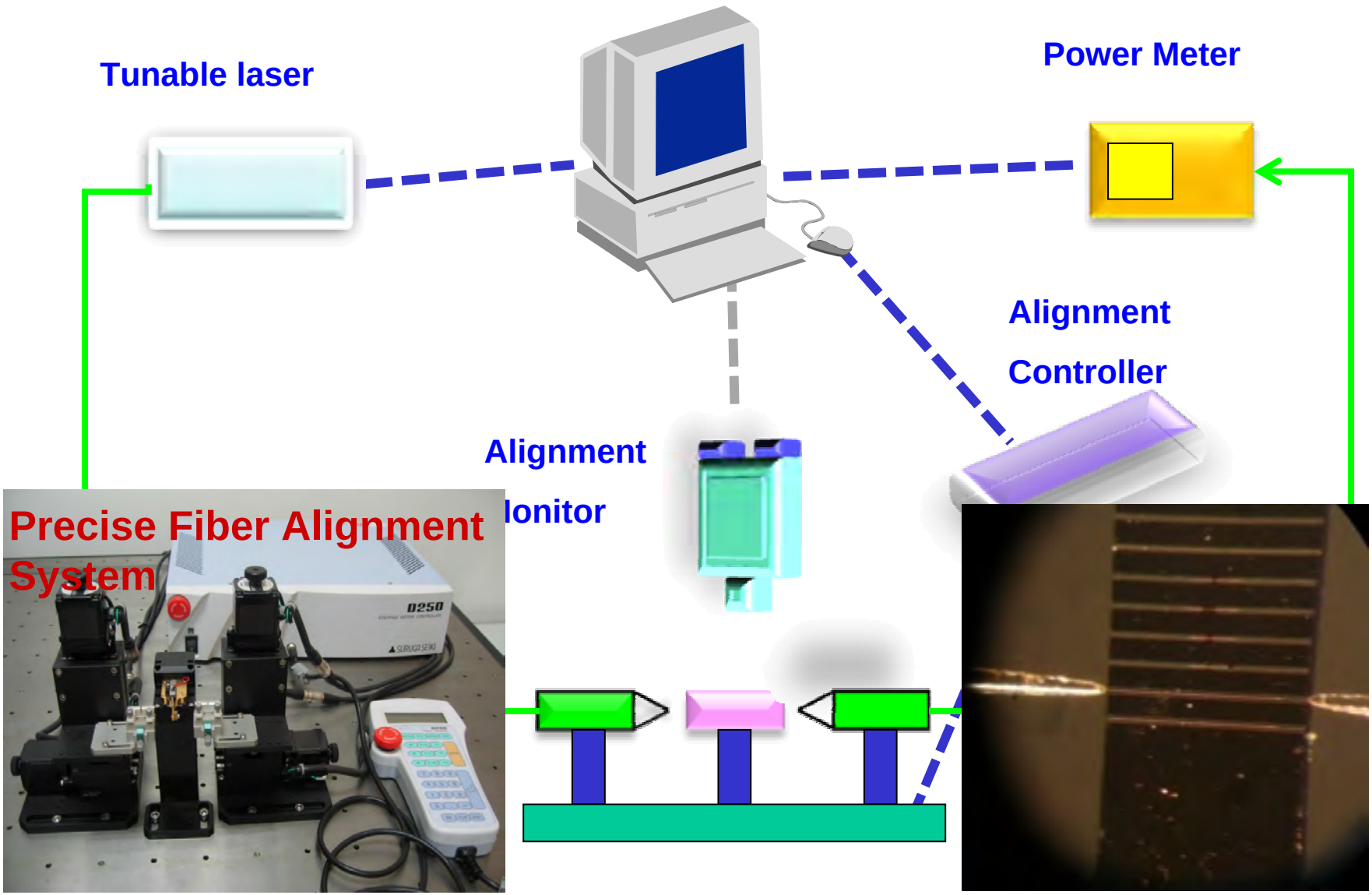


11 periods

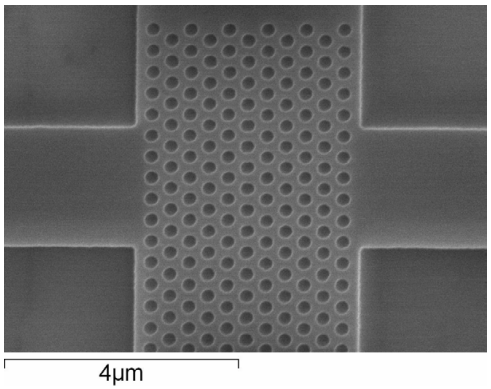


2D PC with
r=90nm
a=340nm
@SOI structure

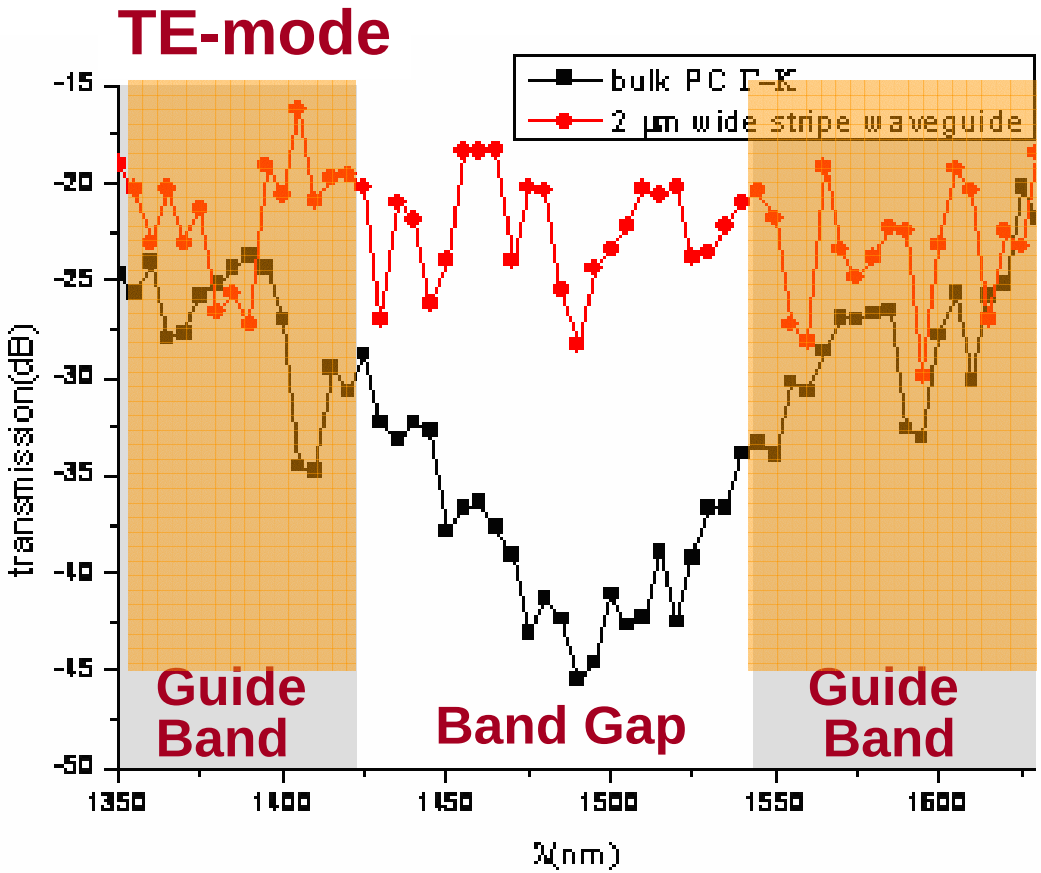
Measurement System



实验确认带隙在1.55μm波段

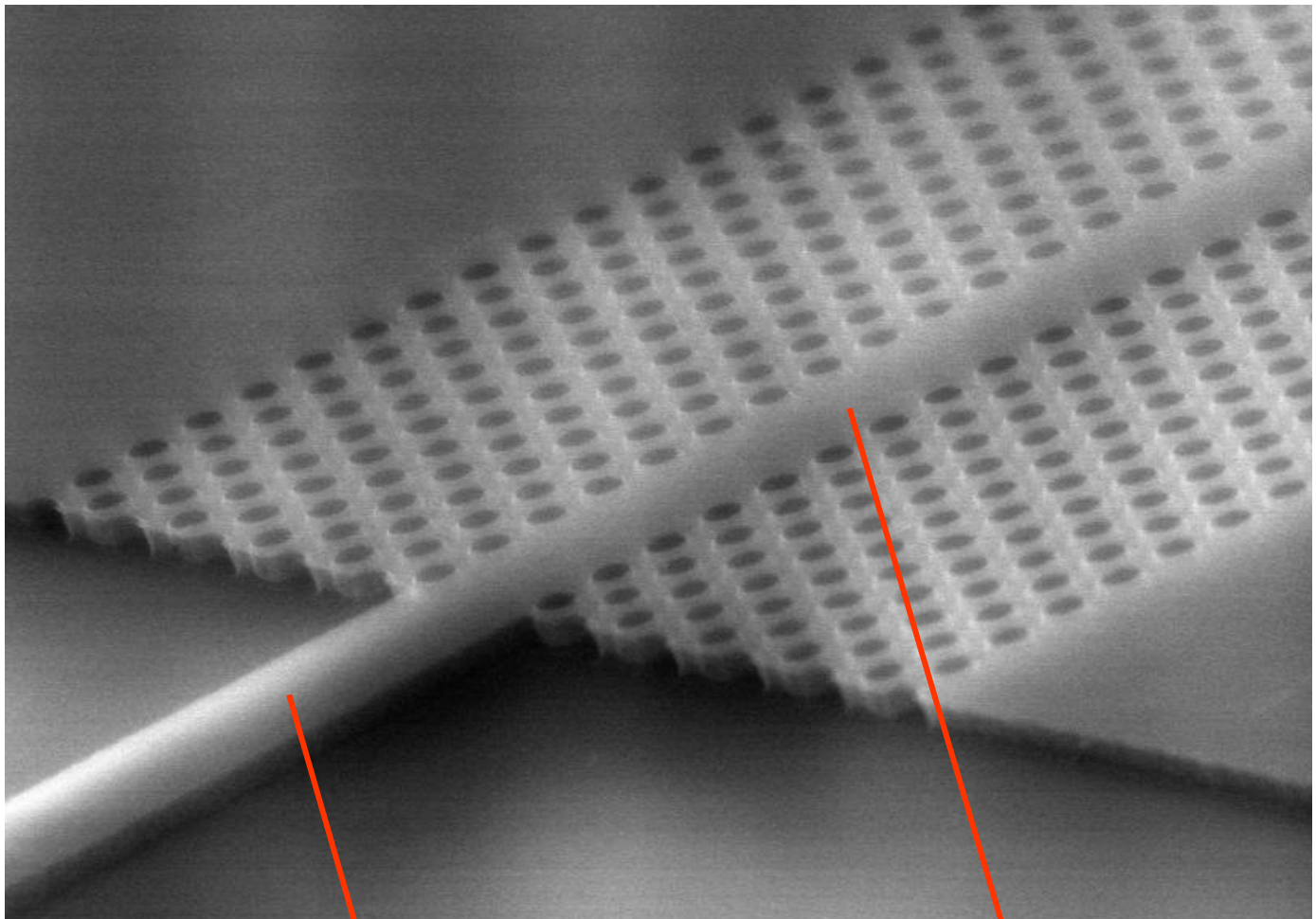


2D PC with
r=90nm
a=340nm
@SOI structure



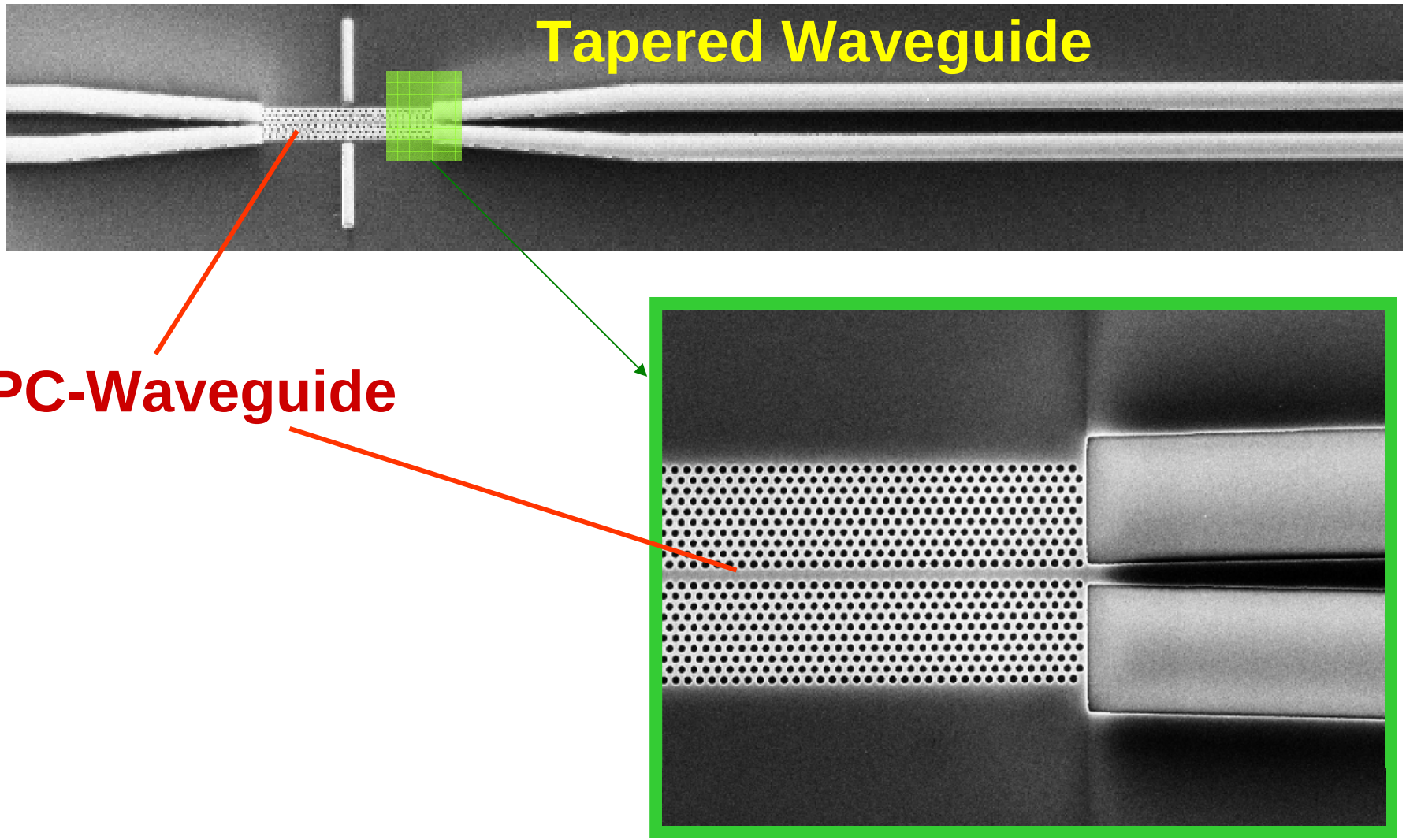
- **Normalized transmission for TE polarization @1550nm**
- **Shade area represents simulation result, the measurement results fit it well**

研制出光子晶体慢光波导



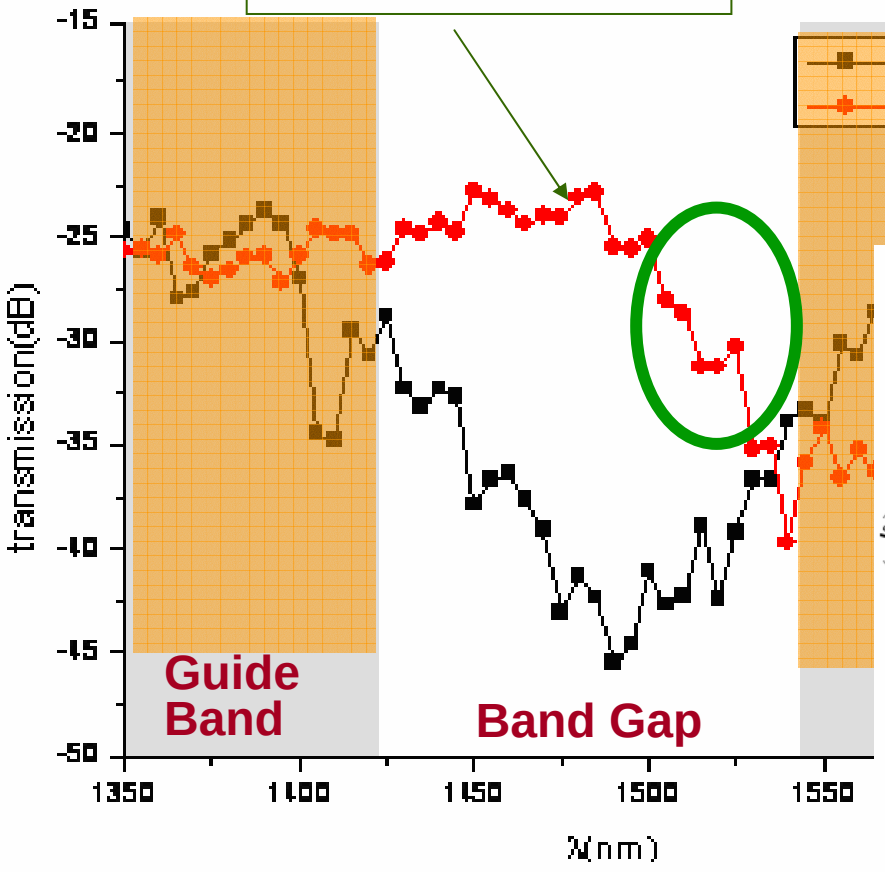
Photonic Crystal Waveguide

To Reduce Coupling Loss



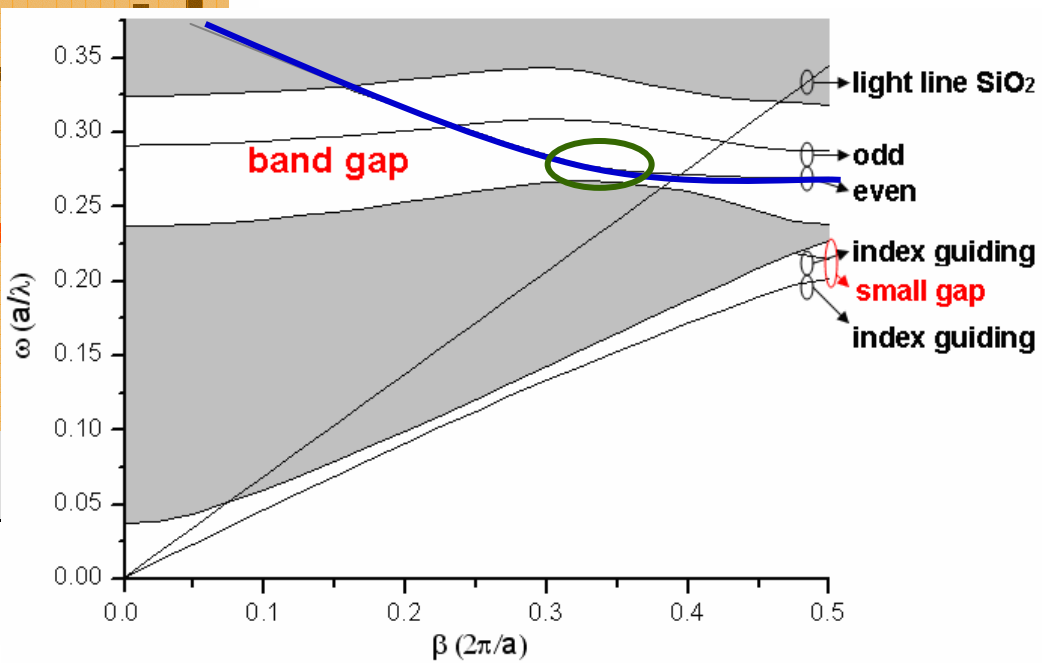
实验确认带隙波导缺陷导模

缺陷模式



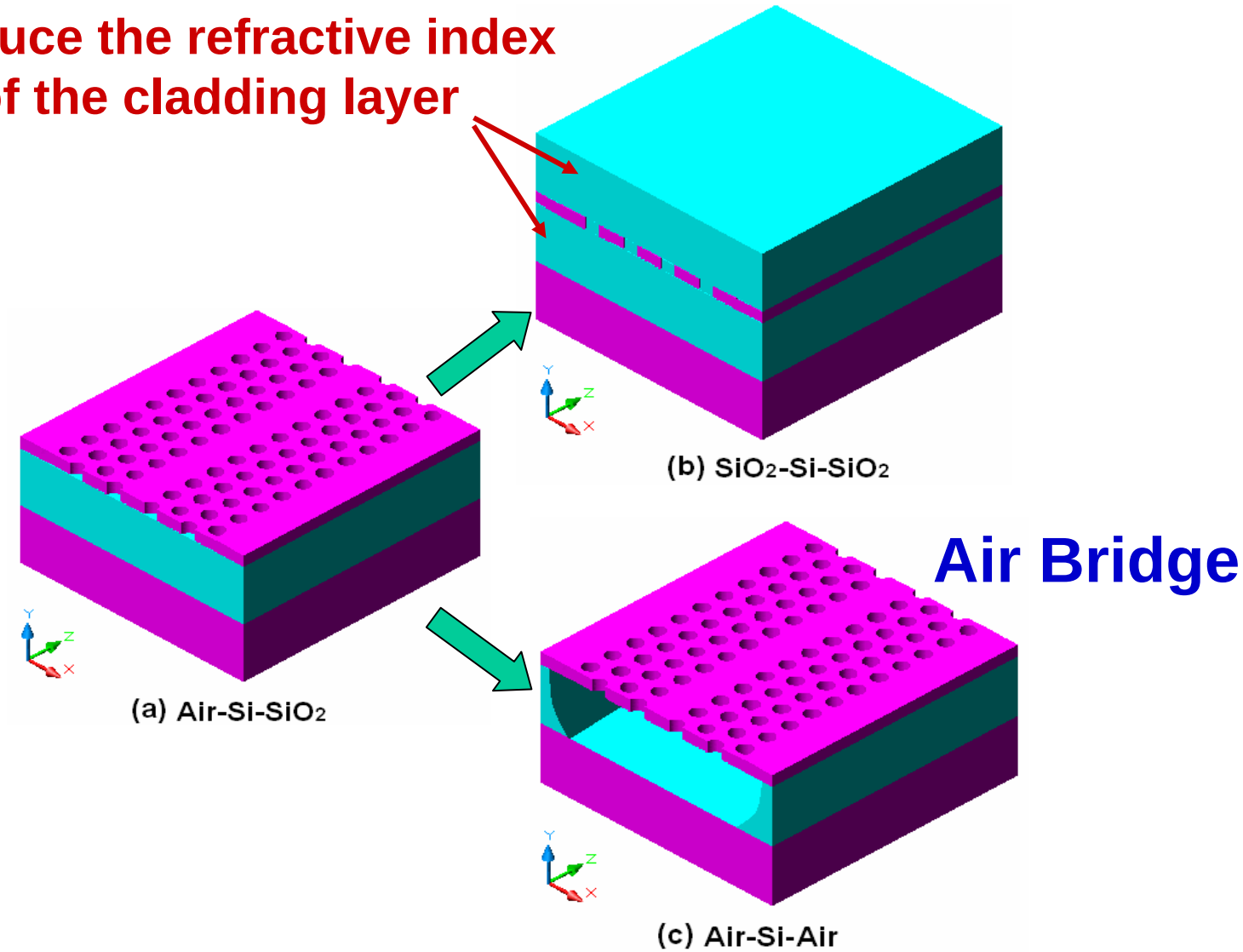
TE-mode

60 Periods



PC-WG with Air Bridge Structure

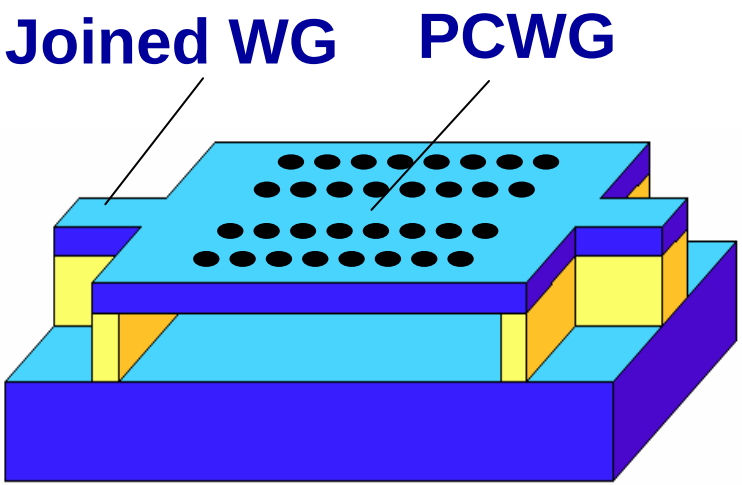
Reduce the refractive index of the cladding layer



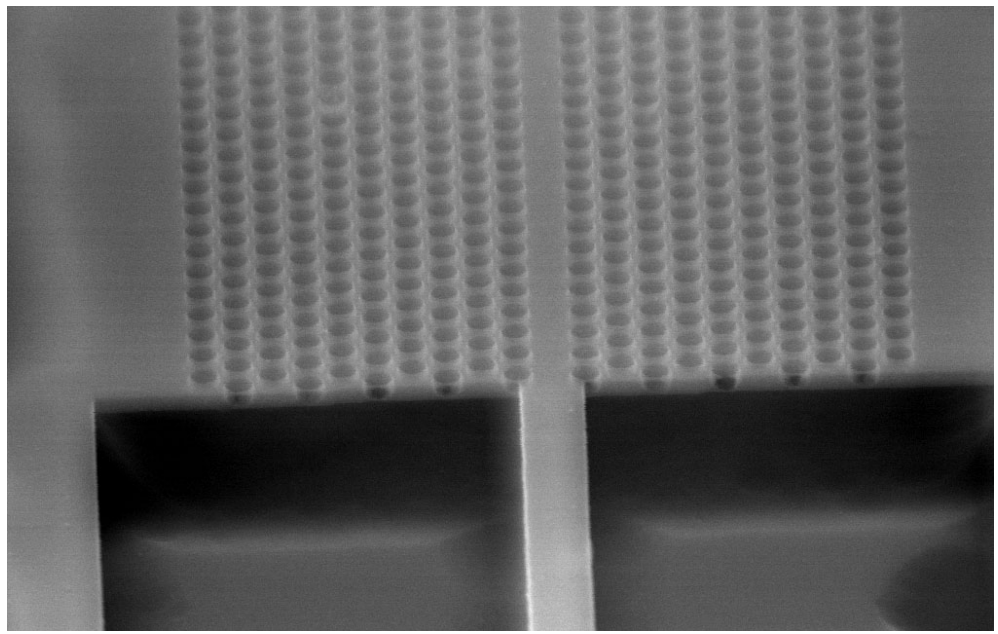
Air Bridge

PCWG with Air Bridge Structure

空气桥结构光子晶体波导

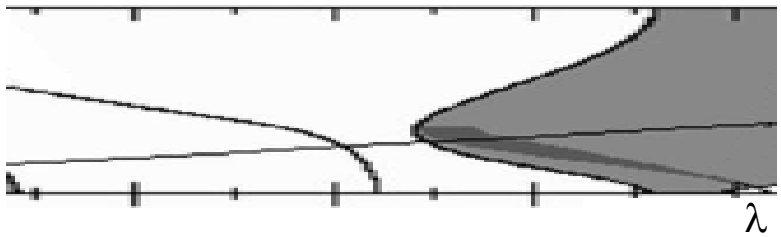


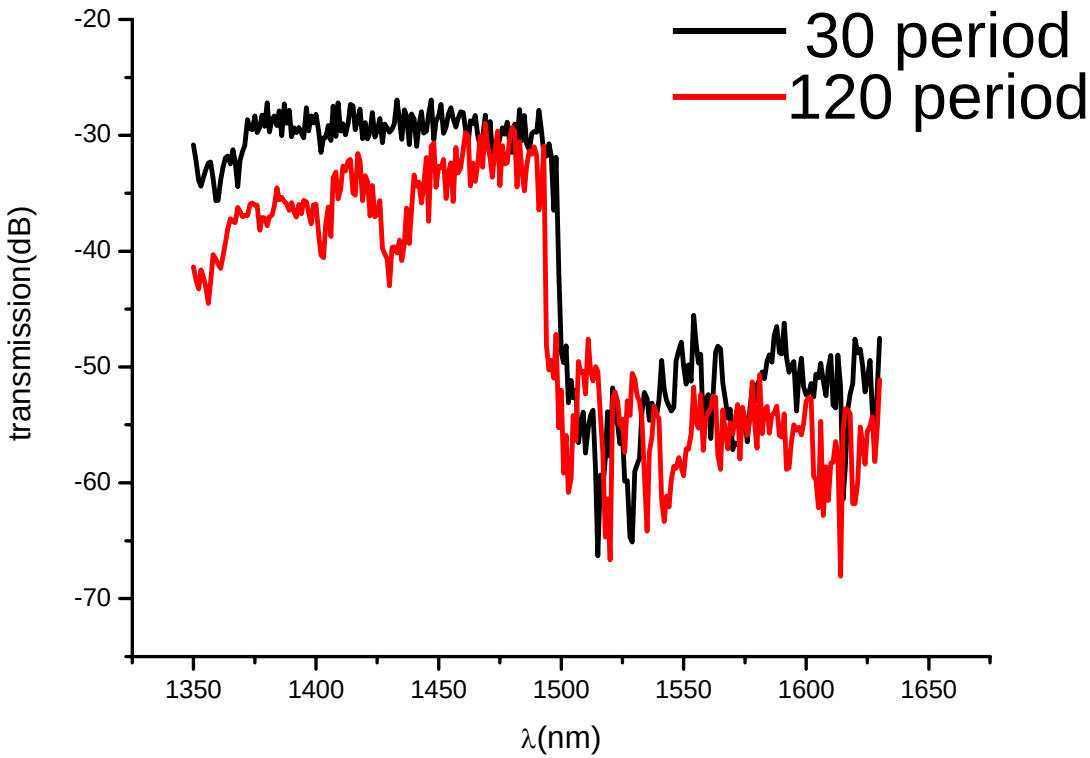
Air Bridge Structure



a =420 nm，*r* =124 nm，*h* =200 nm

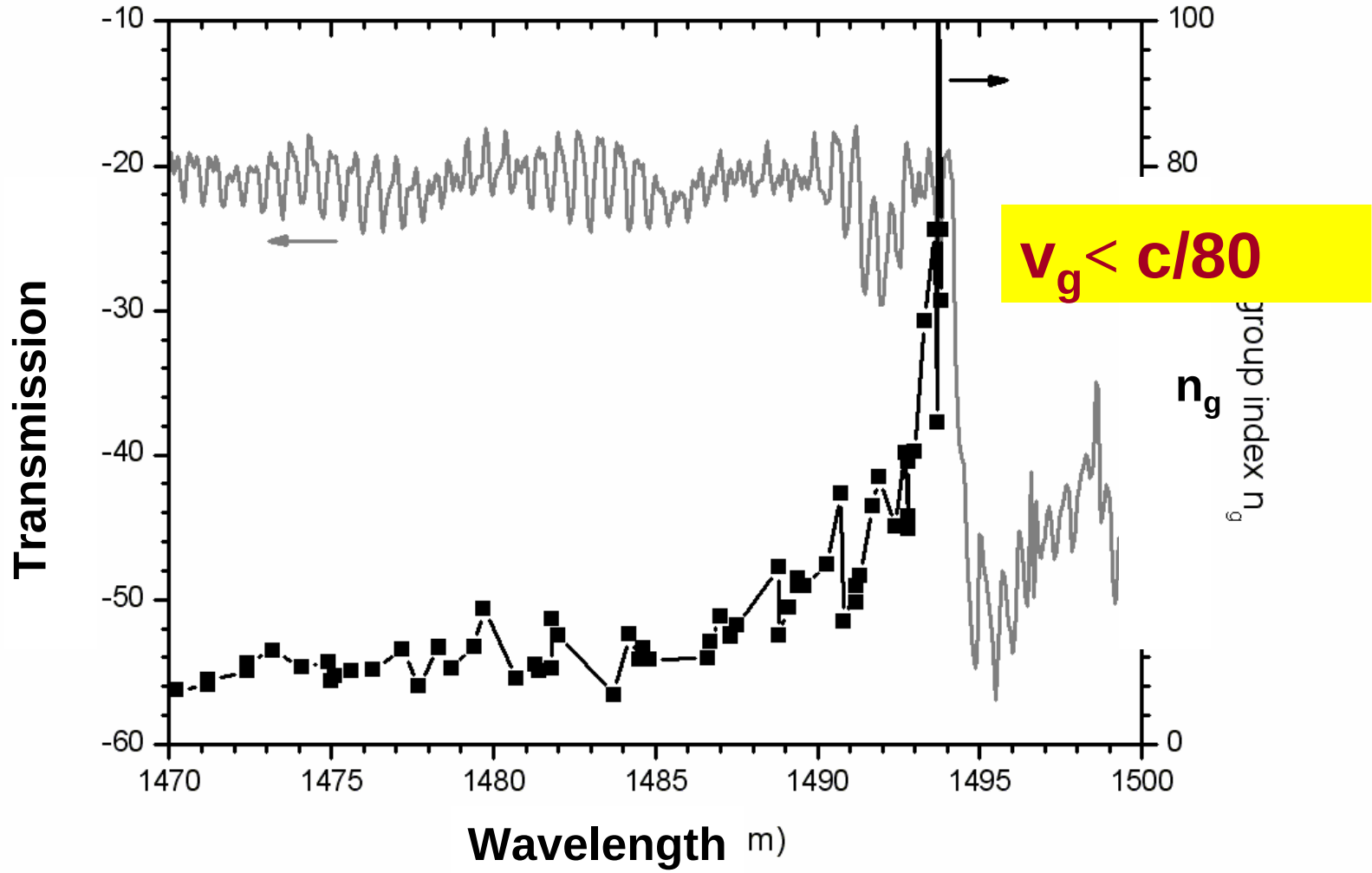
Measurement Results



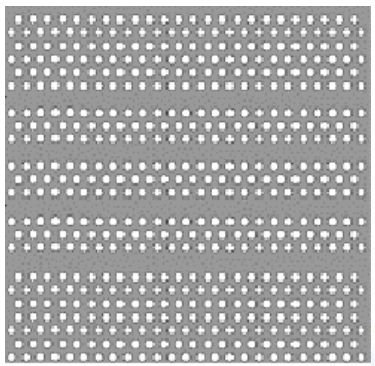


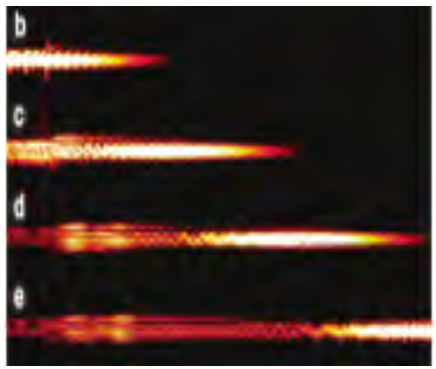
a **=420 nm，** ***r*** **=124 nm，** ***h*** **=200 nm**

空气桥结构光波导群速度测试结果

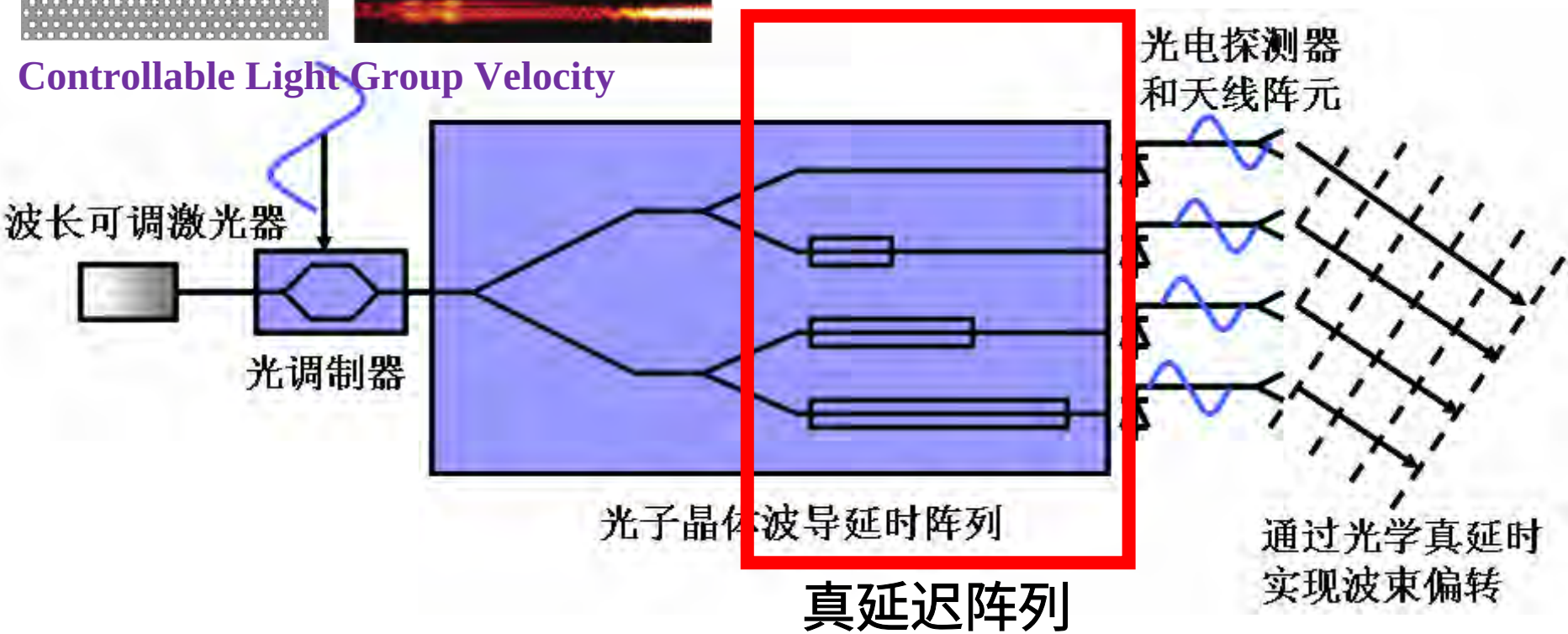


光子晶体慢光波导
光学真延迟结构设计



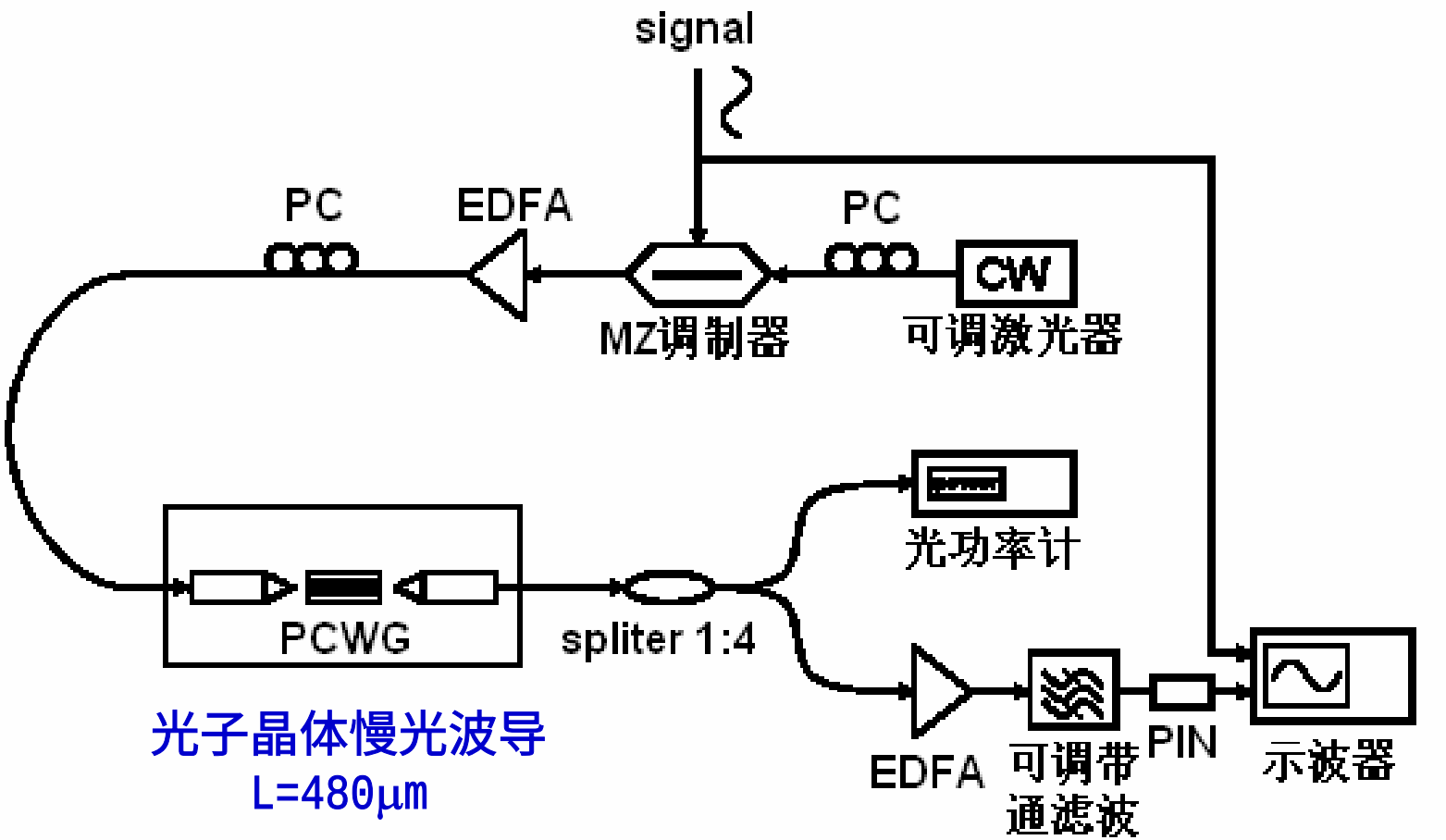


Controllable Light Group Velocity



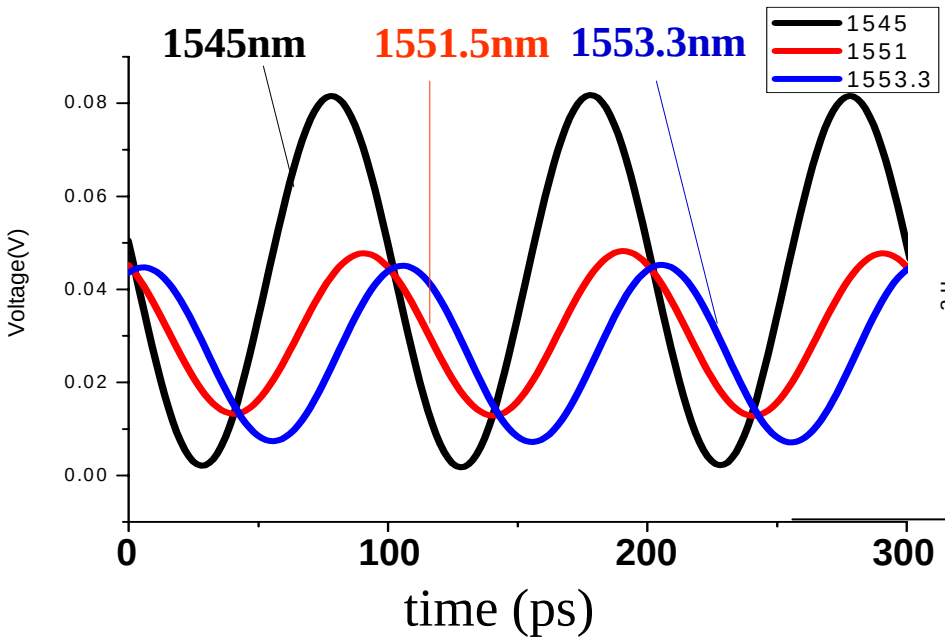
光子晶体波导慢光的重要应用—微波信号可调真延时的实验论证

实验系统

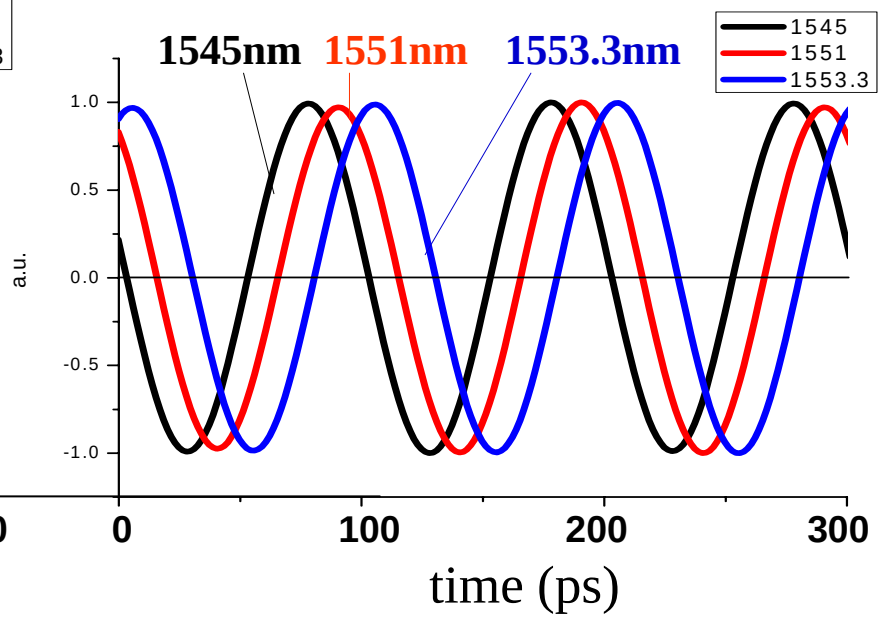


光子晶体波导慢光的重要应用—微波信号可调真延时的实验论证

实验测量的波形



强度归一化后的波形

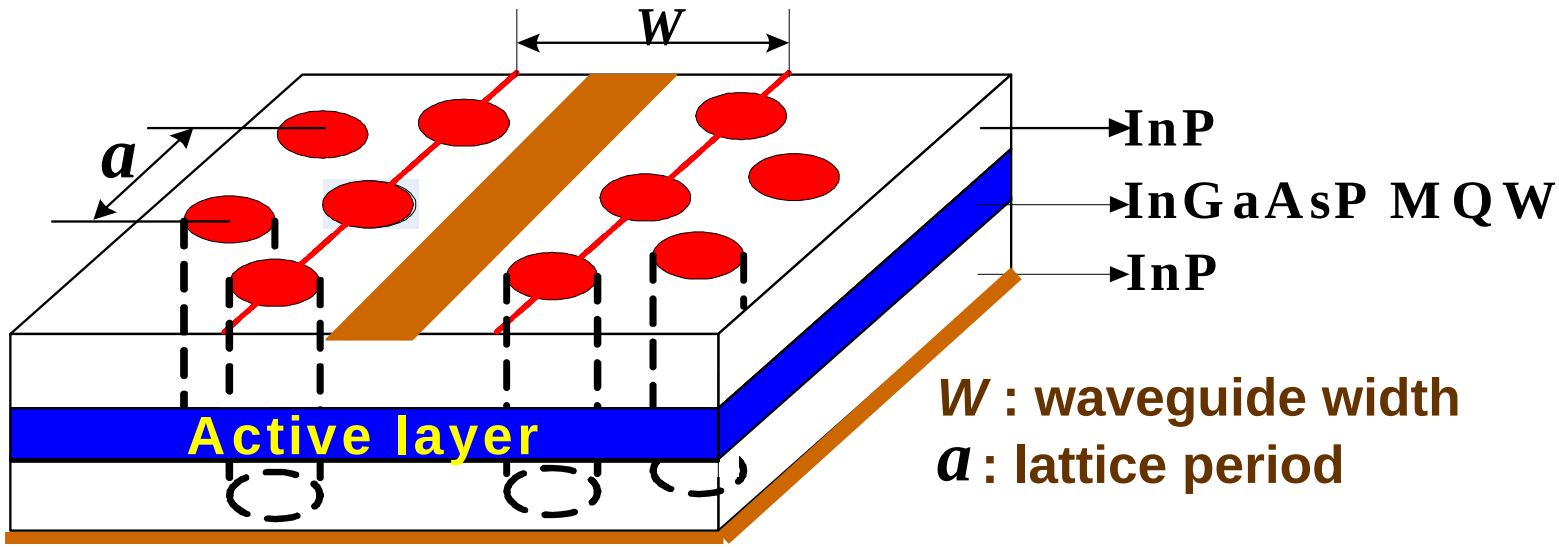


- 在单频激光上强度调制10GHz微波信号，观察不同激光波长下微波信号的延时
- 光子晶体波导长480μm，测量得到最大延时差25ps，波形无明显畸变 （对应n_g=15）

有源慢光波导

(1) Abnormal v_g → Controllable Gain?

(2) Electrical injection can avoid the hole region

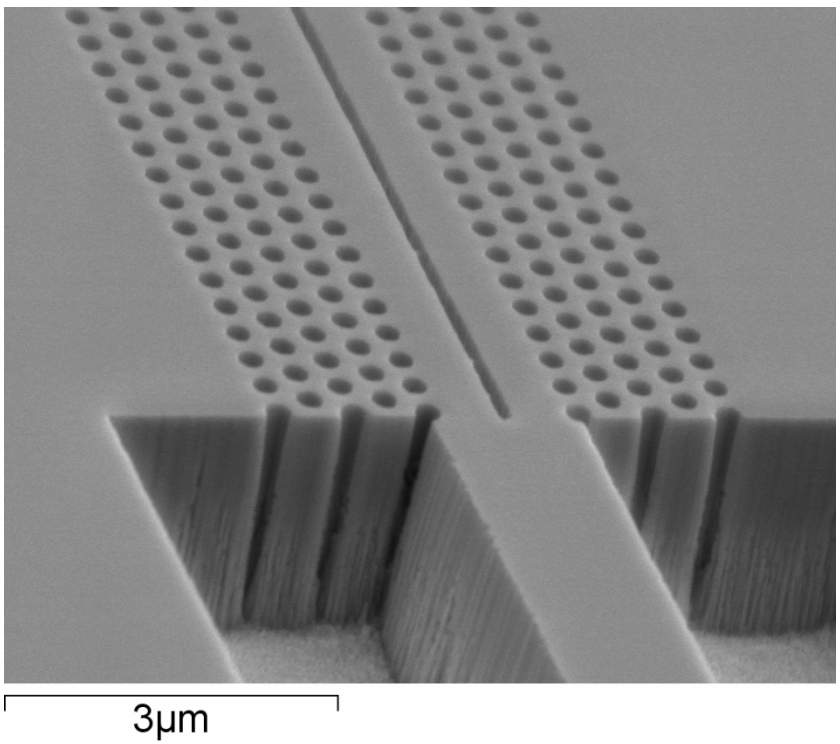


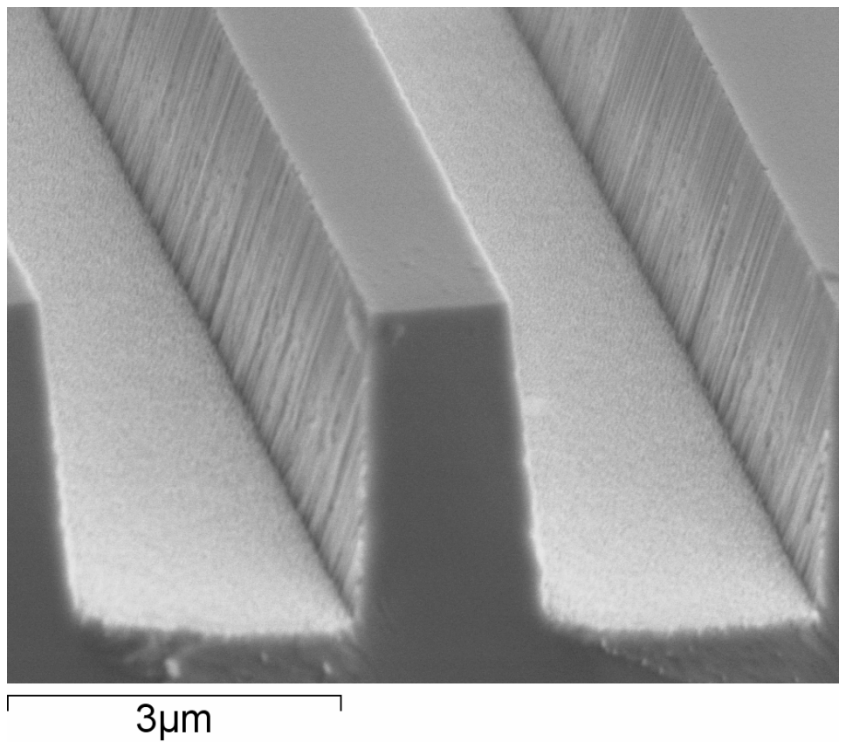
PC Waveguide - a line defect waveguide along ΓK direction

J. LIGHTWAVE TECH., VOL. 26, NO. 11, JUNE 1, 2008

InP基材料深刻蚀

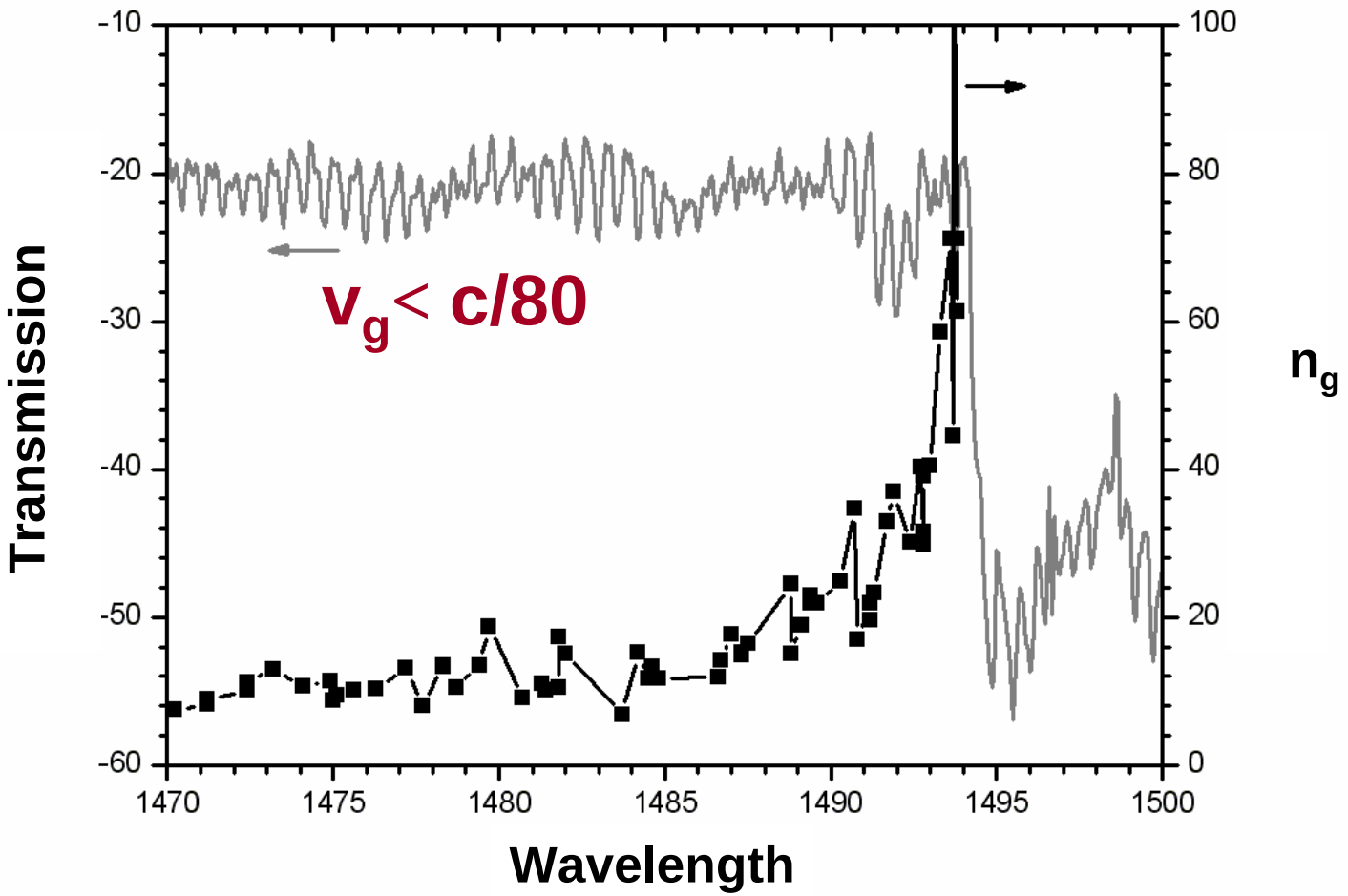
- ICP/Bias=180W/200W Pressure=0.1Pa
  $Cl_2/SiCl_4$=1/3sccm Time=4min



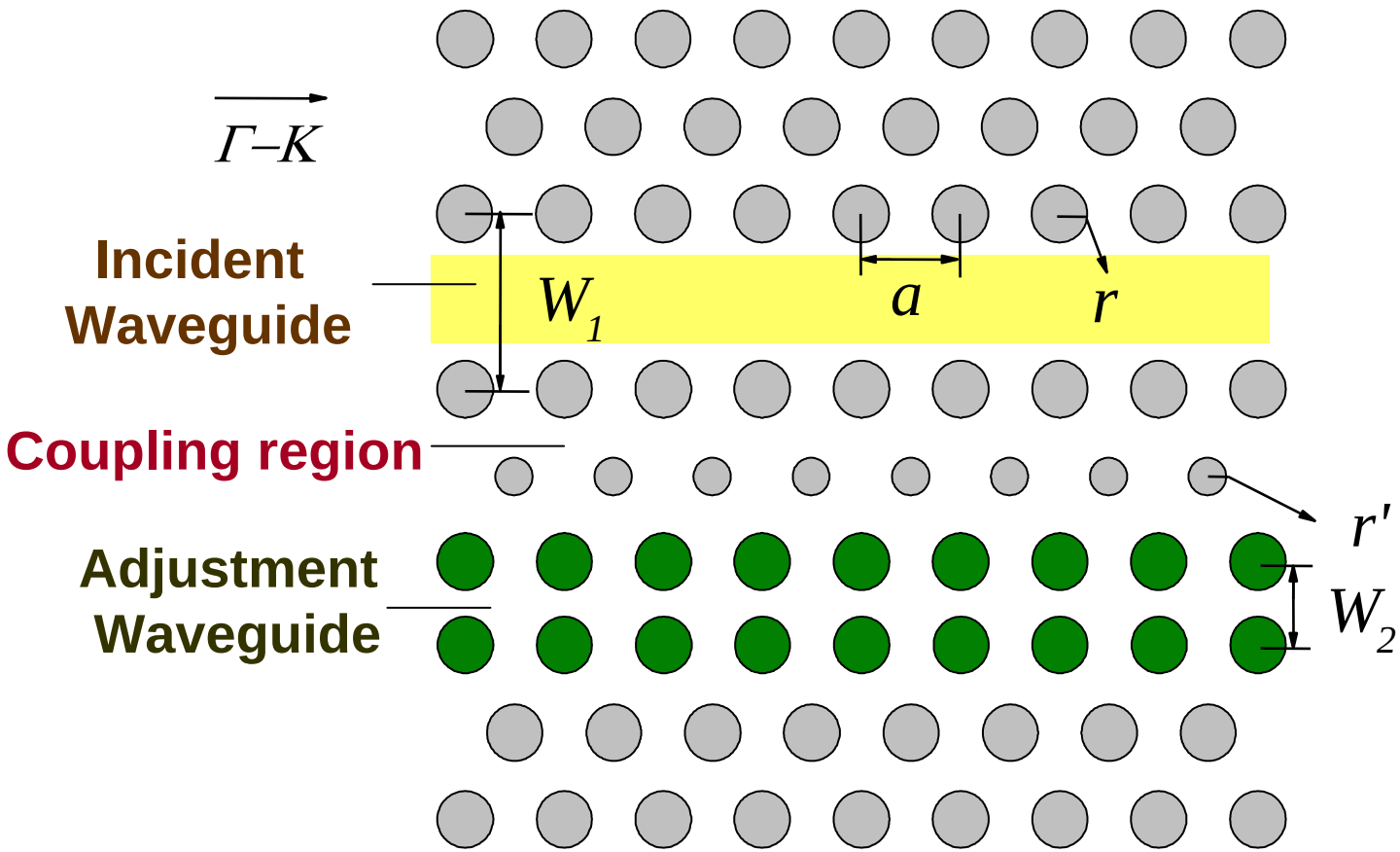


深宽比>10

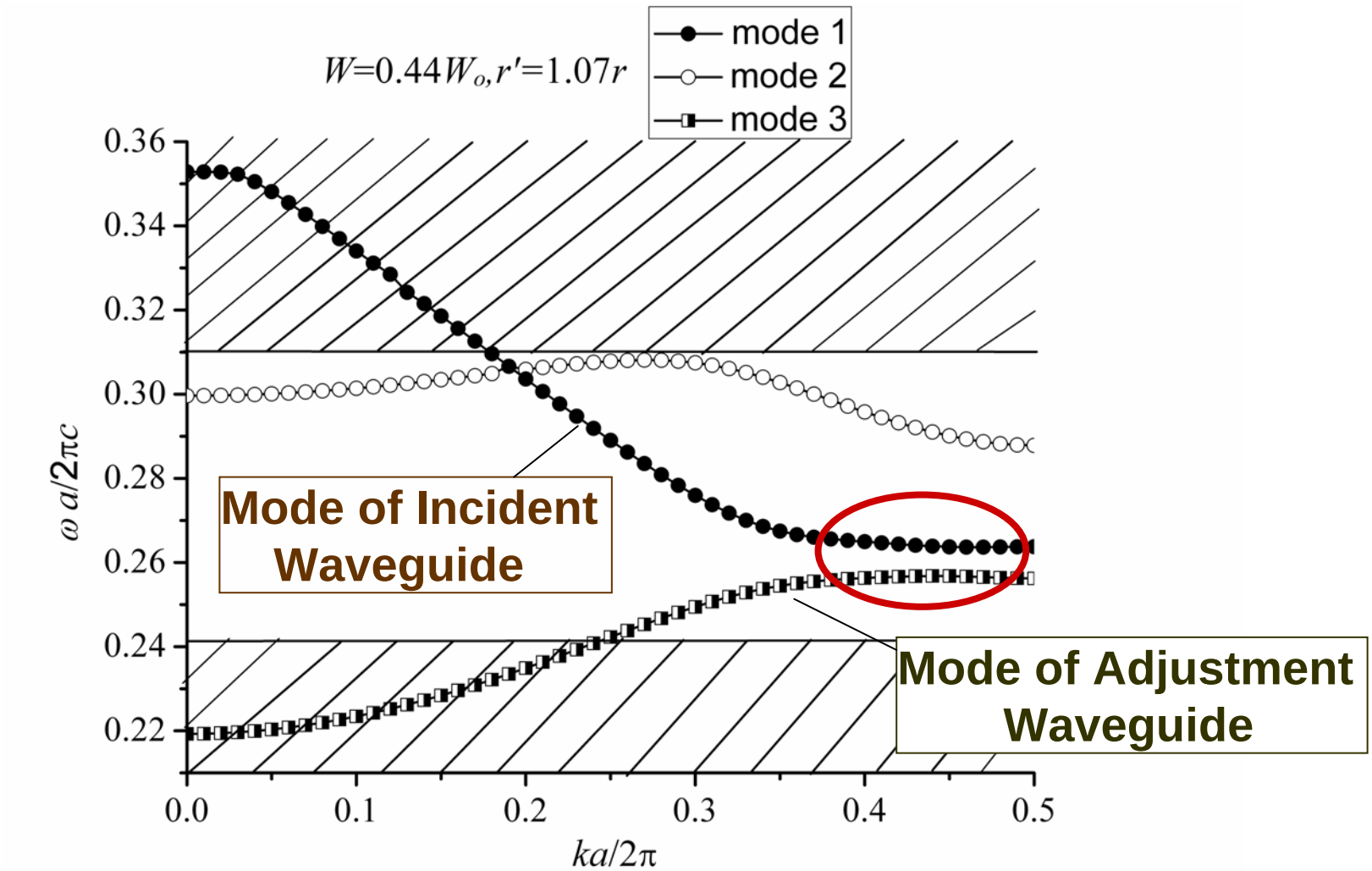
空气桥结构慢光波导测试结果



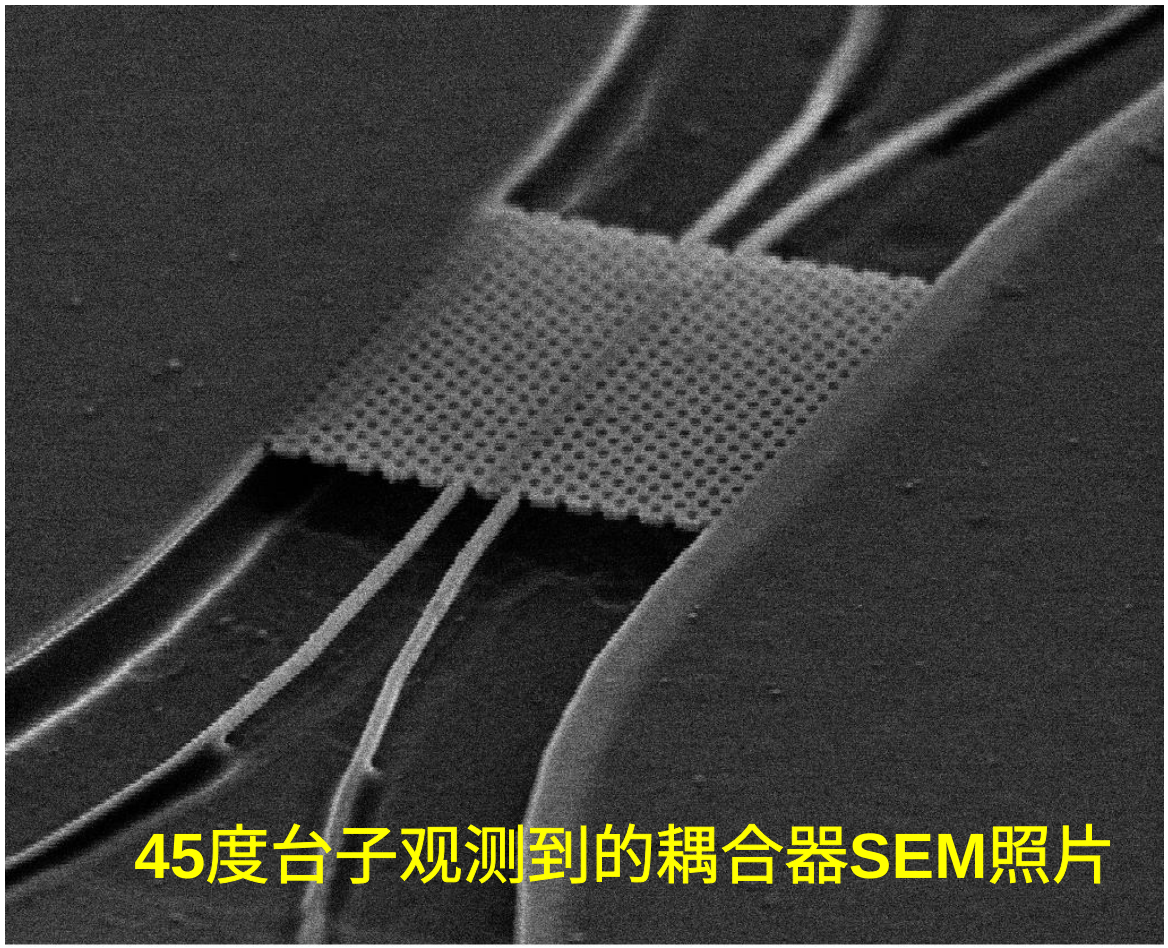
Zero GVD Slow Light with Coupled PC WG



Band Structure of the Coupled PC-WG

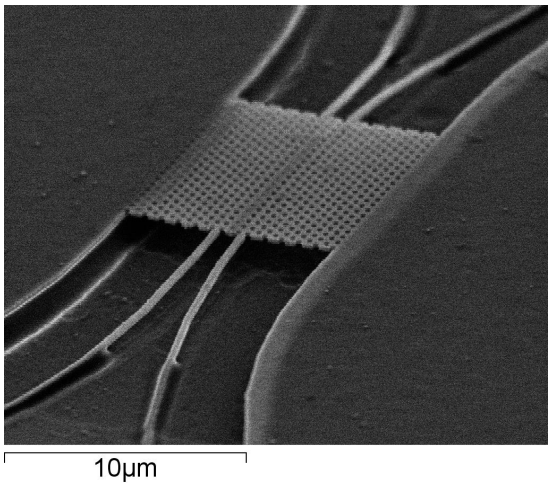


光子晶体波导耦合器

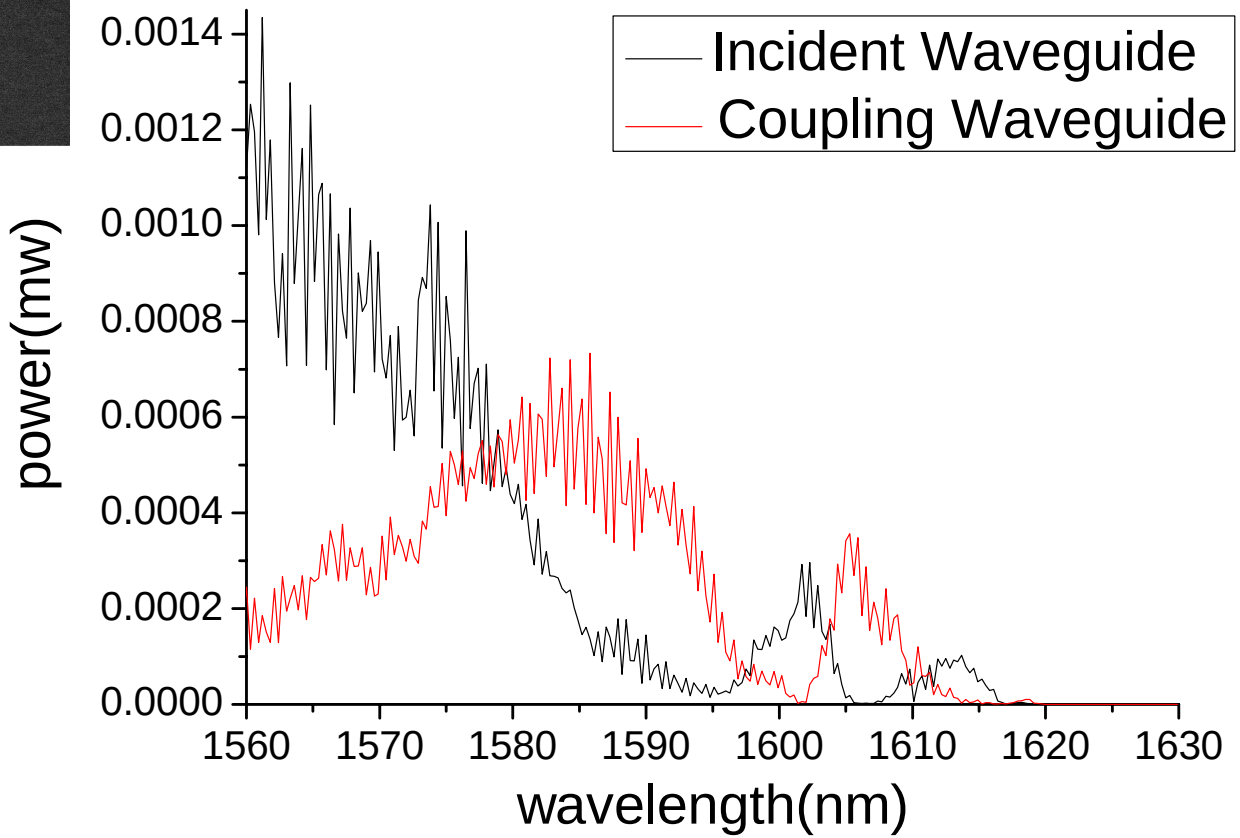


实验参数：*a*=460nm，*r*=130nm, *r*’=90nm，平板厚度为200nm

光子晶体波导耦合器

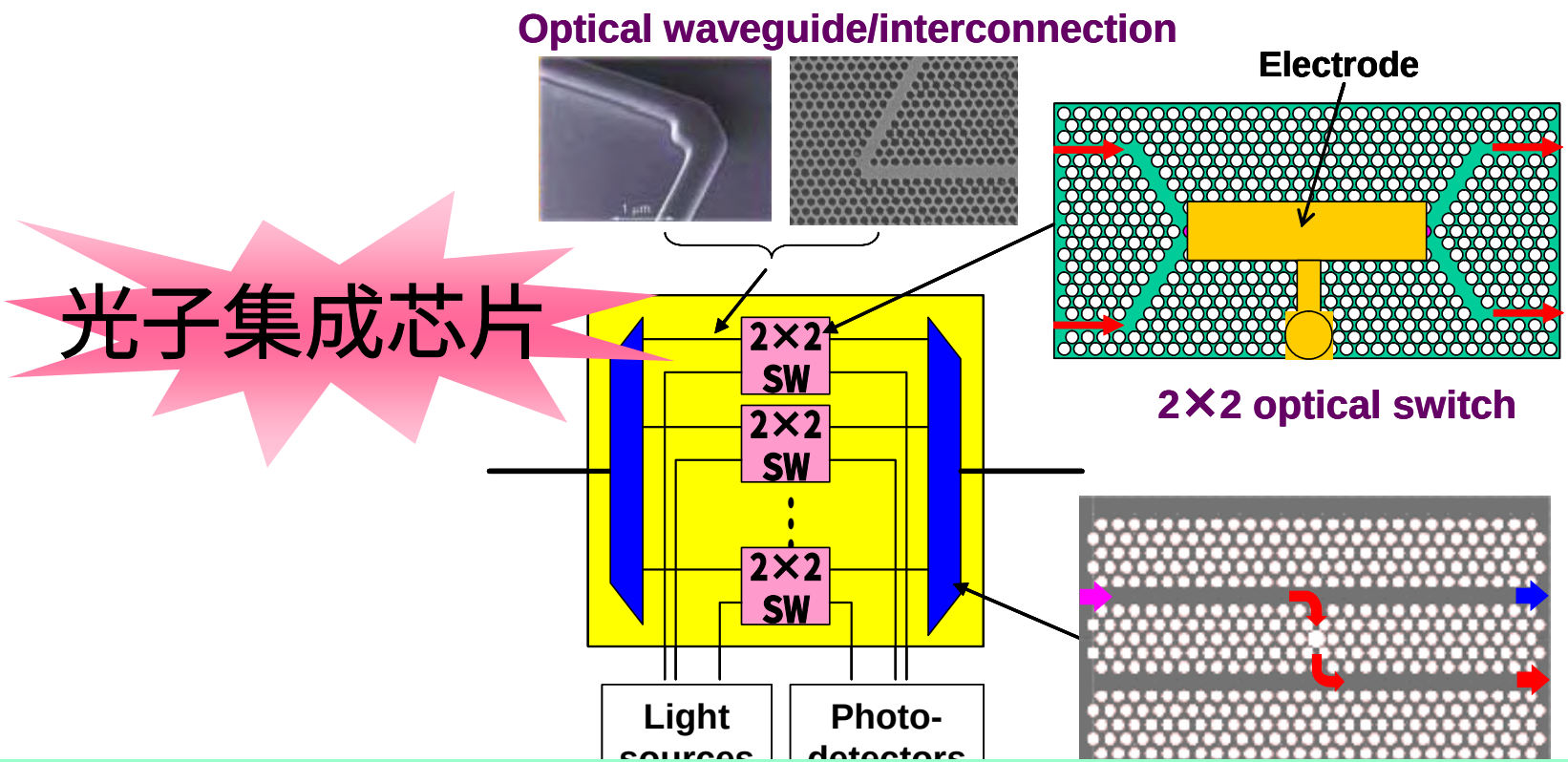


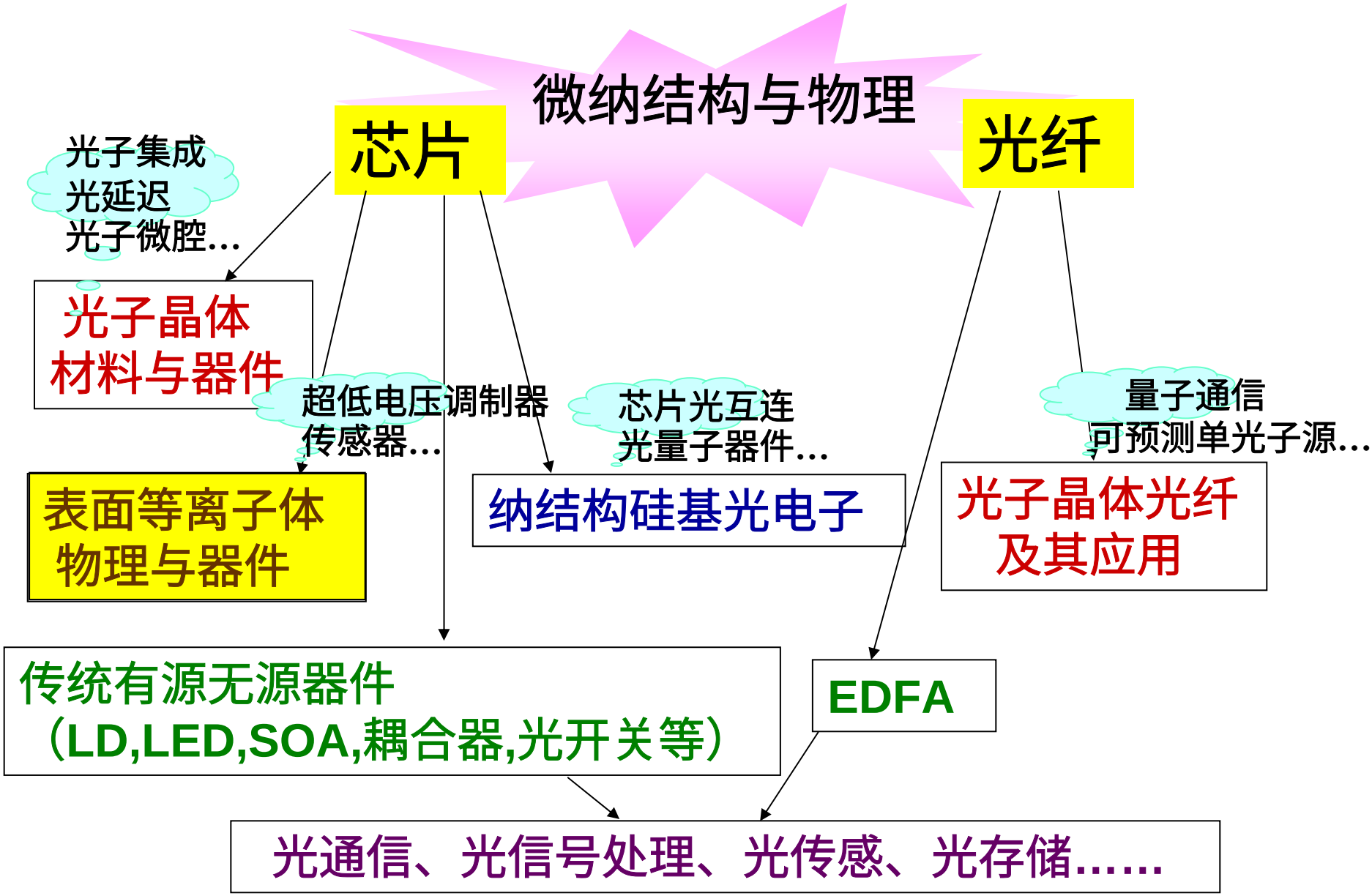
成功观测到了两个光子晶体波导间的能量耦合现象



光 子 晶 体

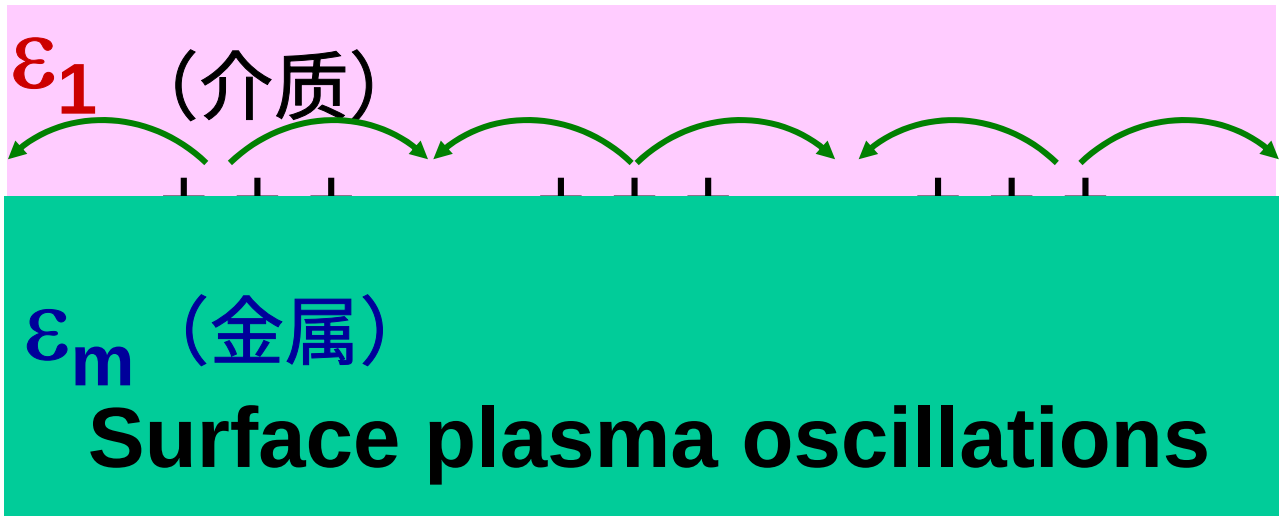
展示出一系列新的物理现象和独特的光学特性，为下一代光电子功能器件的发展提供了崭新的创造空间，也为光子集成的实现带来了新的希望




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……

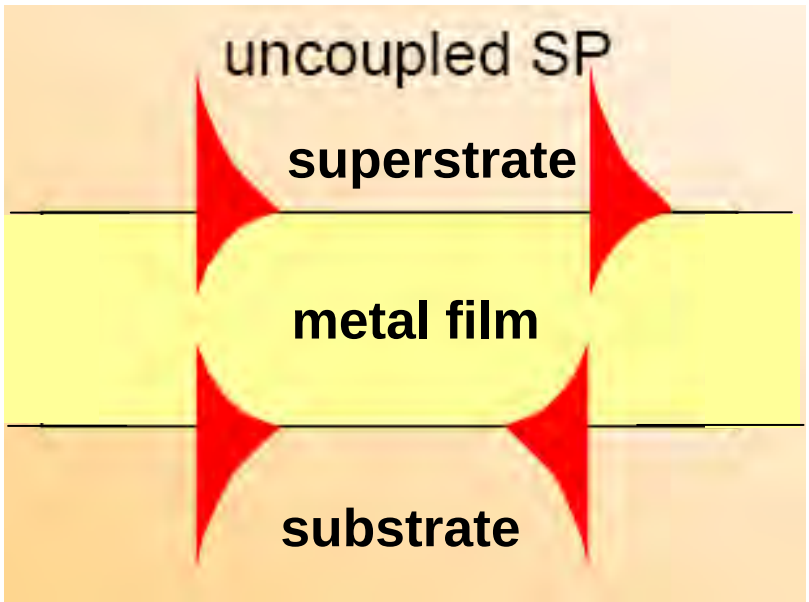
表面等离子波

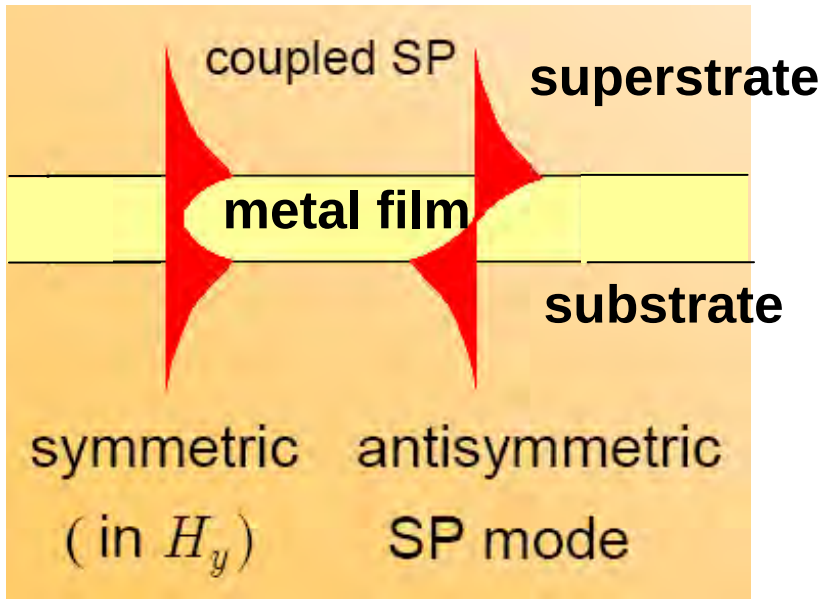
金属表面电子浓度的起伏形成表面等离子振荡



损耗非常大，只能传输数十微米

Long Range SPP: LR-SPP

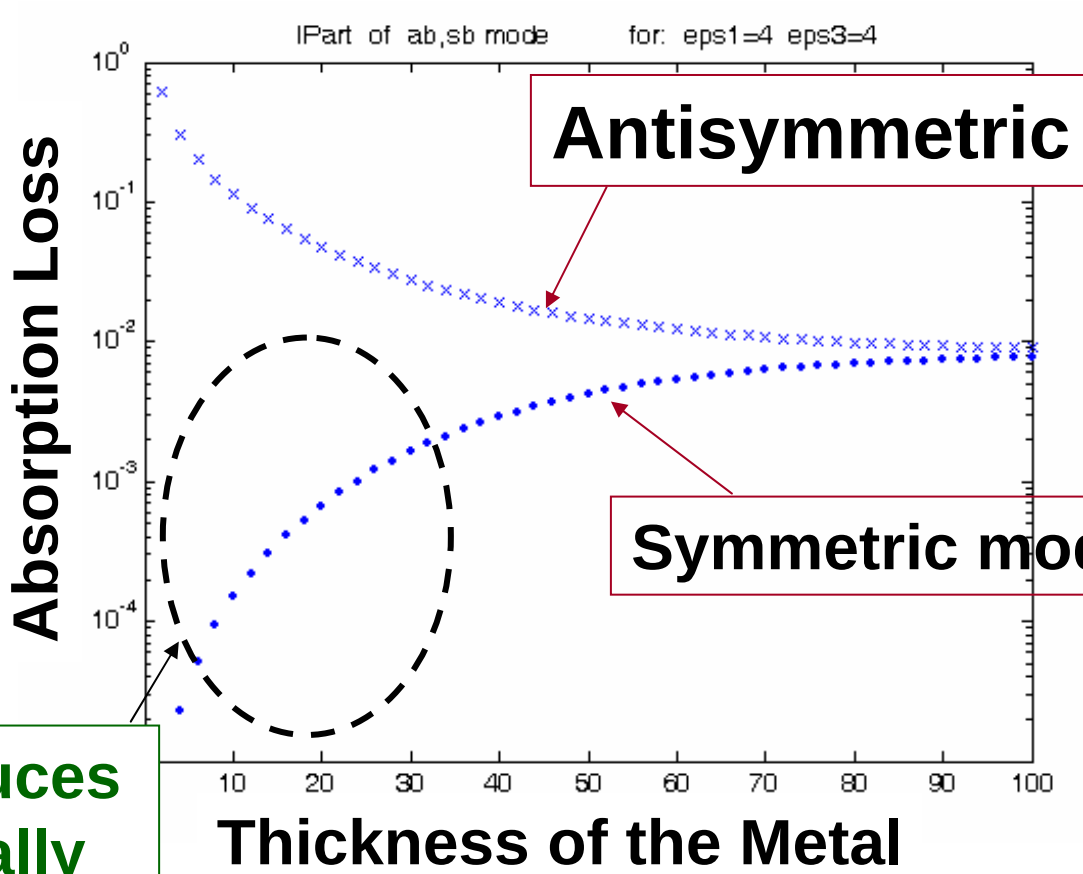




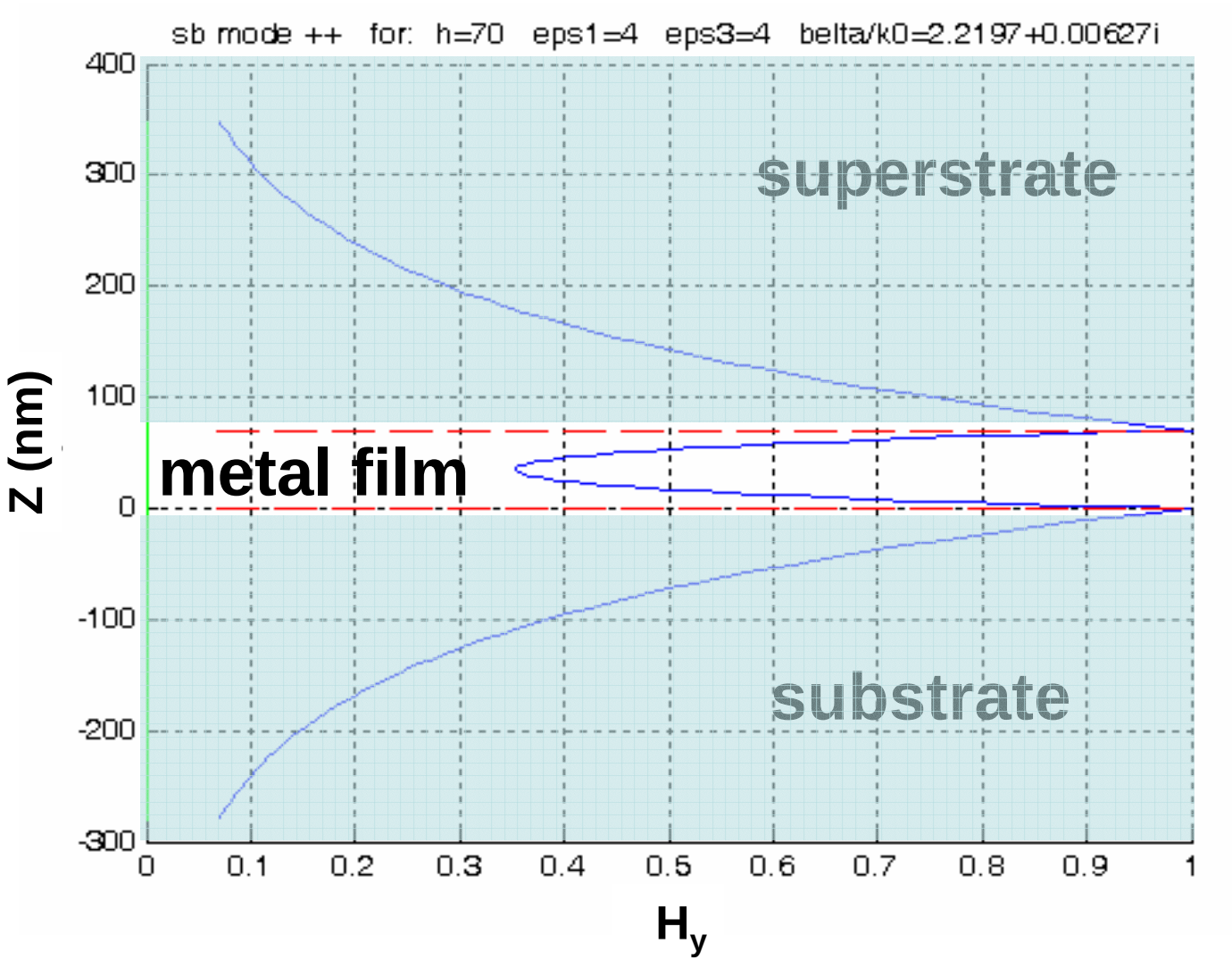
When the metal film is thin enough

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

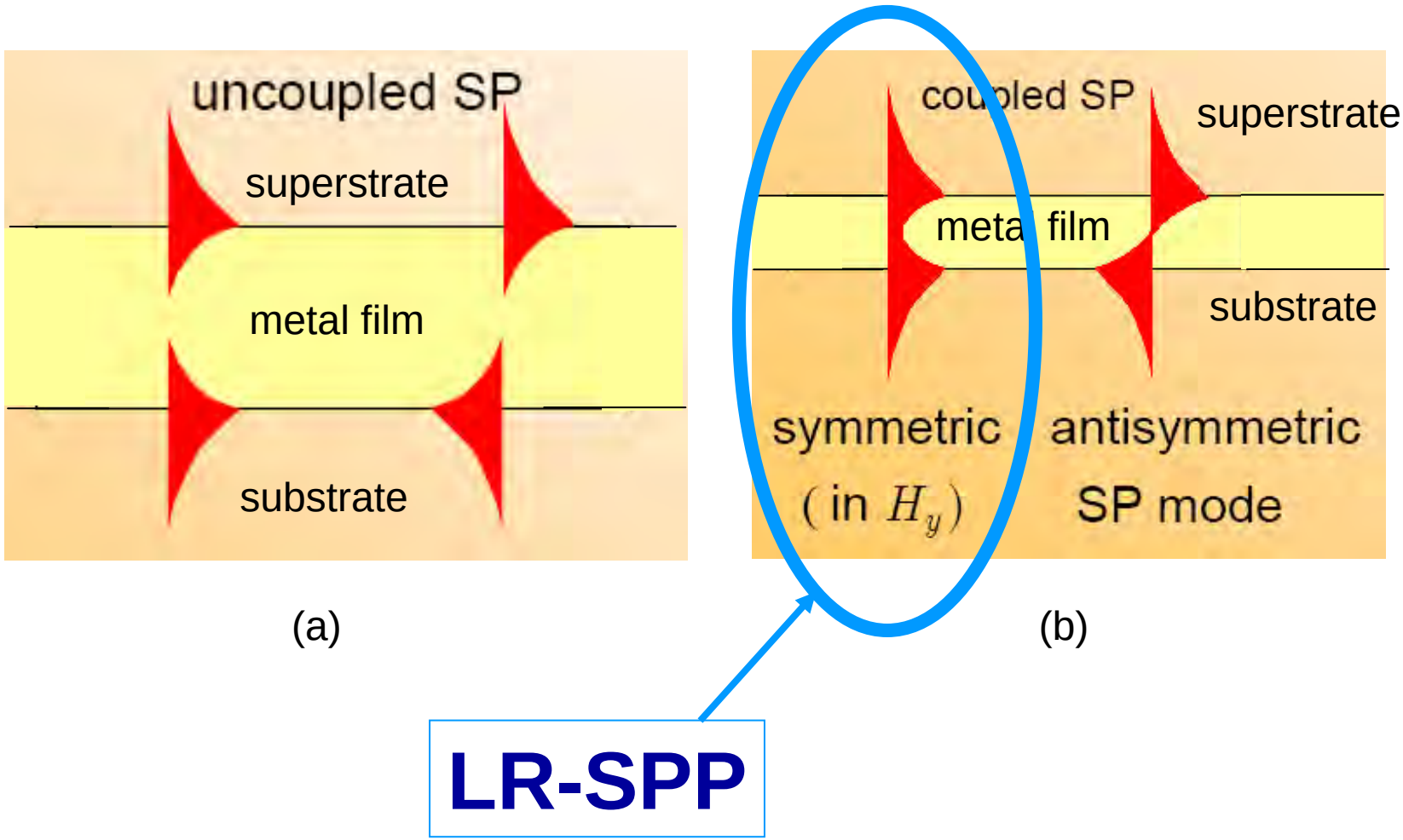
Loss Characteristics



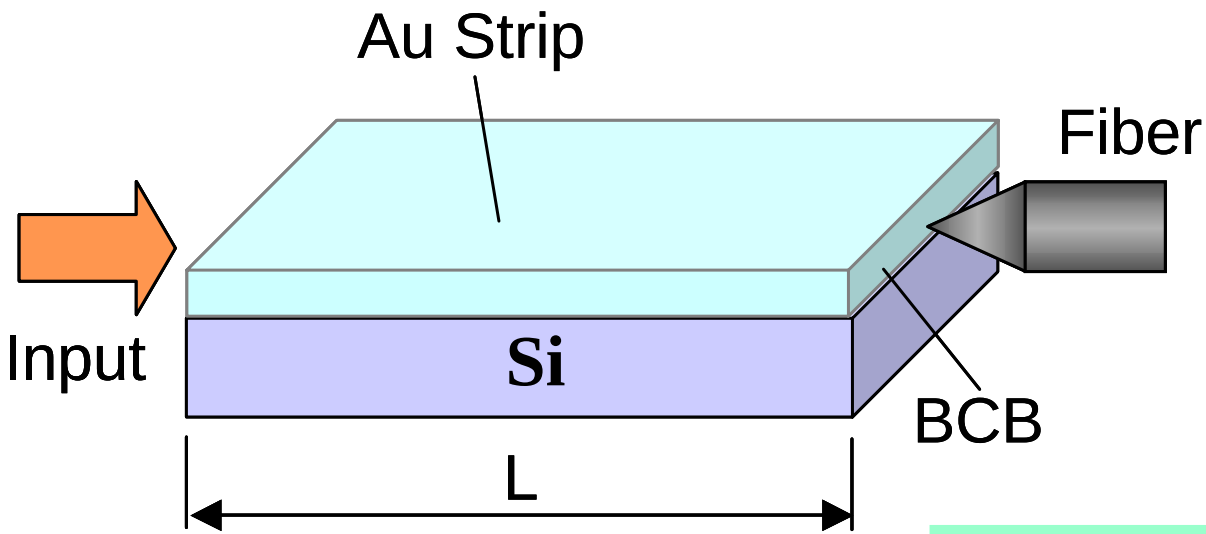
Long Range SPP: LR-SPP

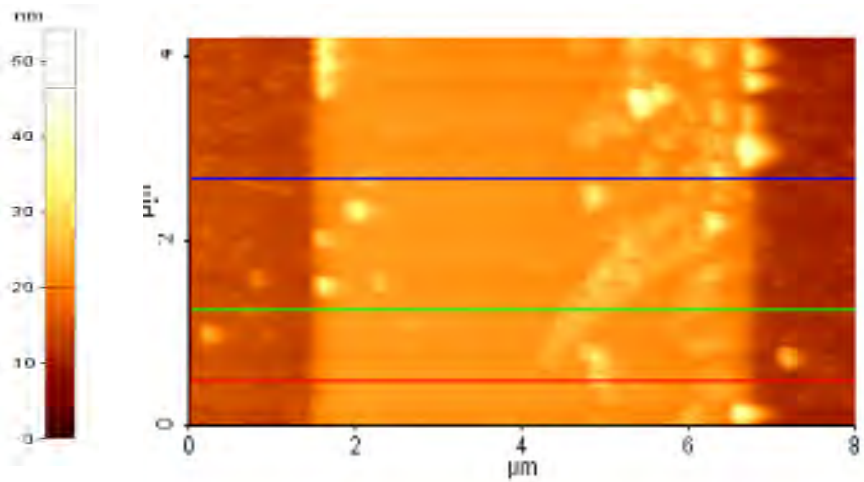


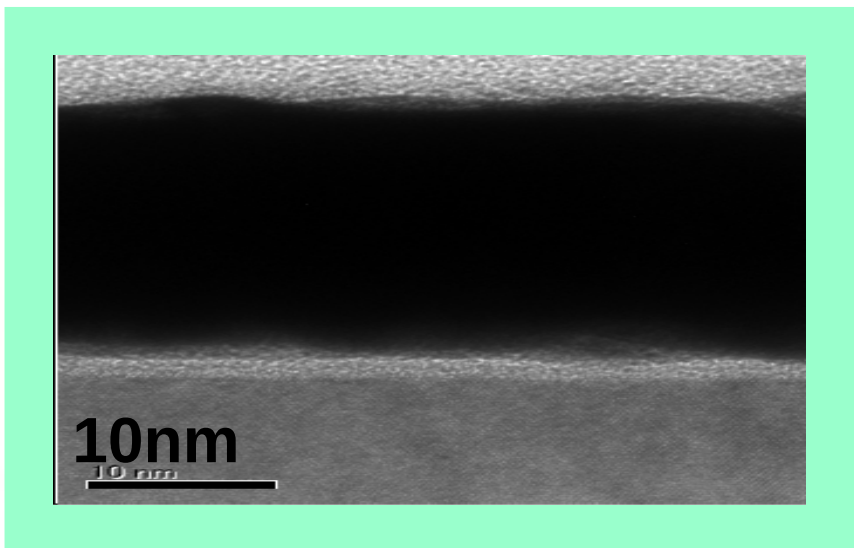
Long Range SPP: LR-SPP



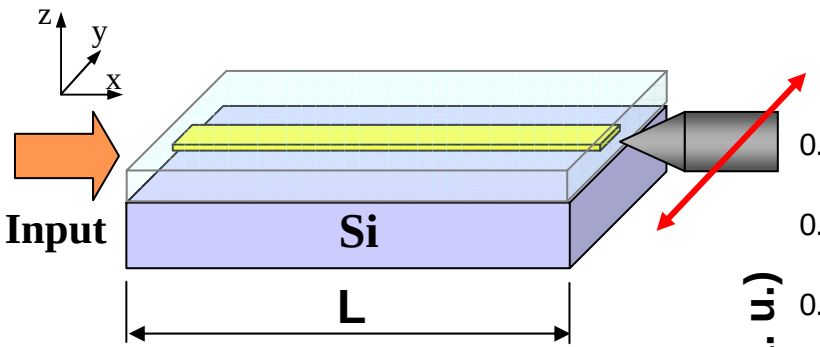
Fabrication of LR-SPP WG



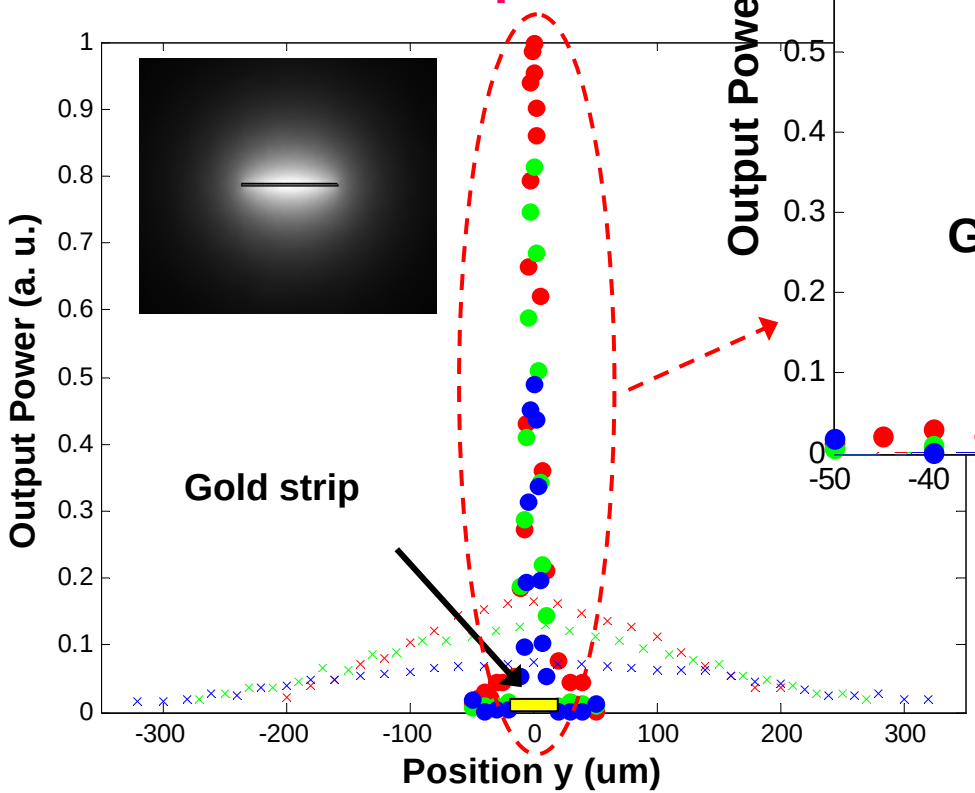


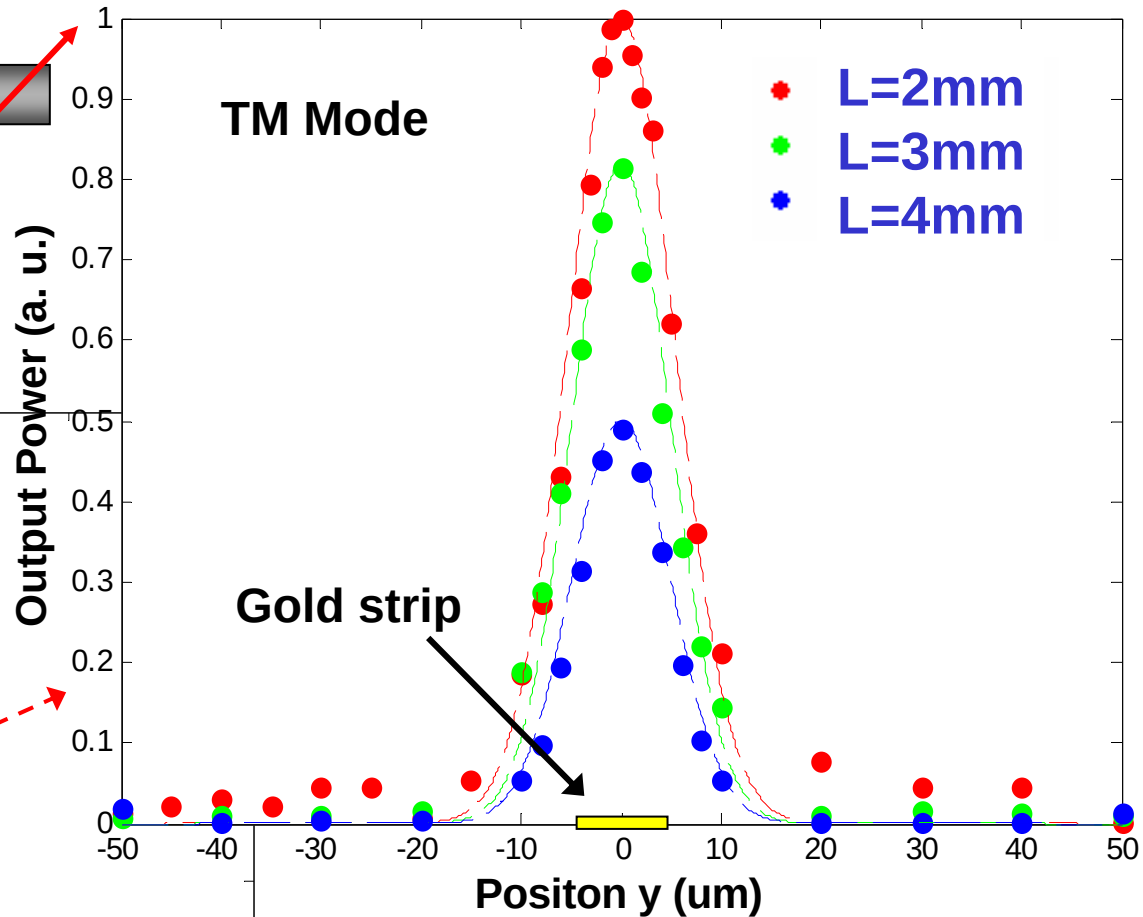


Measurement Results



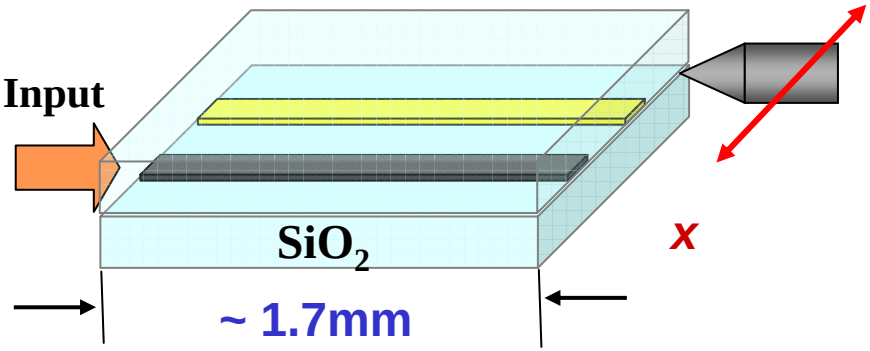
With Metal Strip

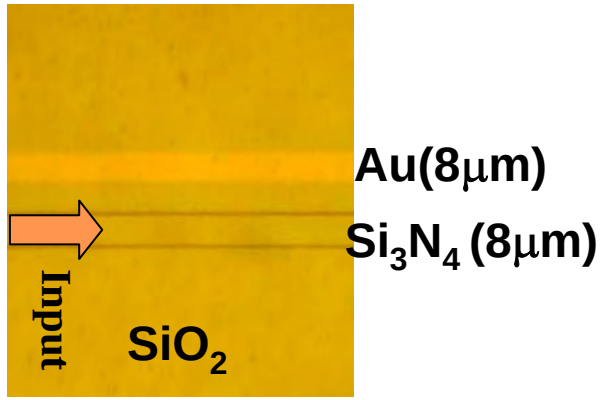




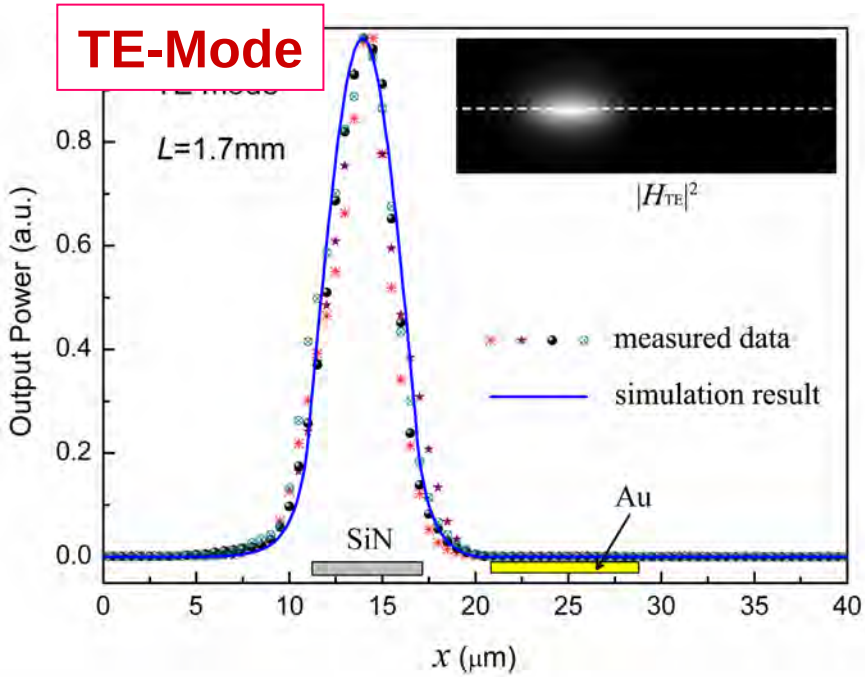
-0.67 dB/mm!

Experimental Results for Hybrid Coupler

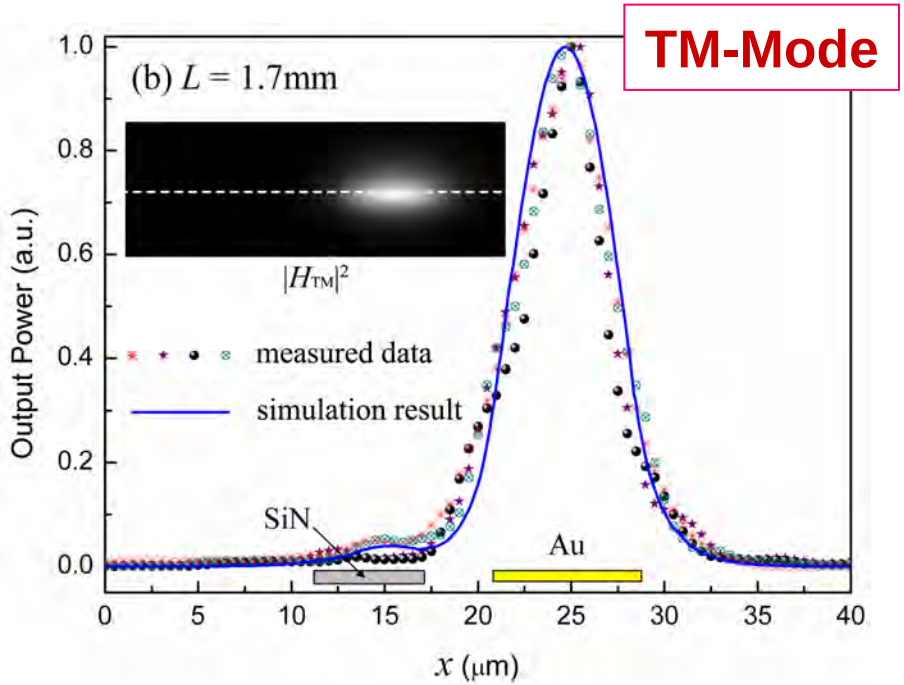




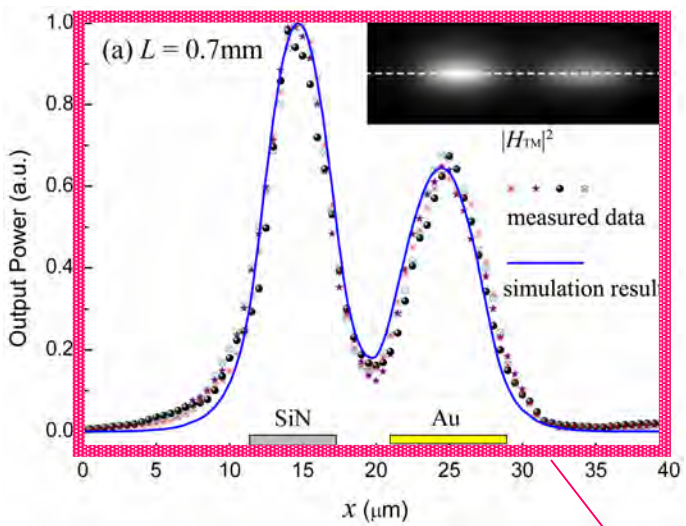
TE-Mode

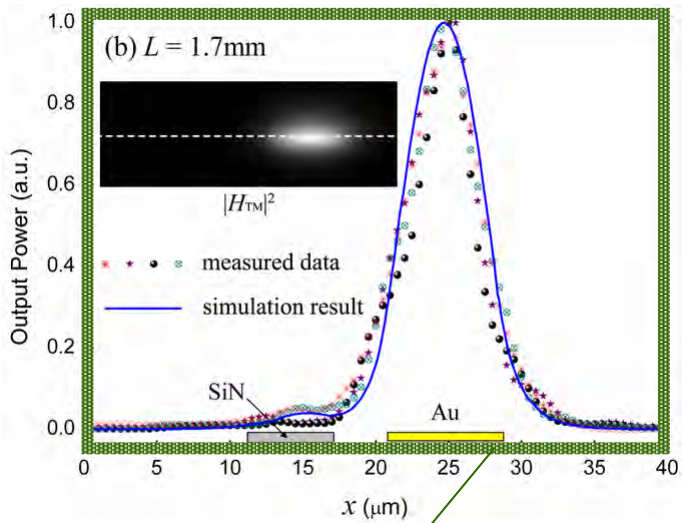


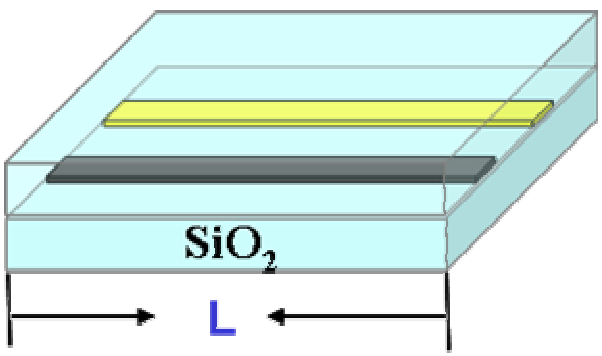
TM-Mode

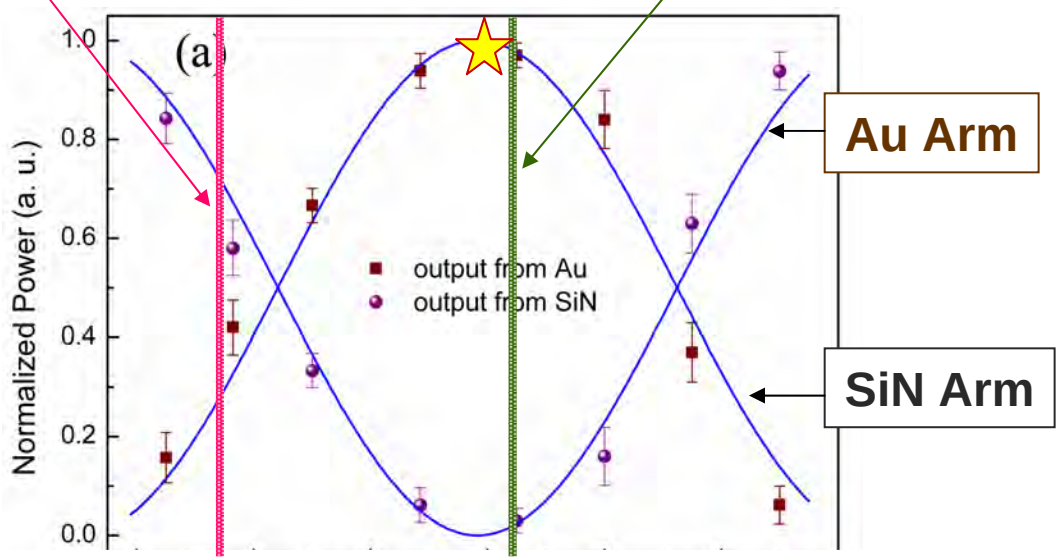


Experimental Results for Hybrid Coupler



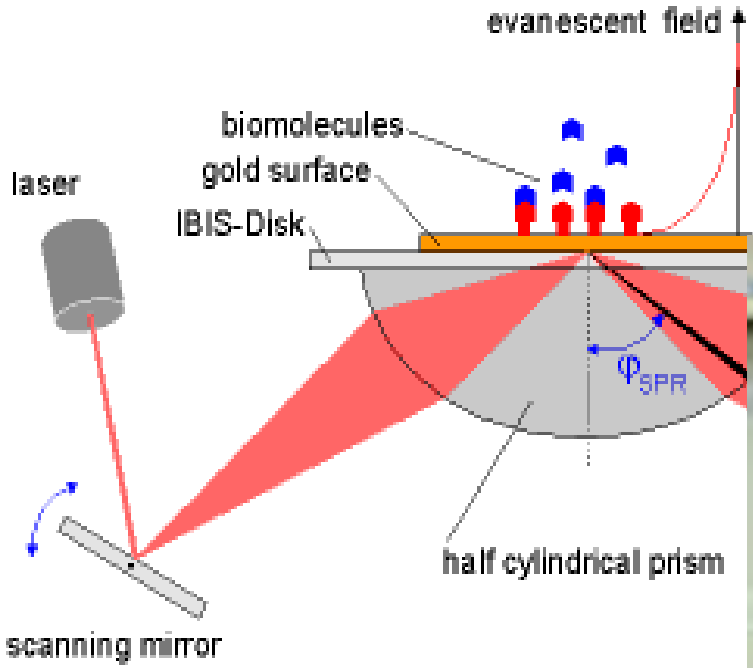


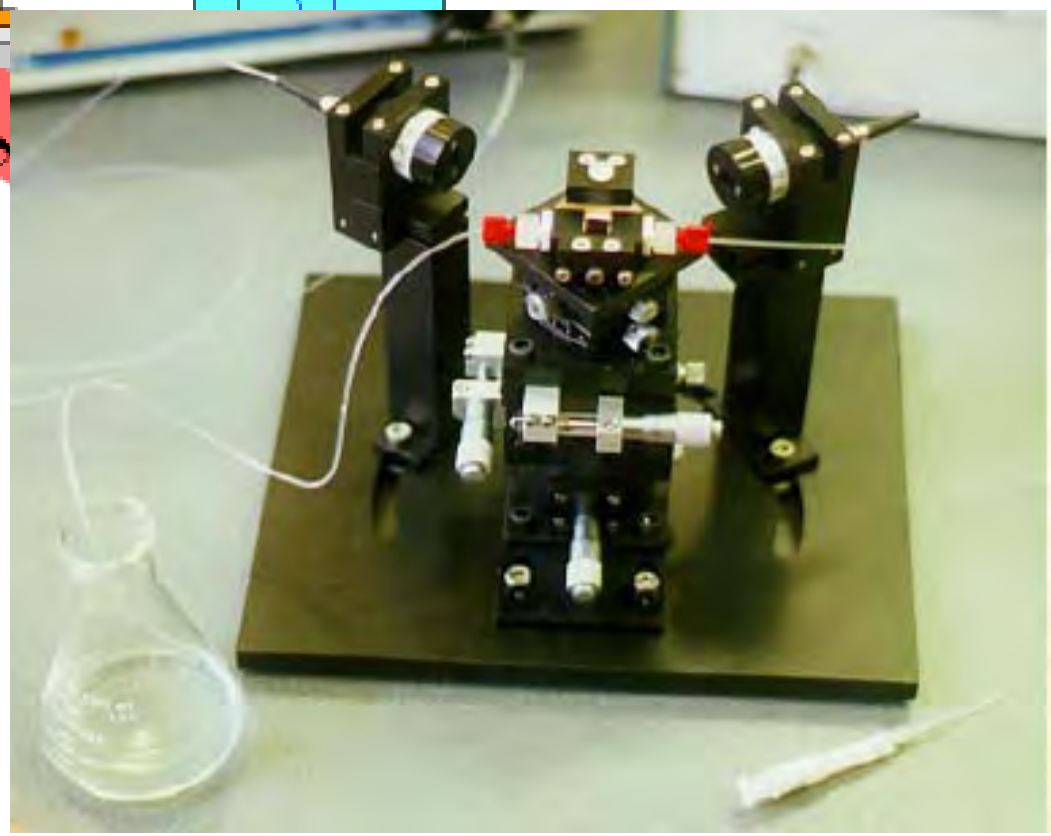




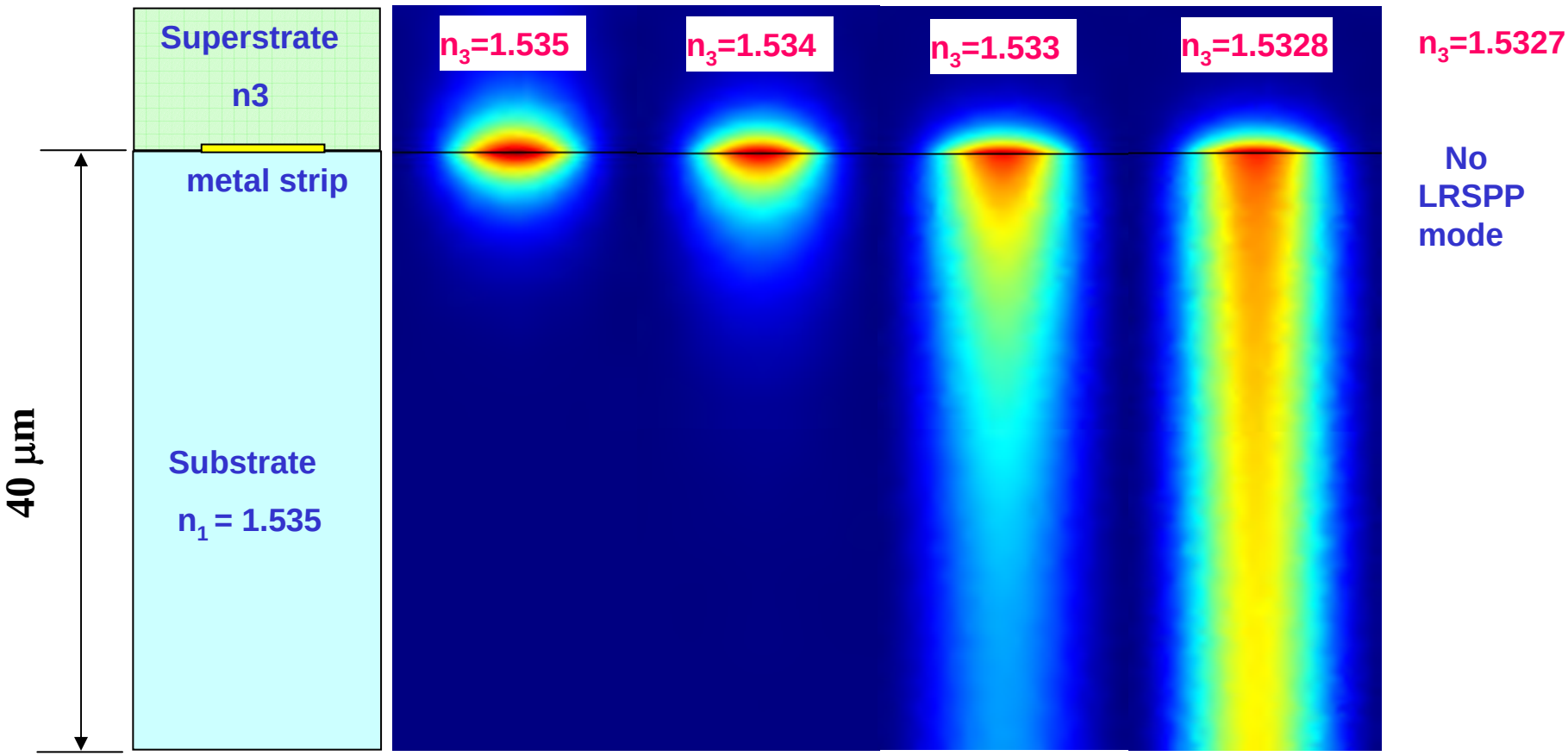
extremely high coupling efficiency >99% !!

Conventional SPP Sensor





LRSPP Supported by Metal Strip

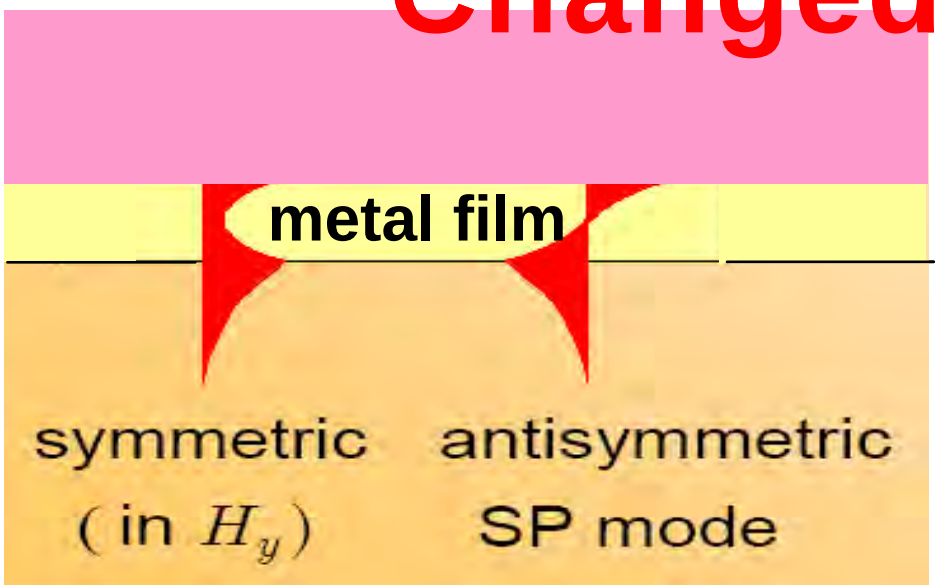


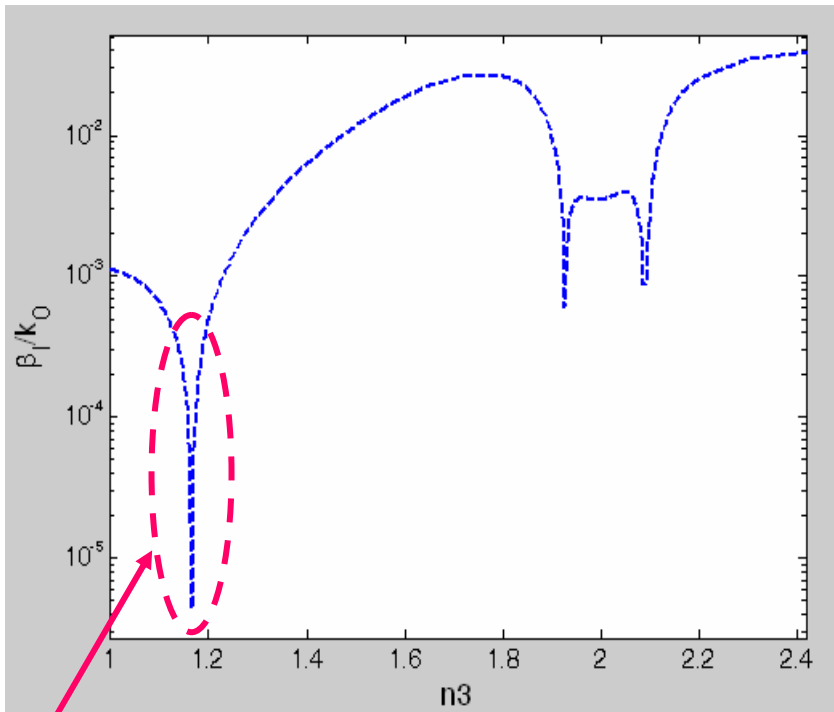
Very Sensitive to n_3!

Sensor with LR-SPP Waveguide

Integrated Refractivity Sensor

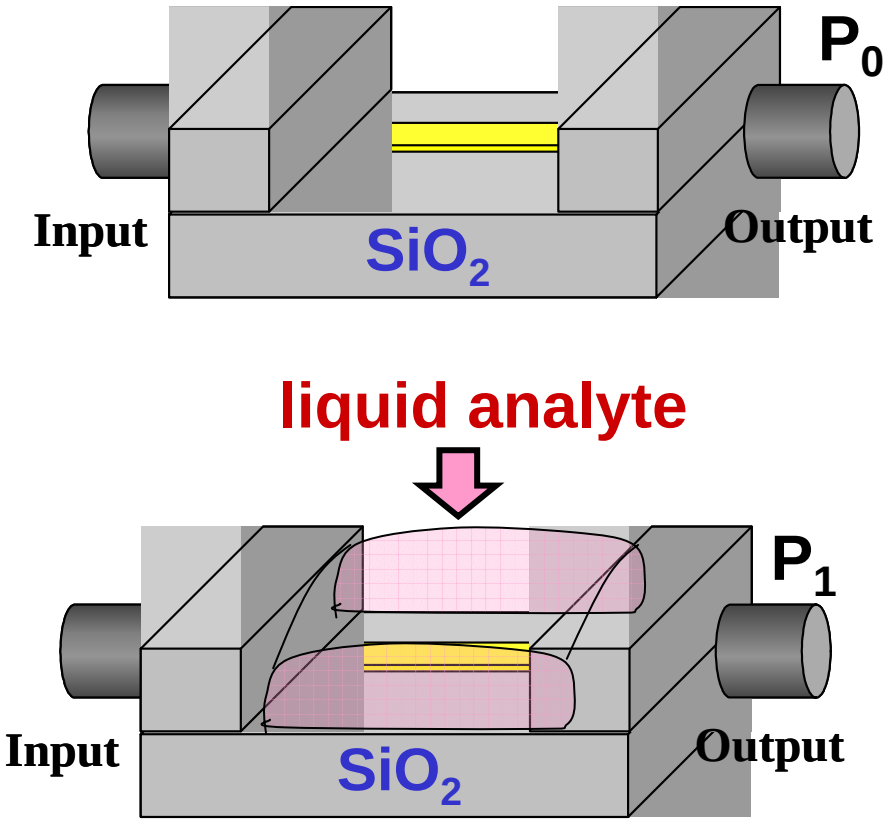
Changed!

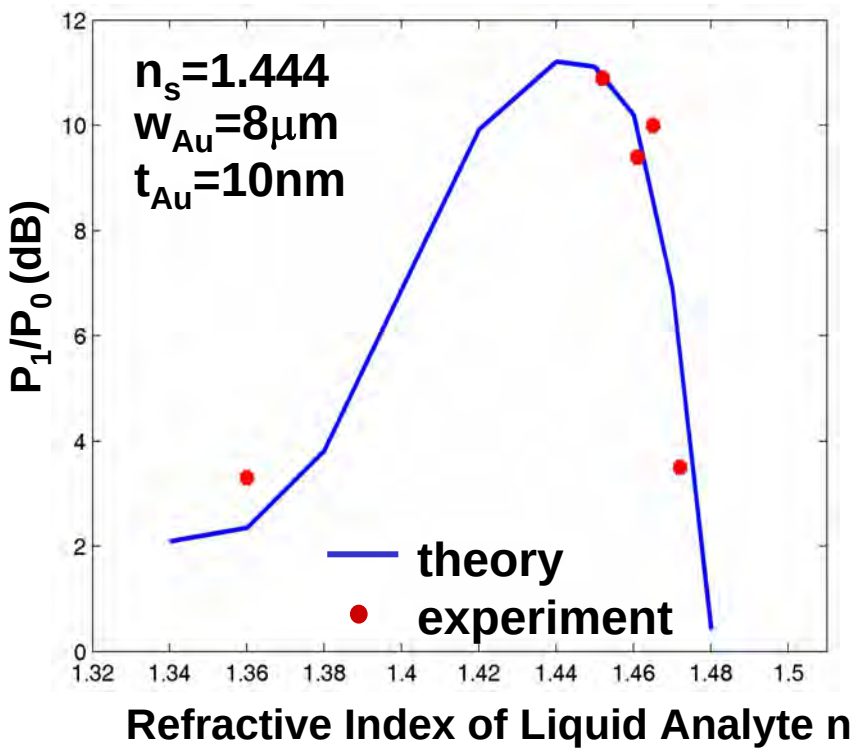




Transmission Dip

Measurement Results

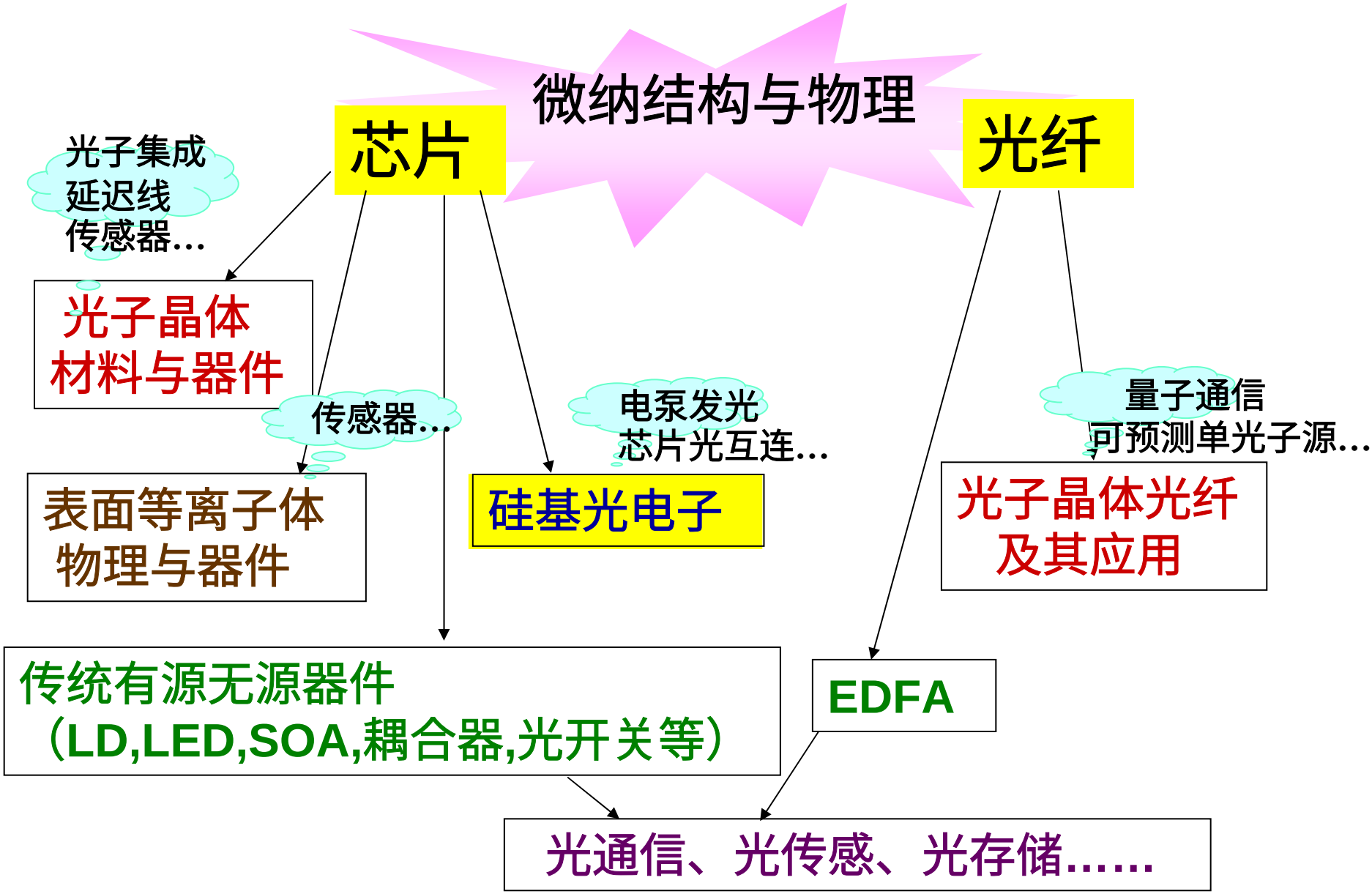




high sensitivity of 10^{-4}

Reported by Nature CHINA

as Research Highlight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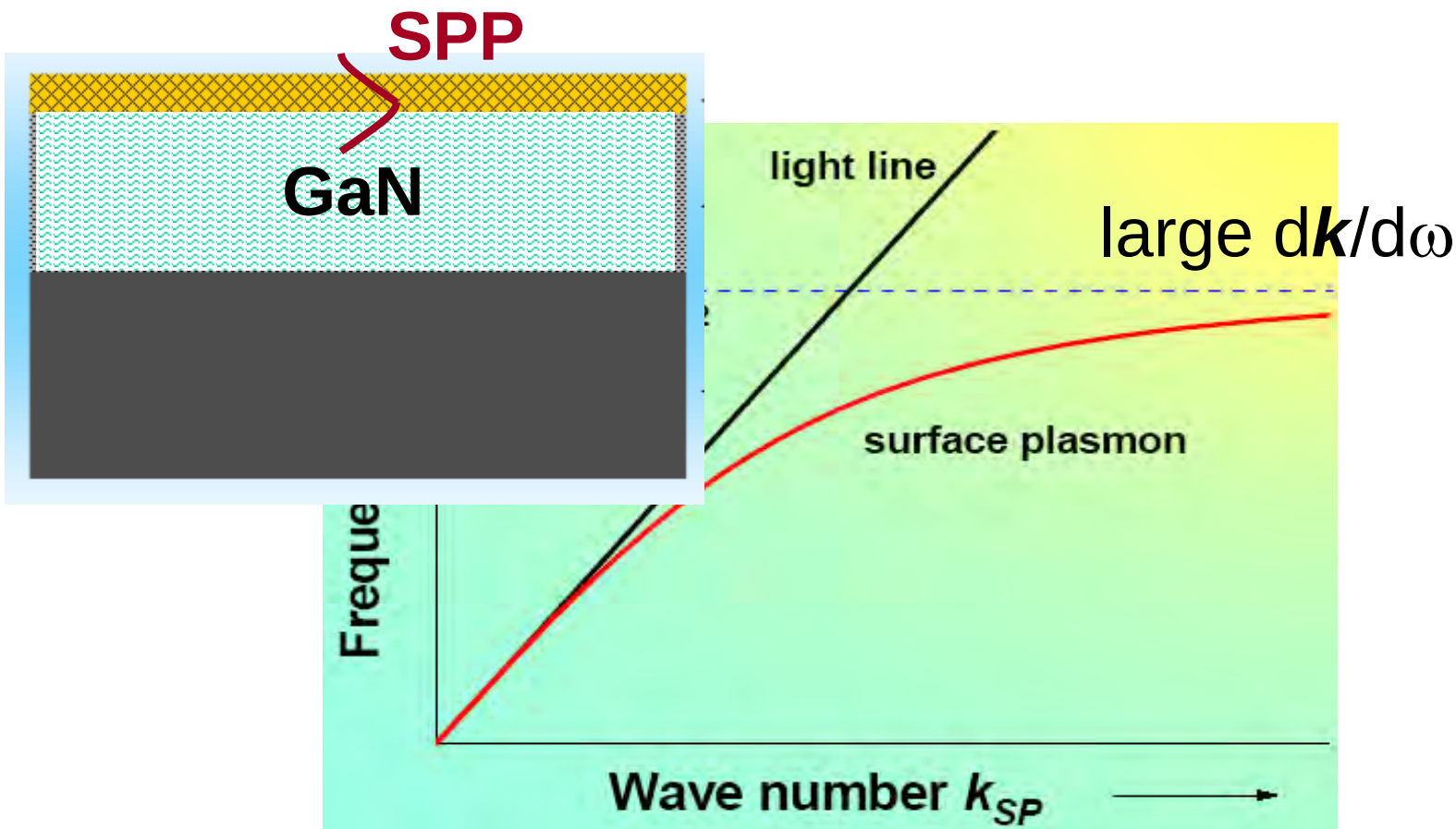
光通信、光传感、光存储……

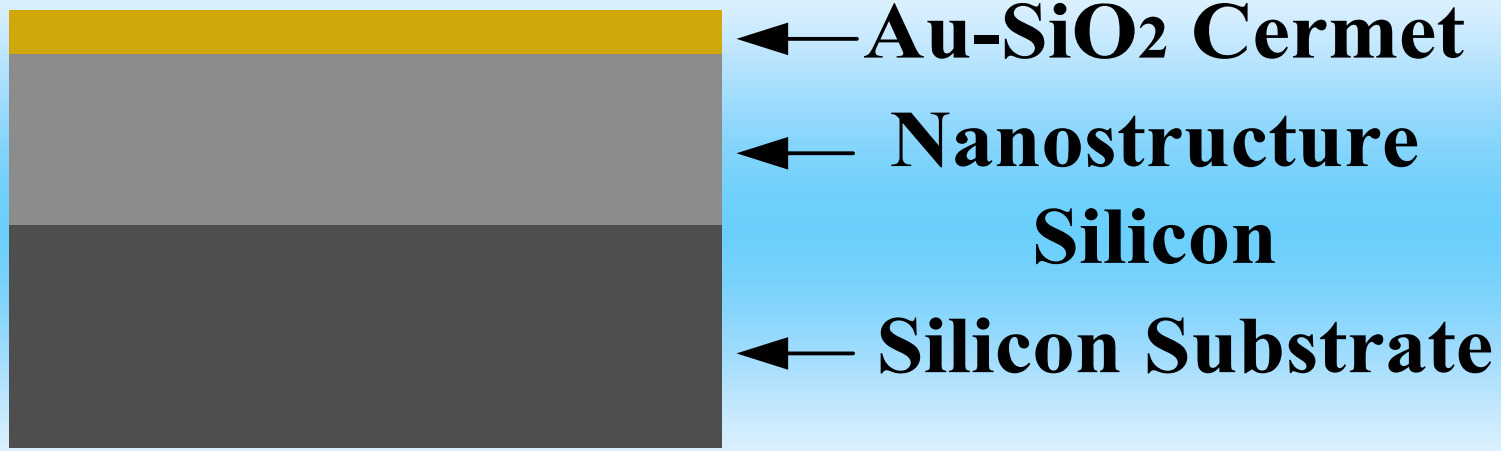
Purcell Effect Associated with SPP

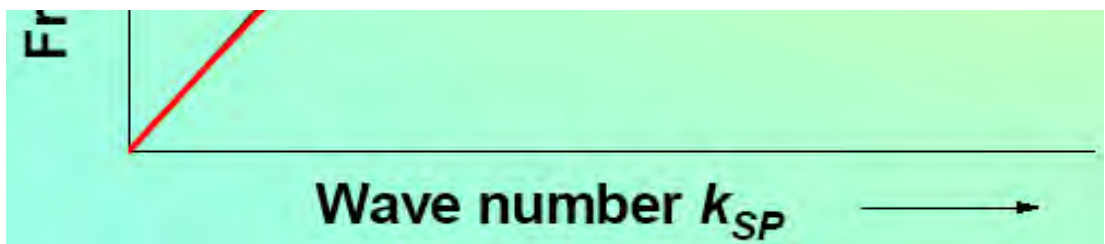
Enhanced Photoluminescence from Porous Silicon?



Purcell Effect Associated with SPP

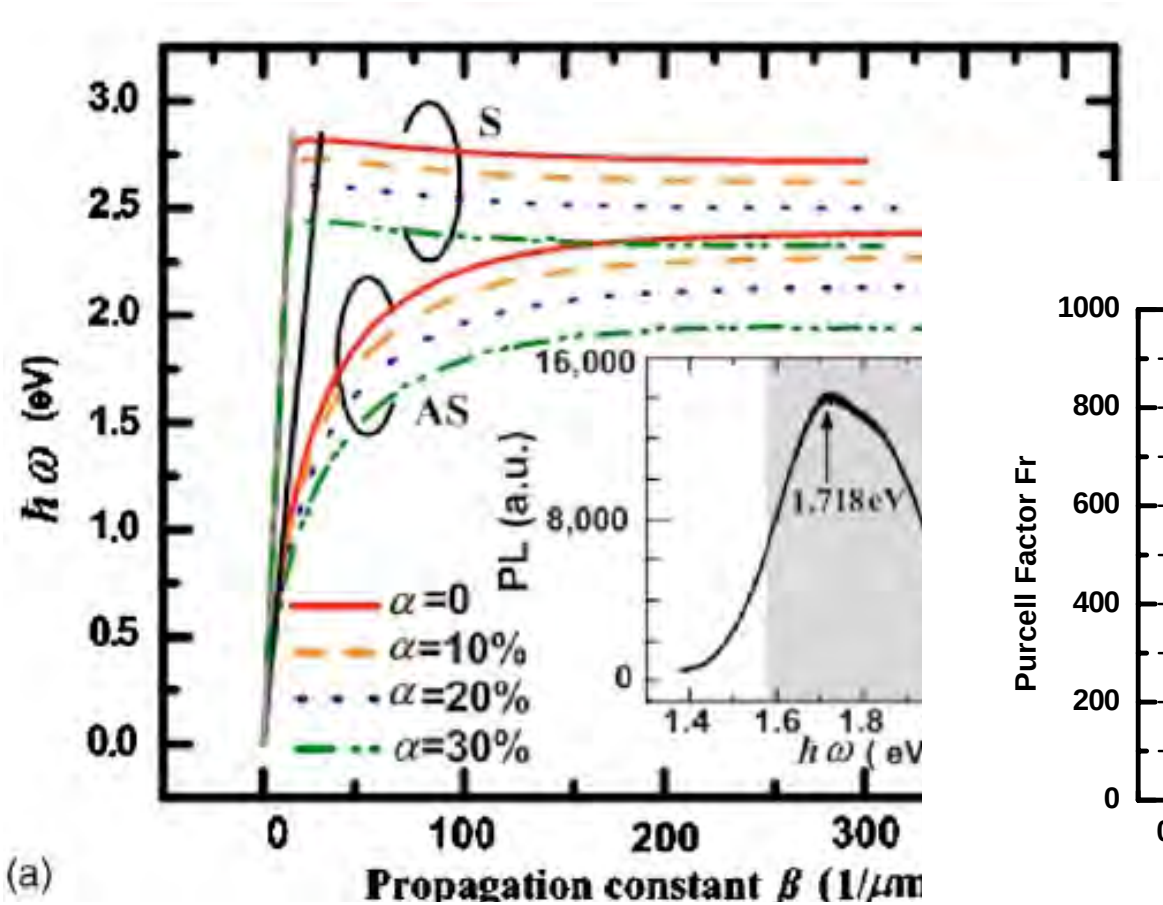
Enhanced Photoluminescence from Porous Silicon?

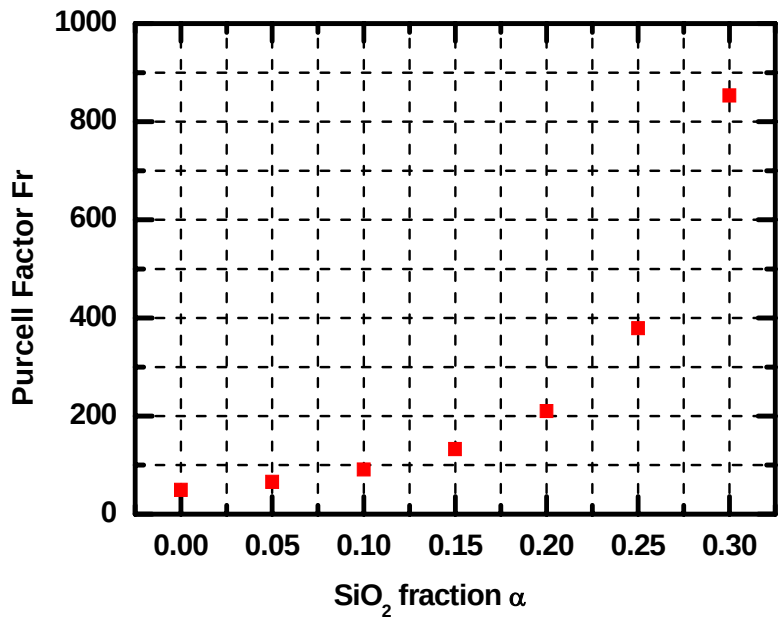




Purcell Effect Associated with SPP

Enhanced Photoluminescence from Porous Silicon



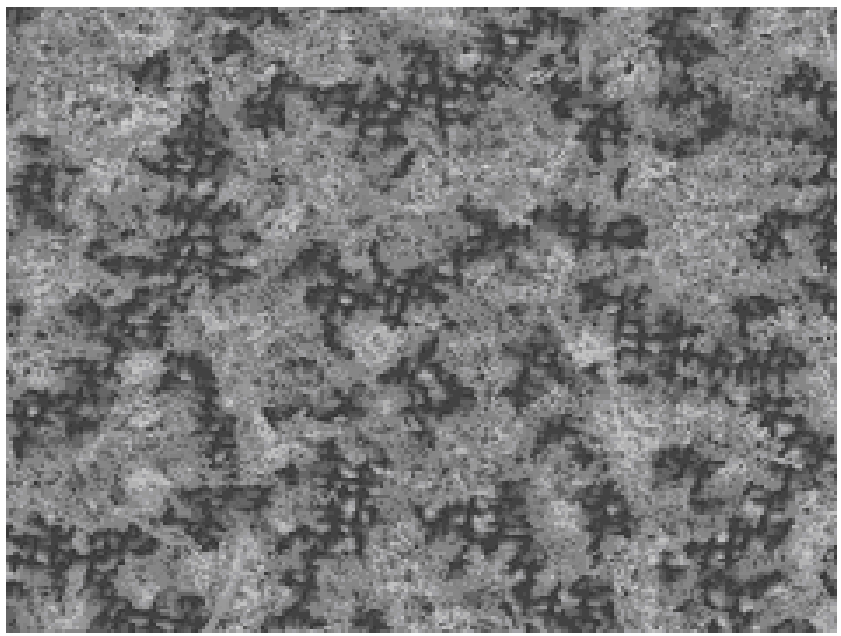


Appl. Phys. Lett. vol. 89, no. 081112, 2006

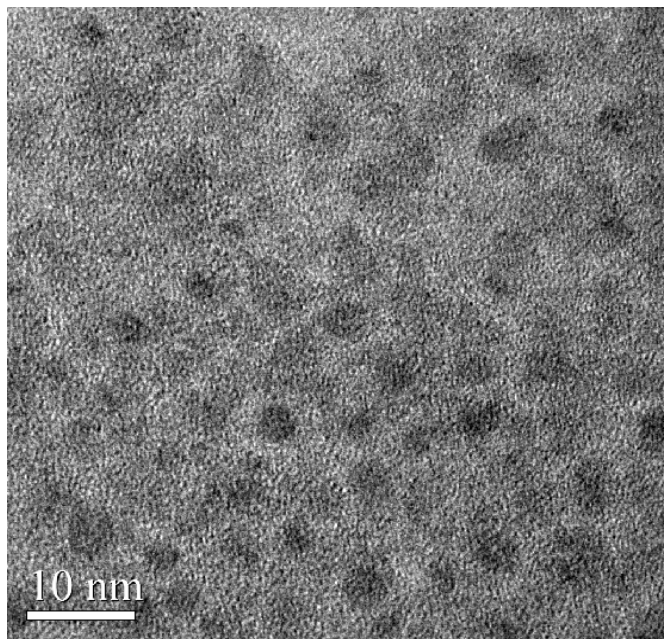
Appl. Phys. Lett. vol. 92, no. 251116, 2008

Nano-Structure Silicon

Porous Silicon

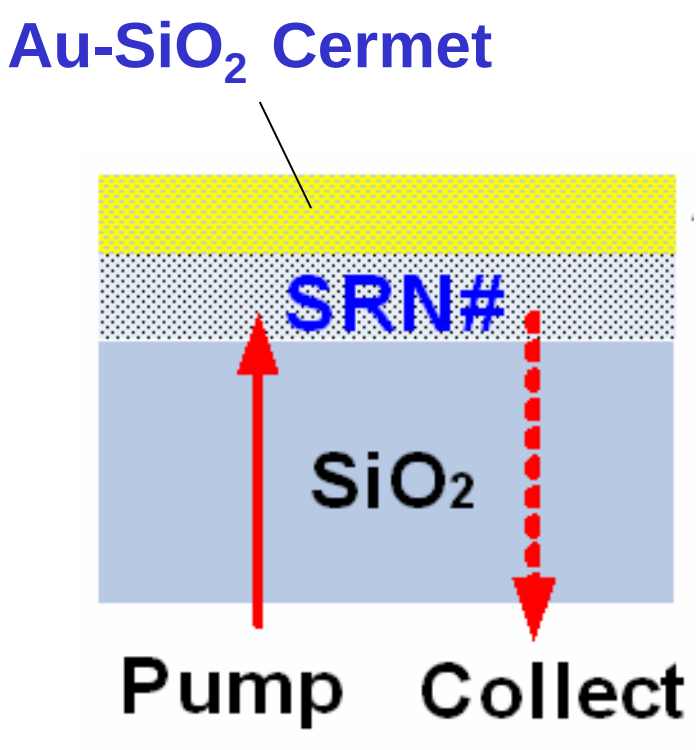


SiN_x Nanocystal

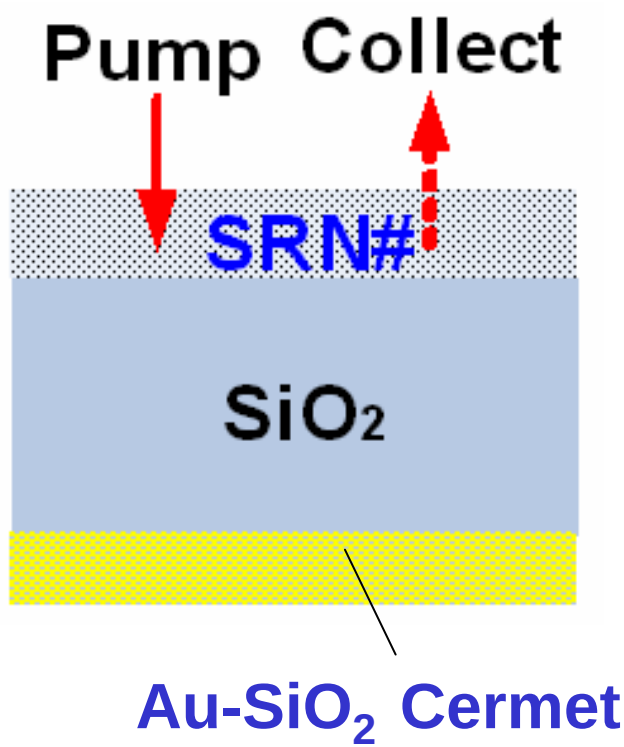


Surface Plasmon Waveguide

Experimental Results

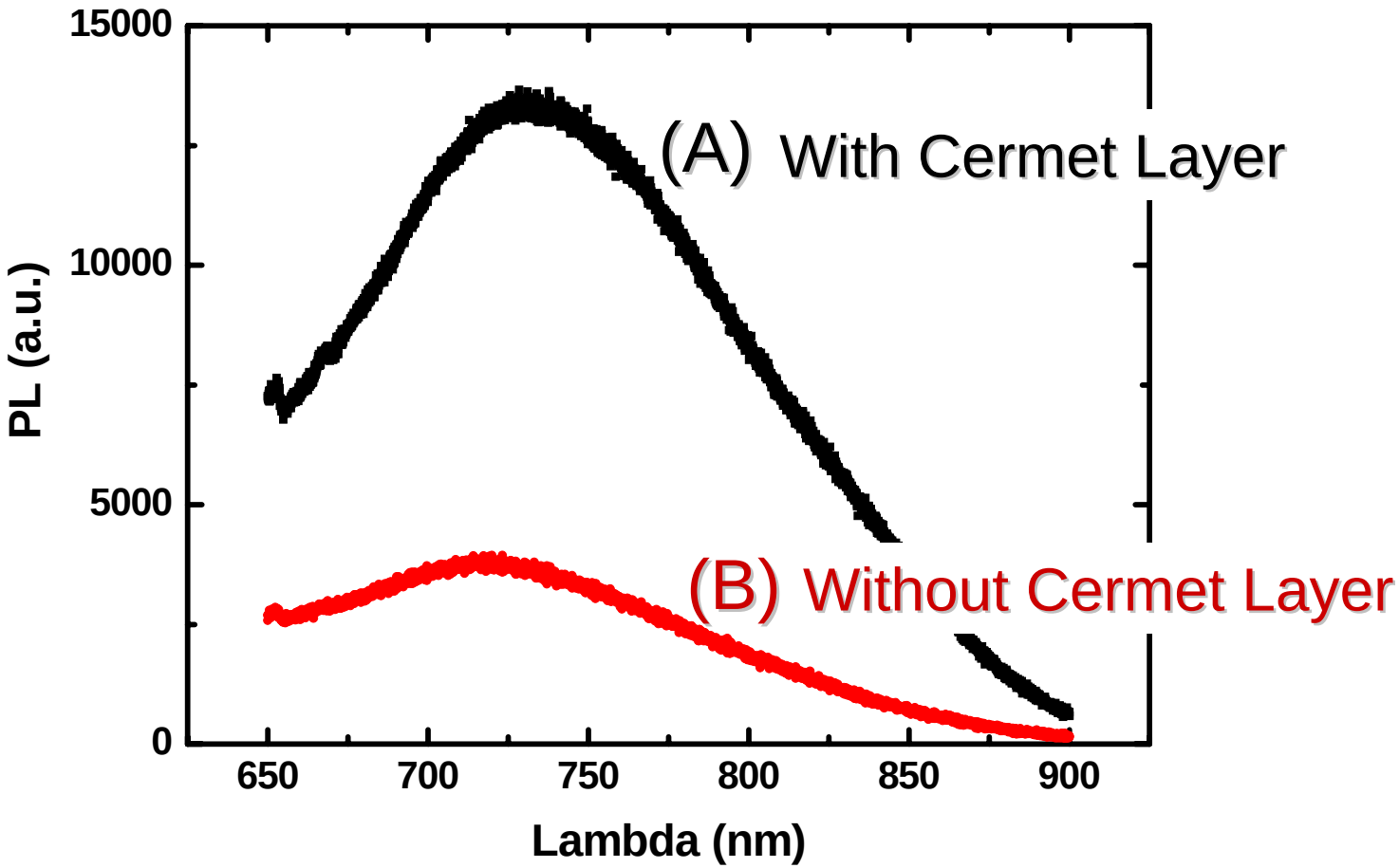


(A)



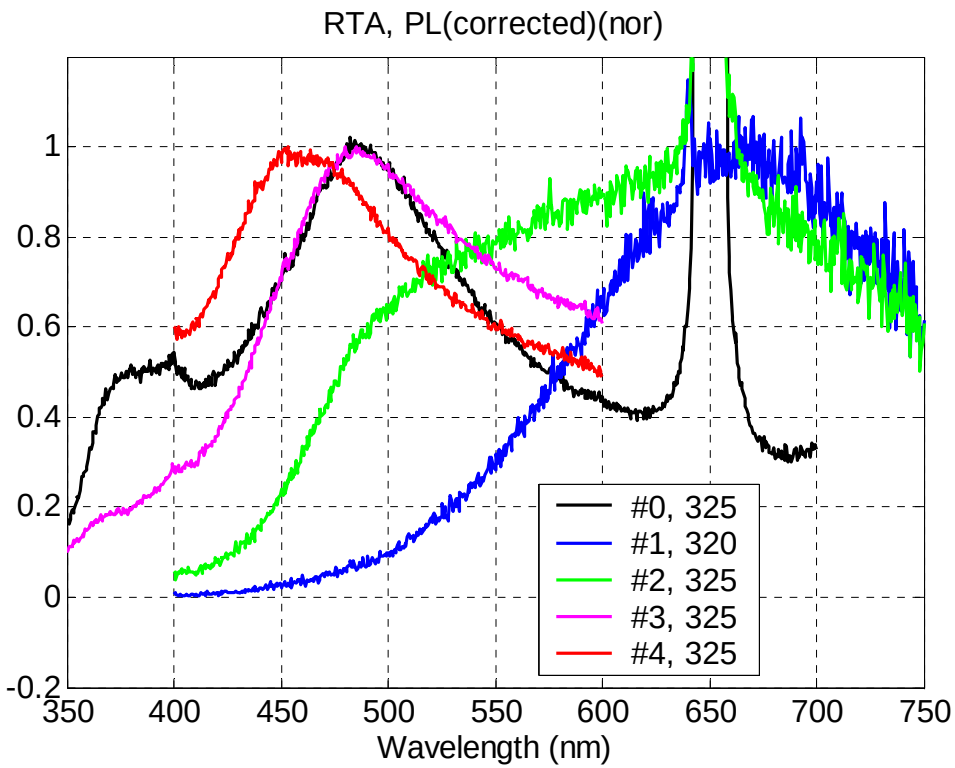
(B)

Experimental Results



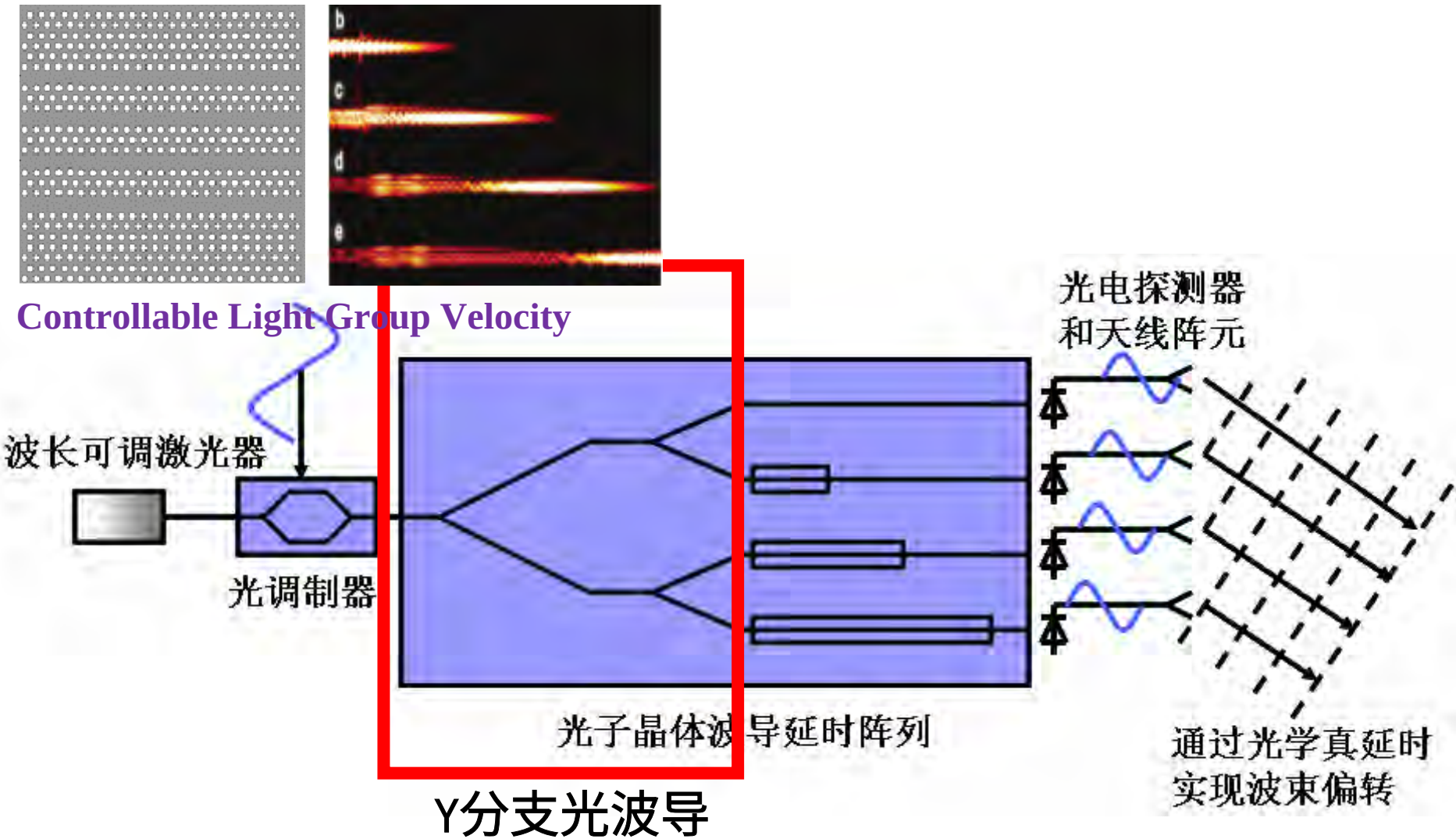
Photoluminescence (PL)

Excited by 325nm laser (0.5mW/mm^2)

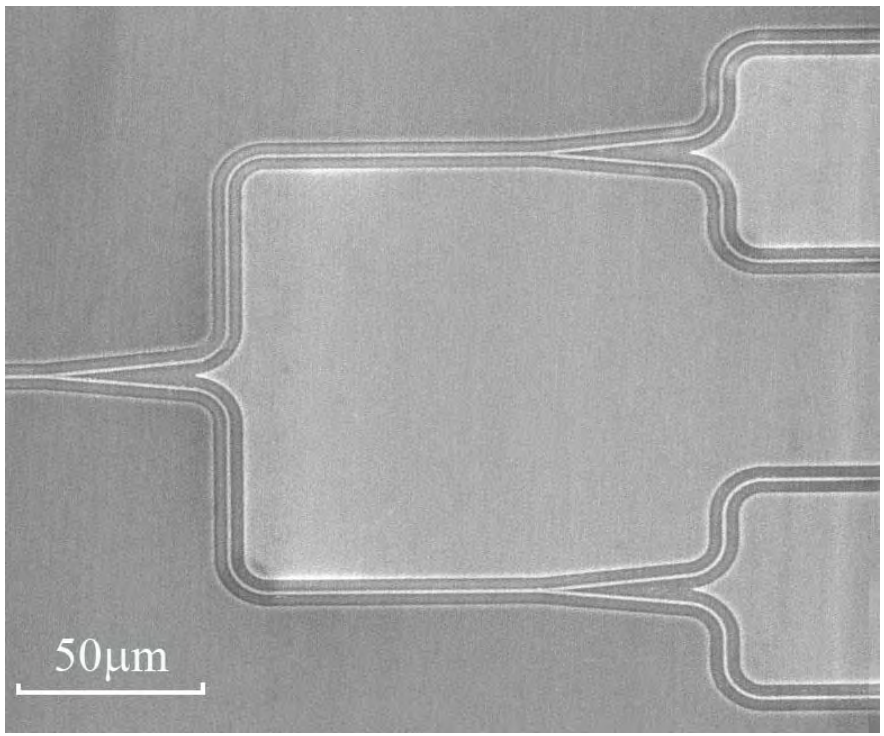


~1% of III-V semiconductor

光子晶体慢光波导
光学真延迟结构设计



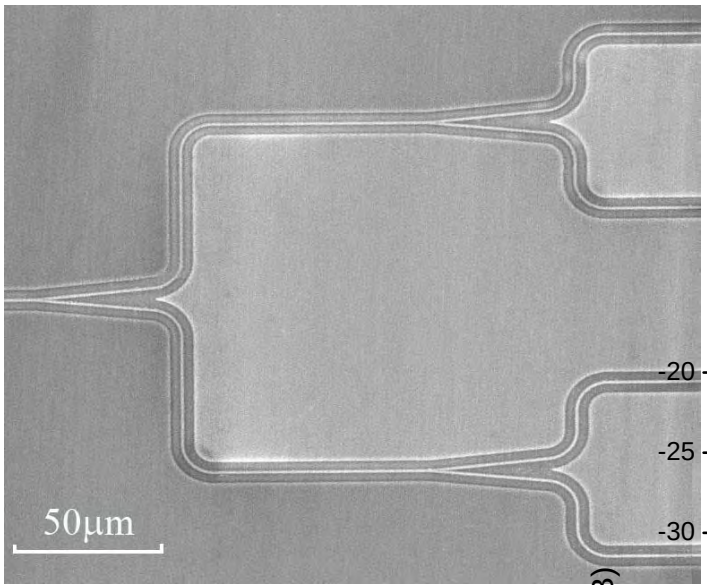
Si 纳米线 Y 分支光波导的制作



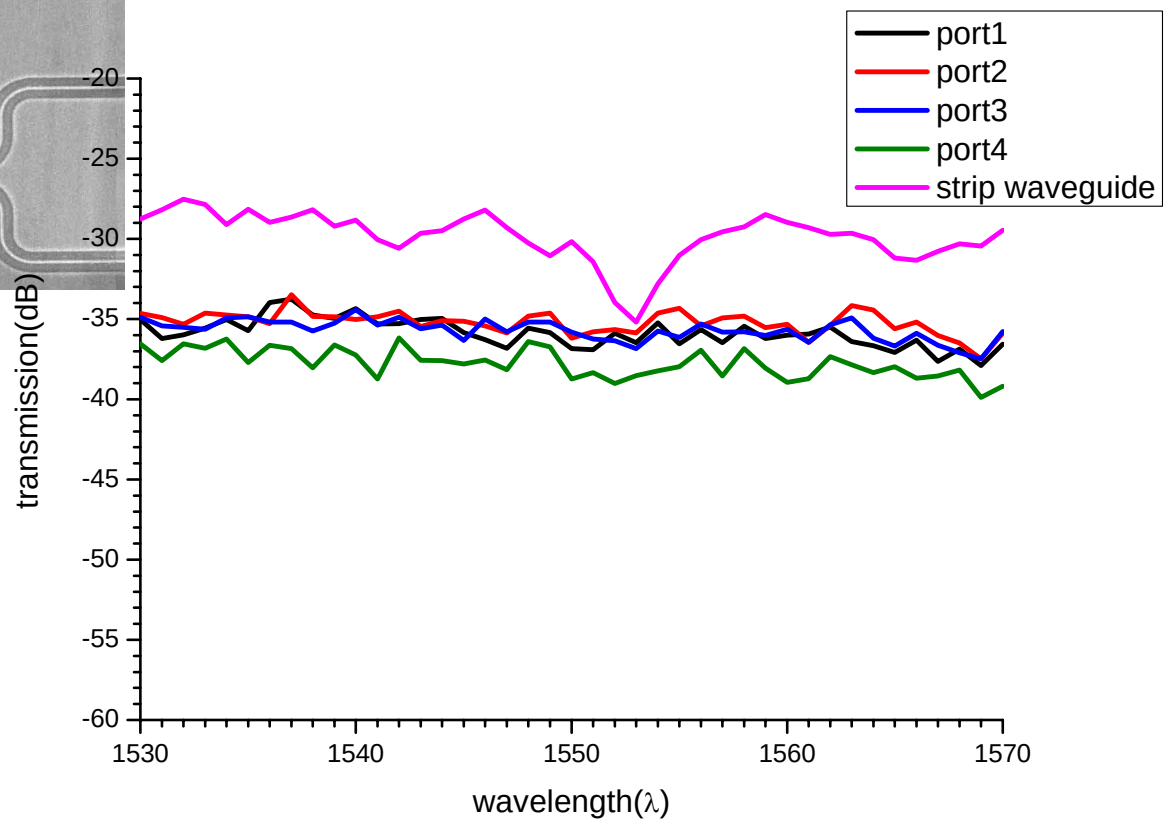
波导宽度=465nm　分支角度=12度　转弯半径=10μm

表面SiO_2覆盖层：600nm

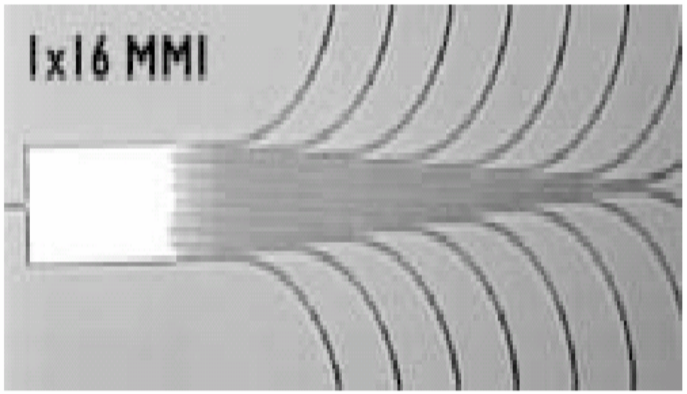
Si 纳米线 Y 分支光波导的制作



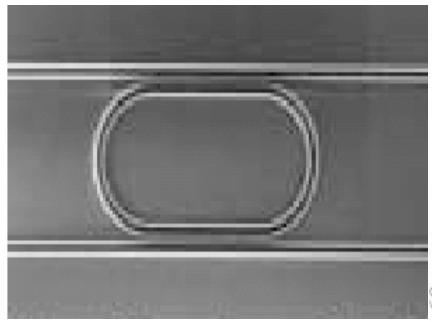
插入损耗：1-2dB



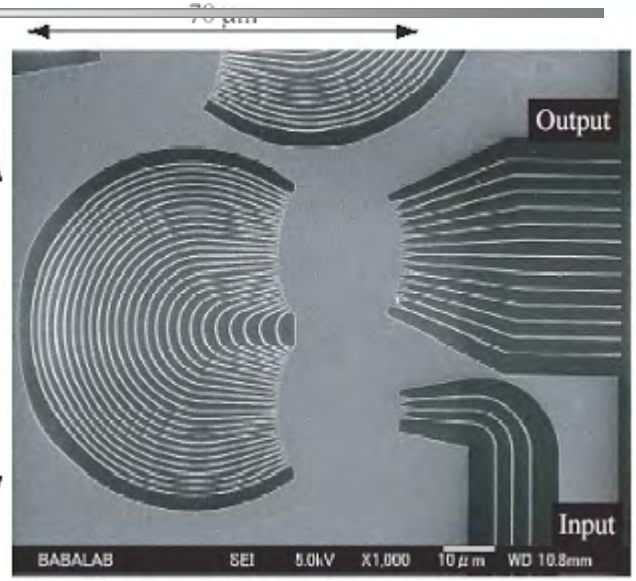
硅纳米线 Si-Nanowire Waveguide



MMI coupler (MIT)

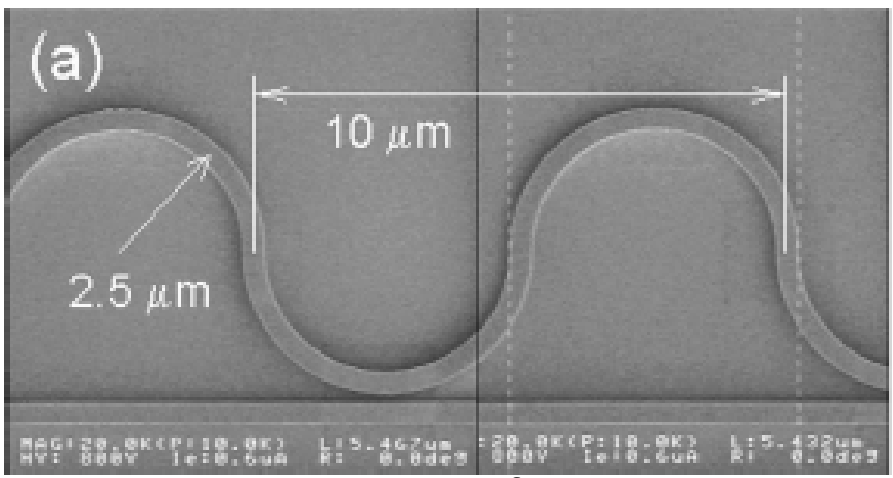


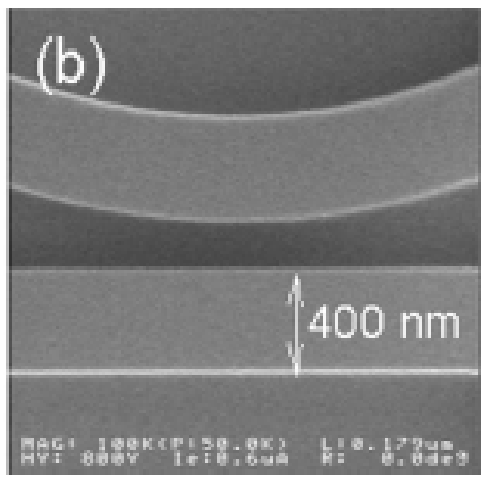
Ring resonator (MIT)



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

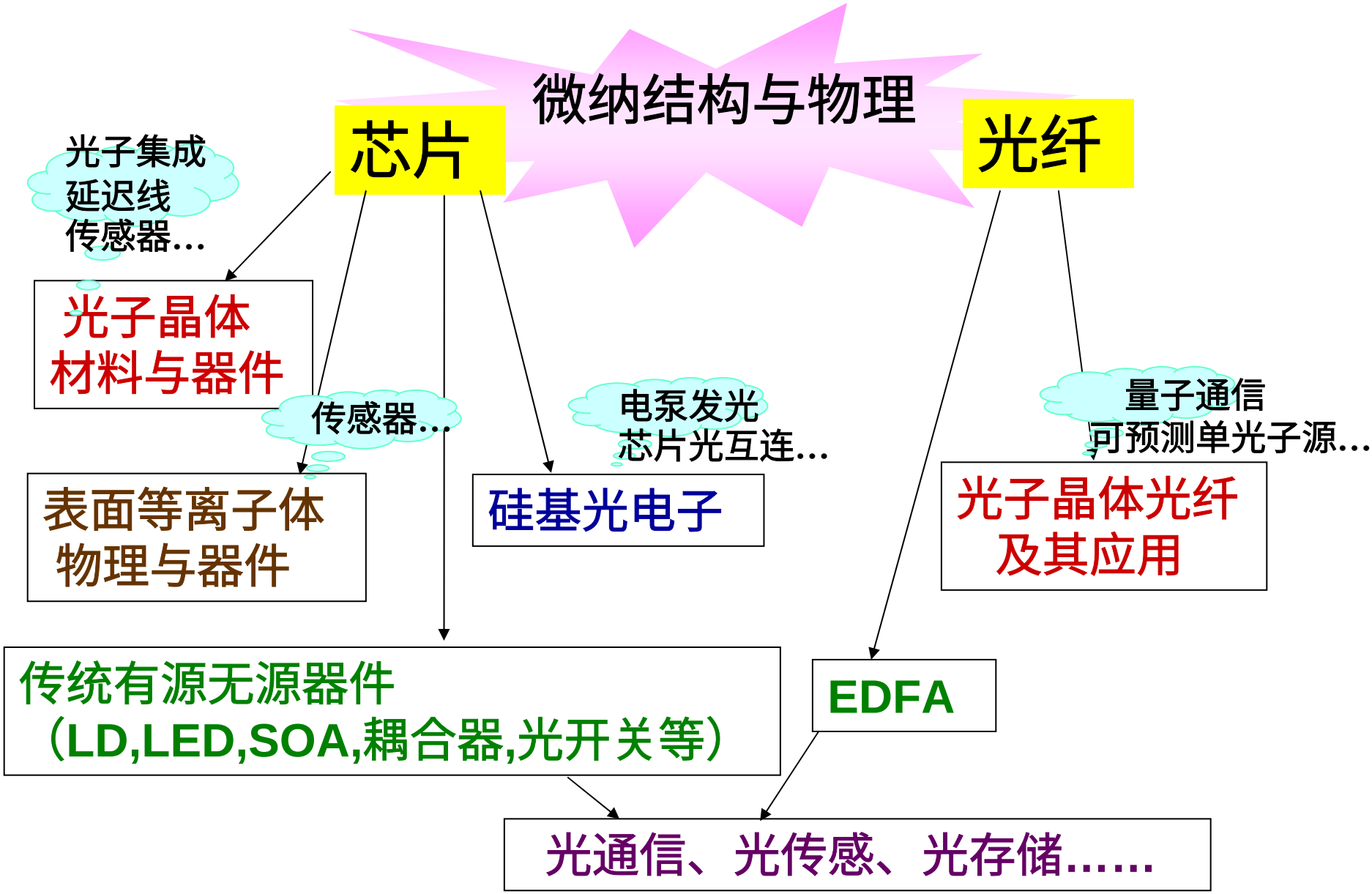
AWG (Yokohama National Univ.)





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…
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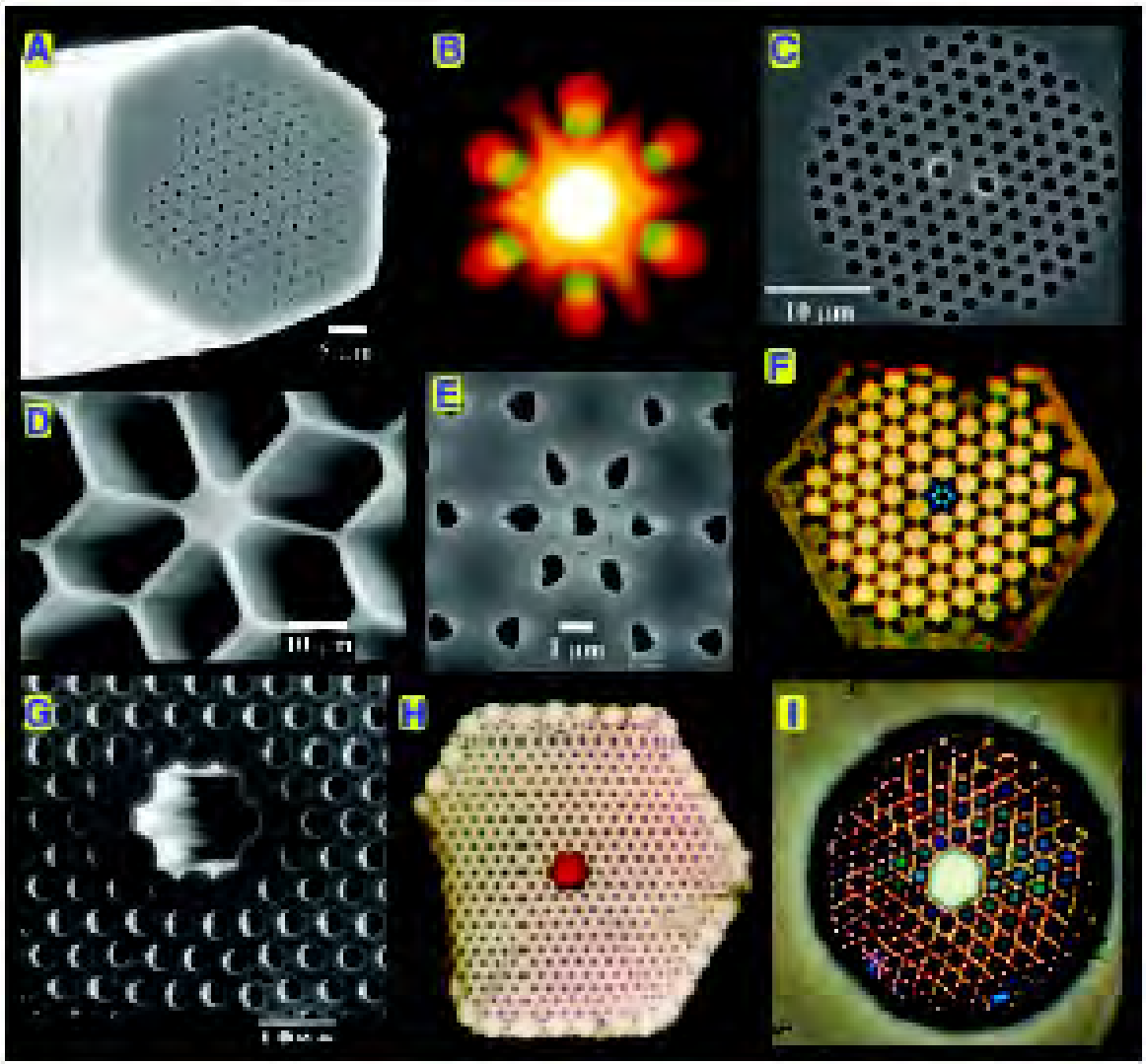
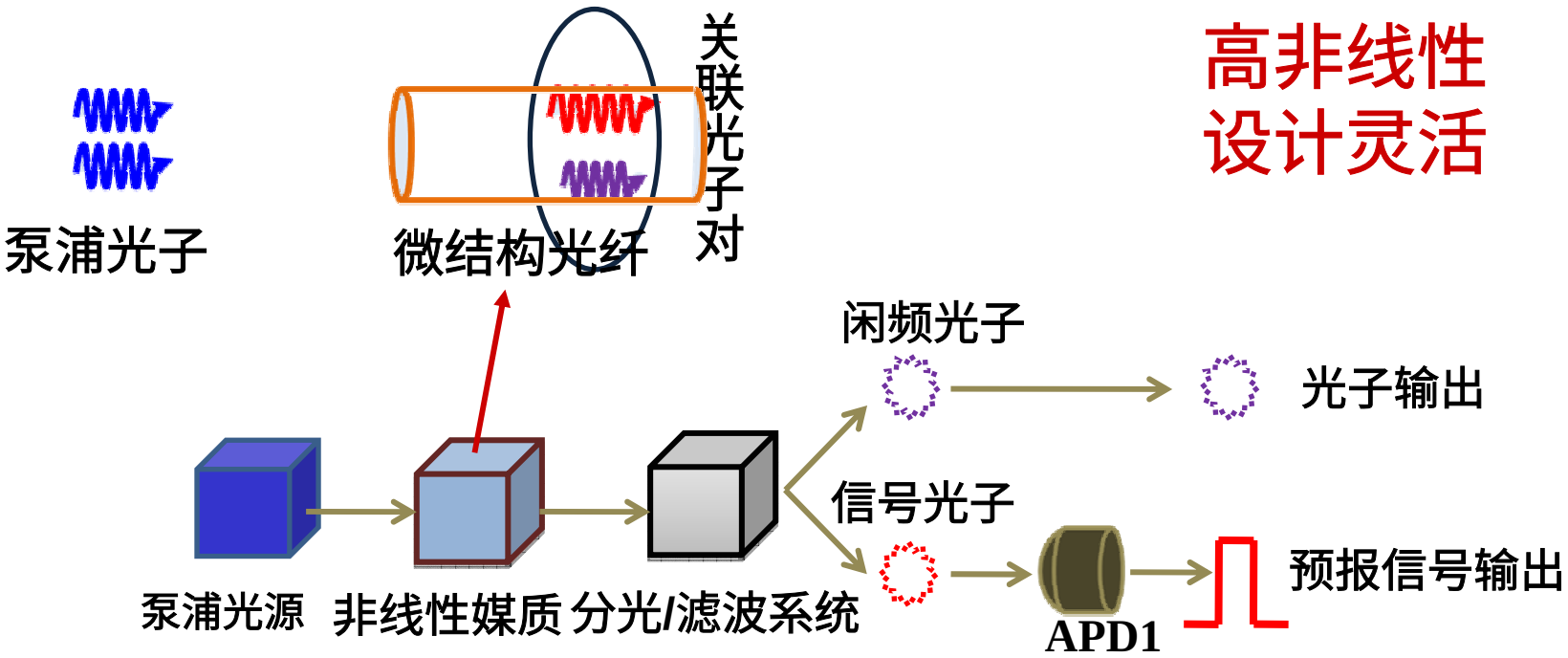
（LD,LED,SOA,耦合器,光开关等）
EDFA
光通信、光传感、光存储……

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



高非线性
设计灵活

➢非线性光学过程产生具有时间关联性的两路光子

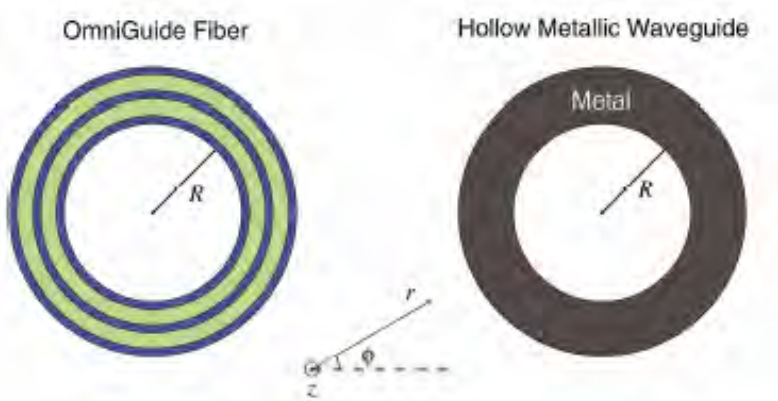
——关联光子对

➢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

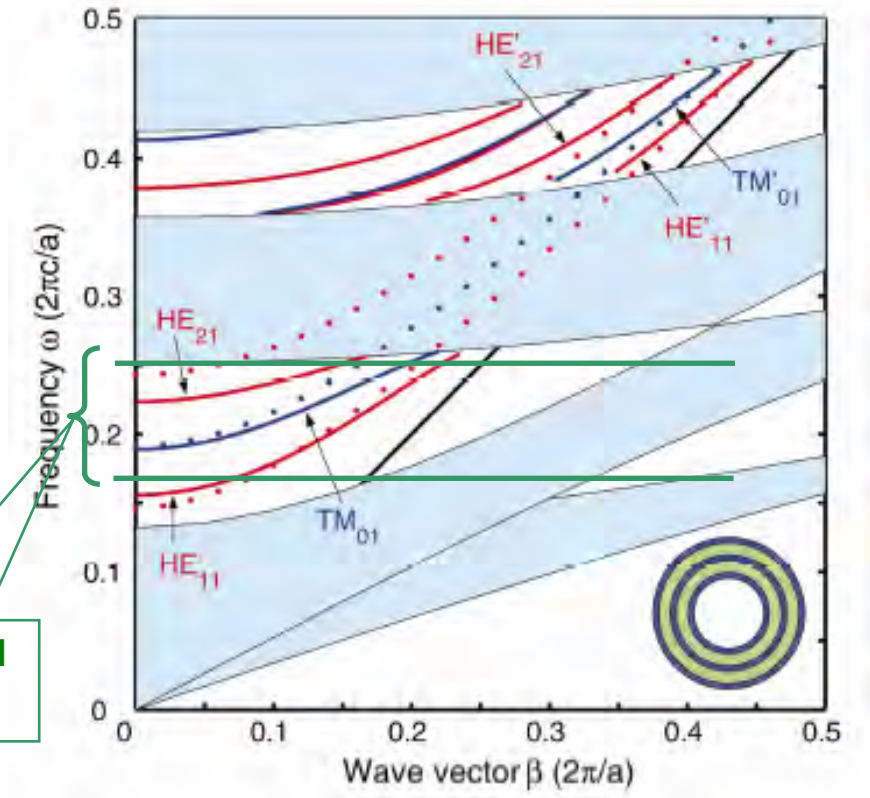
能够在保证单光子输出的基础上，有效避免空脉冲！

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 → 1D PC 全向反射
  - 高反射纤维
  - 全介质空心波导

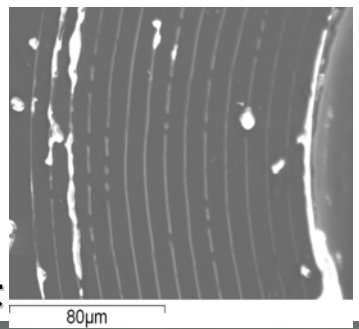


模式特性与金属波导接近

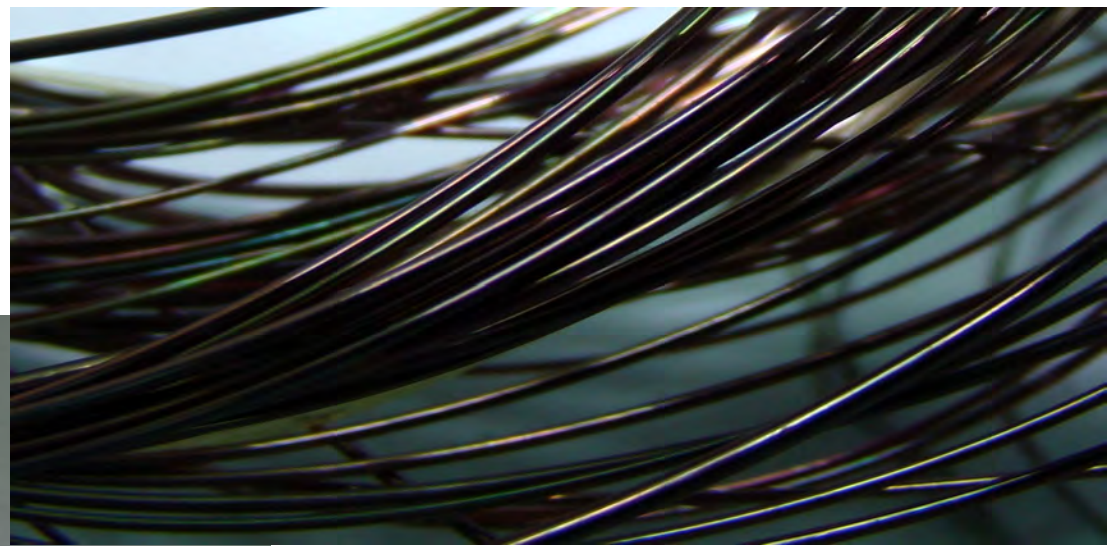


半导体/聚合物Bragg光纤的制备工艺和测试研究

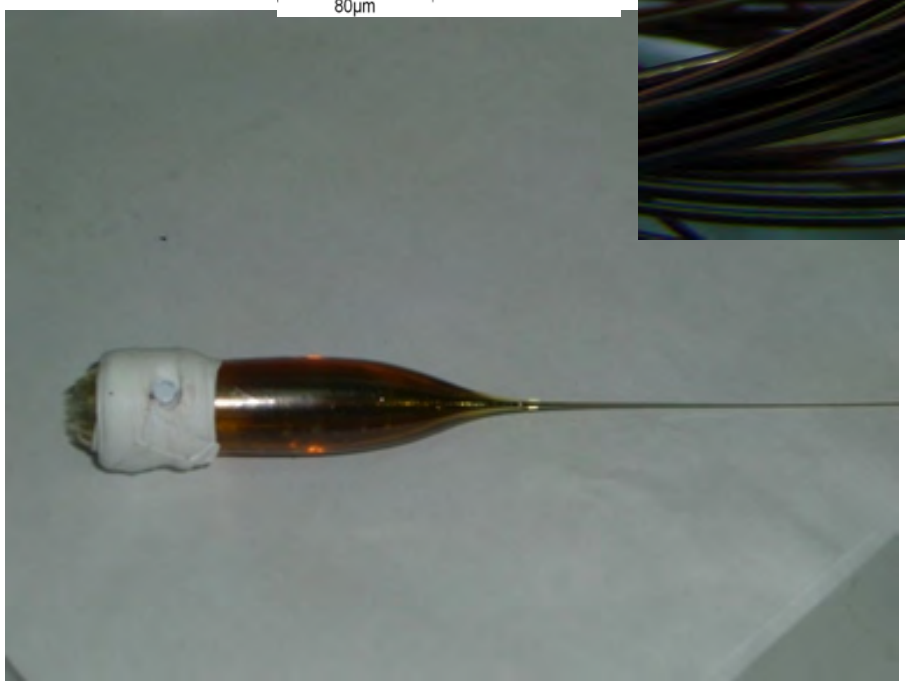
- 半导体/聚合物Bragg光纤制备工艺平台的建立和工艺可行性的实验论证



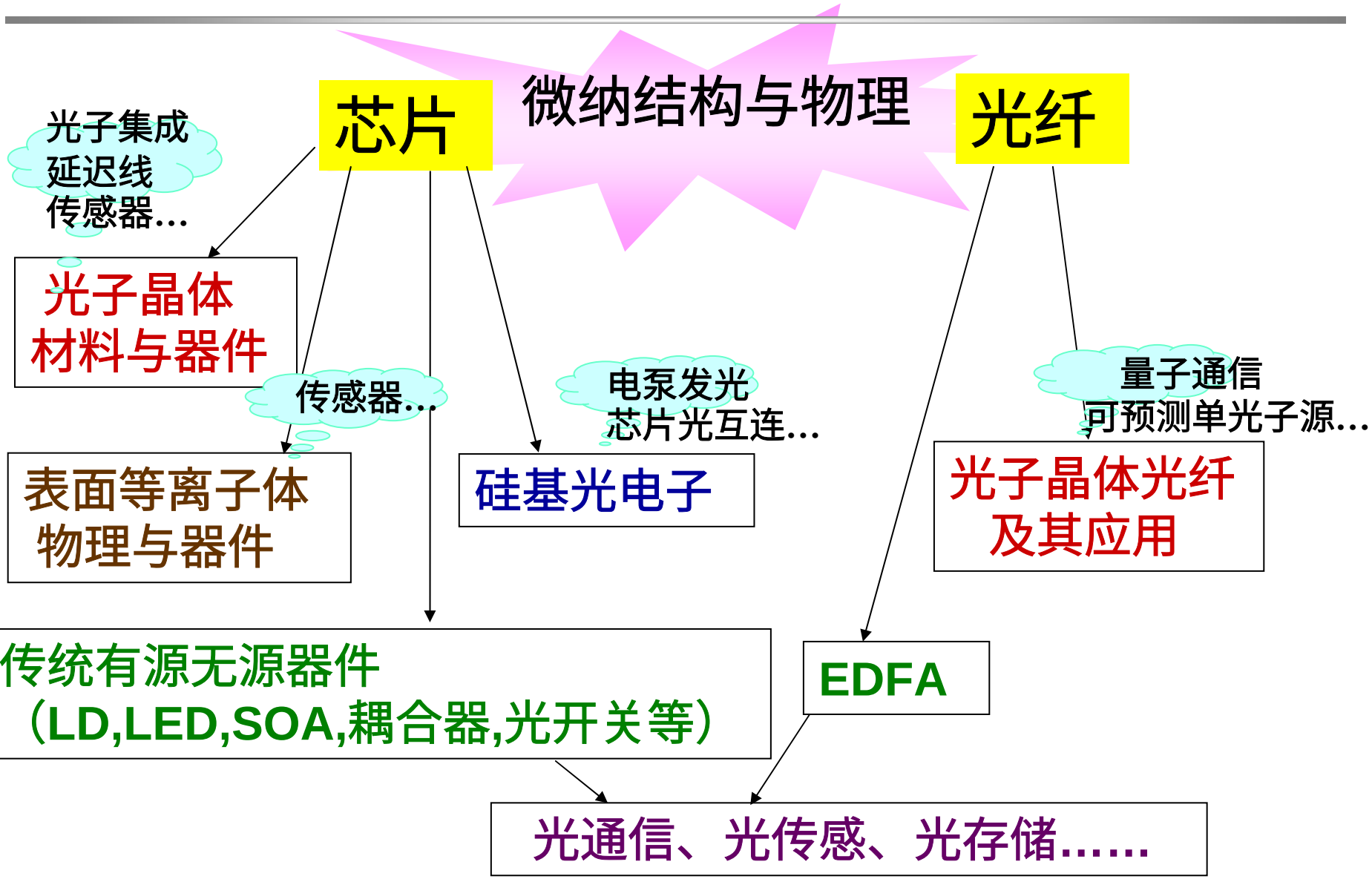
预制棒丝头



半导体聚合物Bragg光纤样品



纳结构光电子器件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谢谢！