等离激元光子学
（物理效应与应用）

李 涛

2017.5

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Nat. Lab. of Solid State Microstructures
College of Engineering and Applied Sciences
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内容纲要

- 背景
- 基本原理
- 物理效应+相关应用
- 结论与展望

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SPP激发对光透射偏振调控

SPP色散、态密度和场增强效应

SPP亚波长约束和纳米光子集成

SPP的面内传播与操控

SPP的量子特性

超构材料（metamaterial）

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热点起源

Extraordinary Optical Transmission (EOT)
(T. W. Ebbesen 1998)

结构调控的SPP激发以及光学特性

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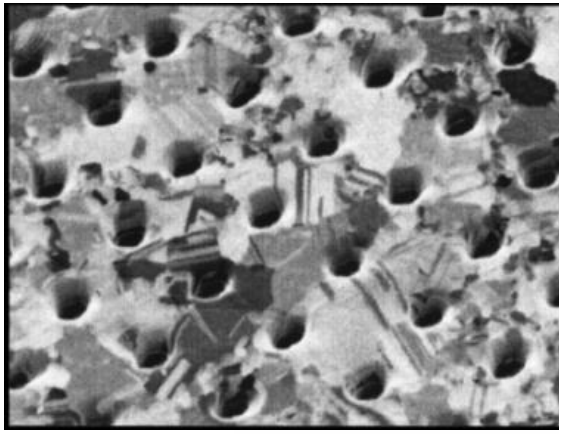
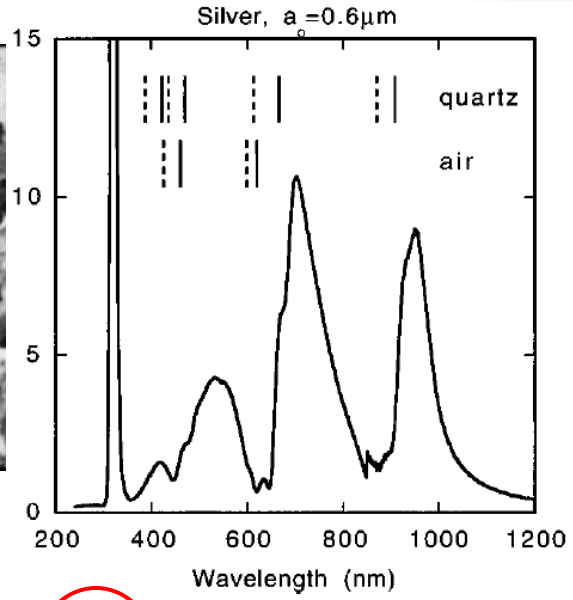
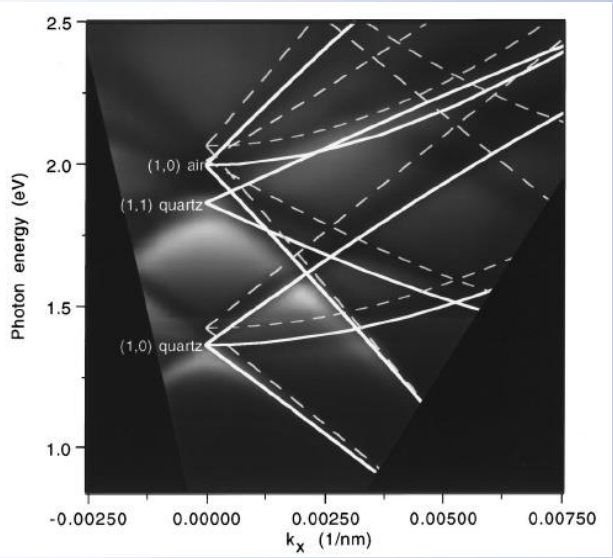
穿孔金属膜的异常光学透射现象

(T. W. Ebbesen 1998)







Ebbesen et al,
Nature, PRB, (1998)

$$\vec{k}_{sp} = \vec{k}_x \pm i\vec{G}_x \pm j\vec{G}_y$$

$$(i^2+j^2)^{1/2}\lambda = a_0\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2}$$

角度色散

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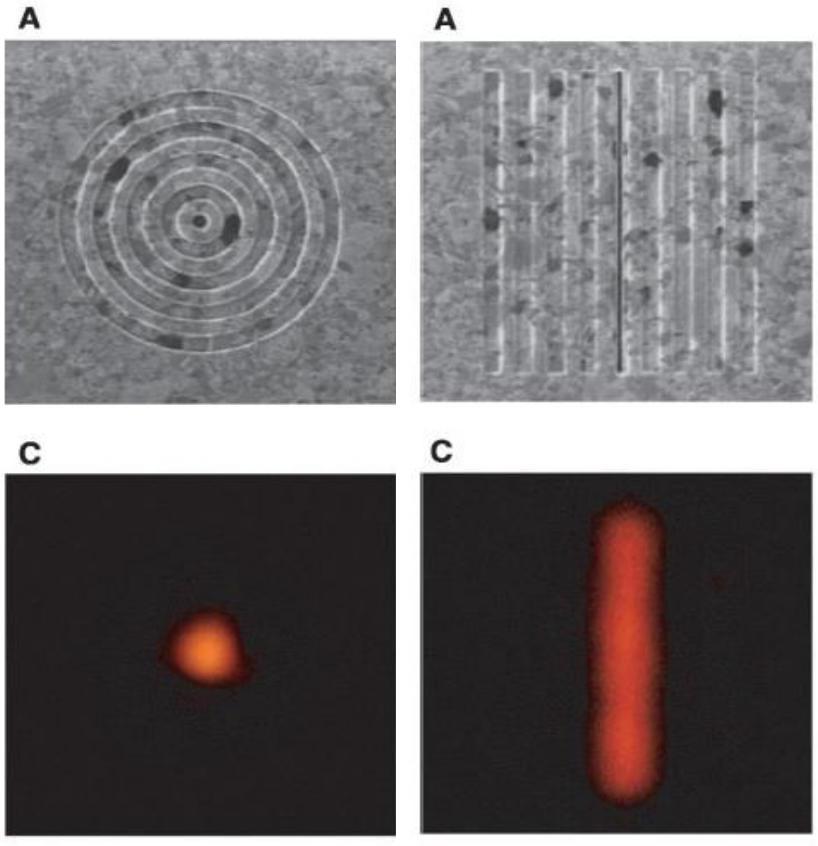
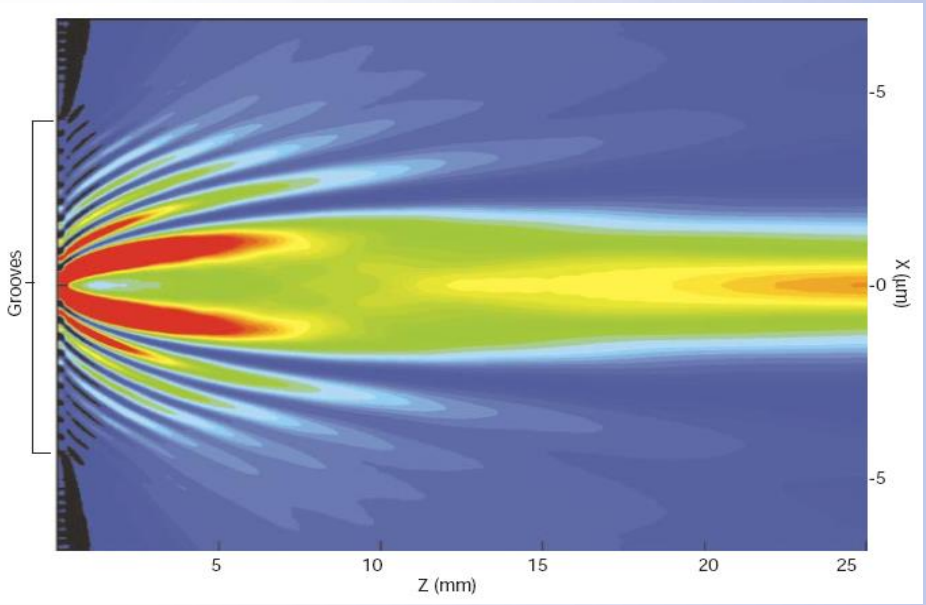
准直光束的发射

Directional Beam Light





Lezec et al, Nature (2002)

通过精心设计的金属纳米结构可以实现对等离激元的激发调控，进而控制光的透射选频、辐射方向和偏振特性等！

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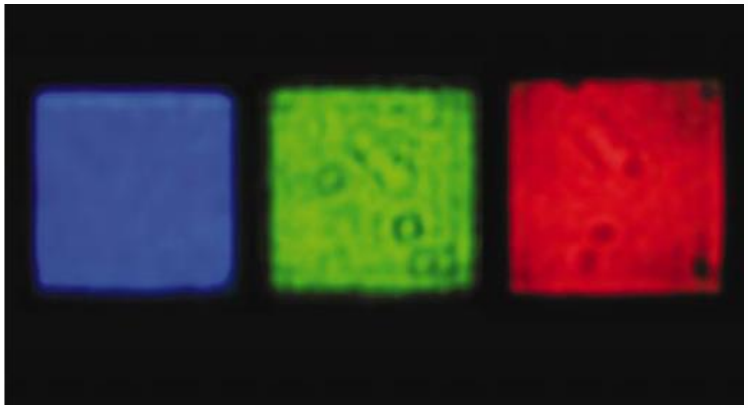
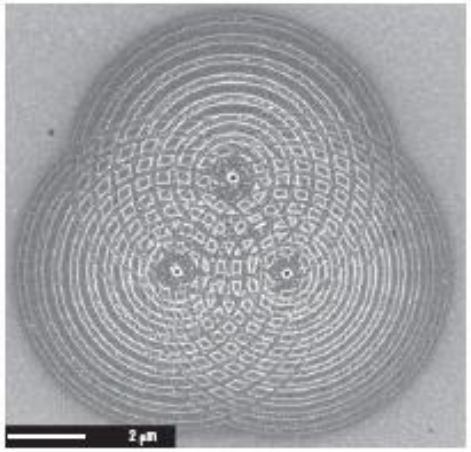
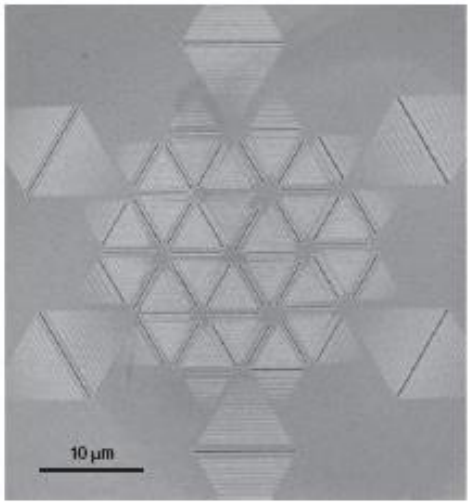
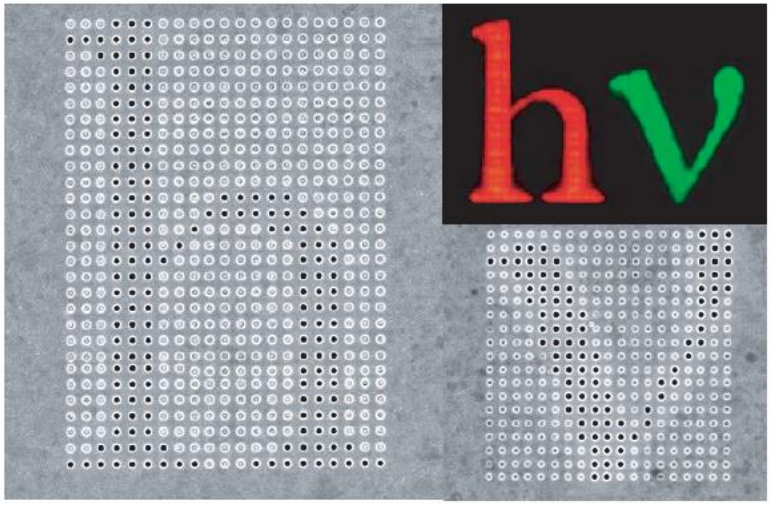
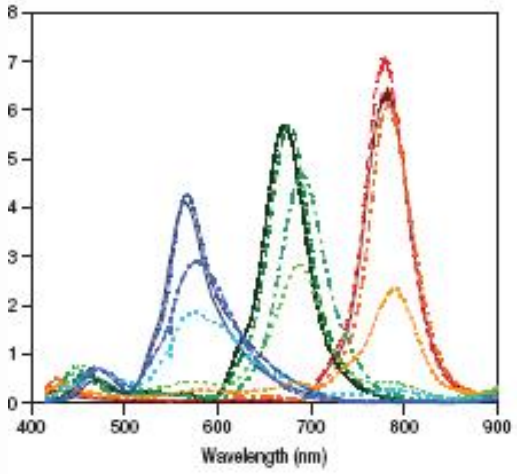
分色显示与成像

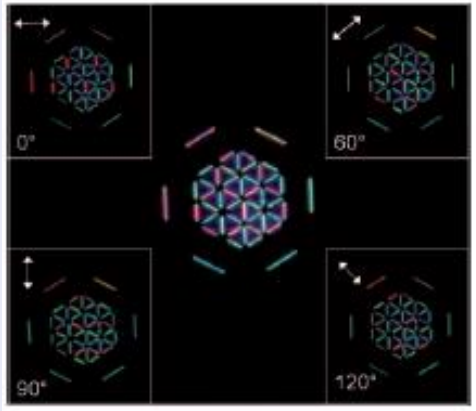












Nat. Photonics 2, 161 (2008)

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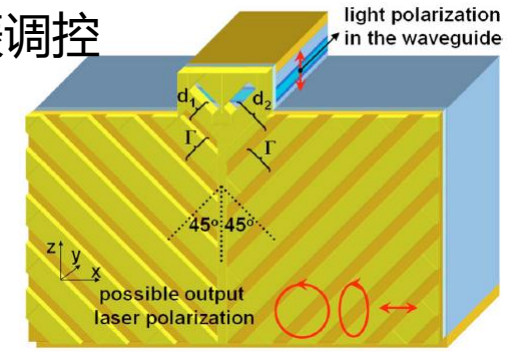
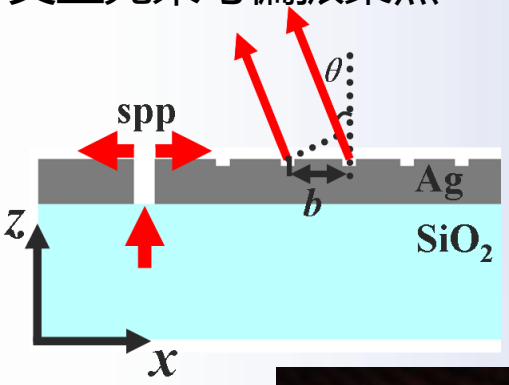
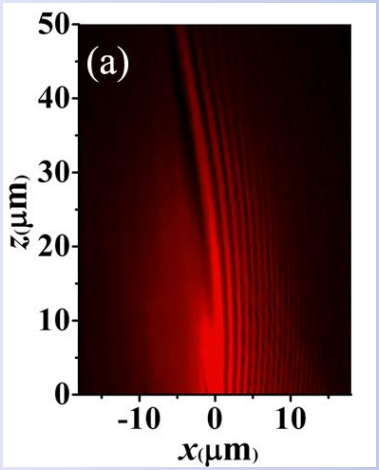
光束调制与整形

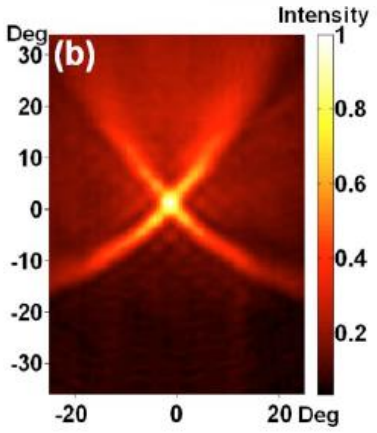
激光束整形
与偏振调控

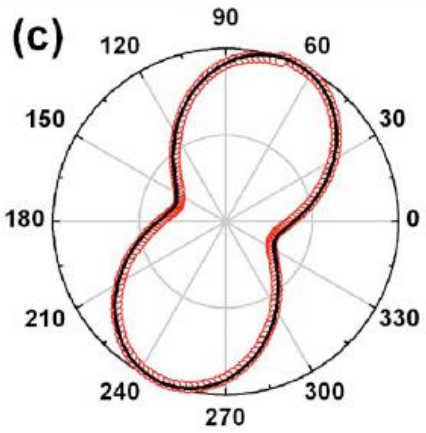


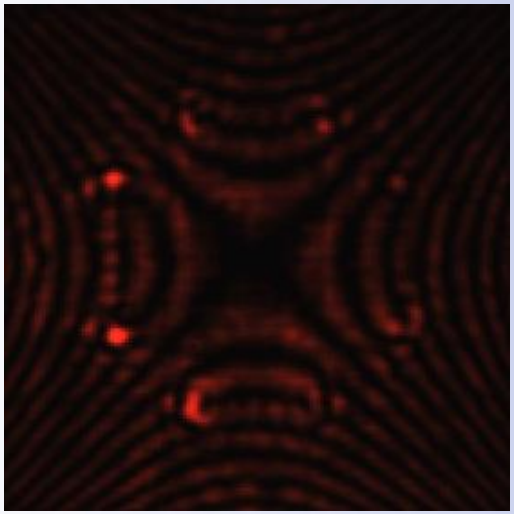
艾里光束与偏振聚焦











APL 94, 151101 (2009), Nat. Mater. 9, 730 (2010)
Capasso group@ Harvard Univ.

OL 38, 1733 (2013). LSA 4, e330 (2015)
Tao LI group @ NJU.

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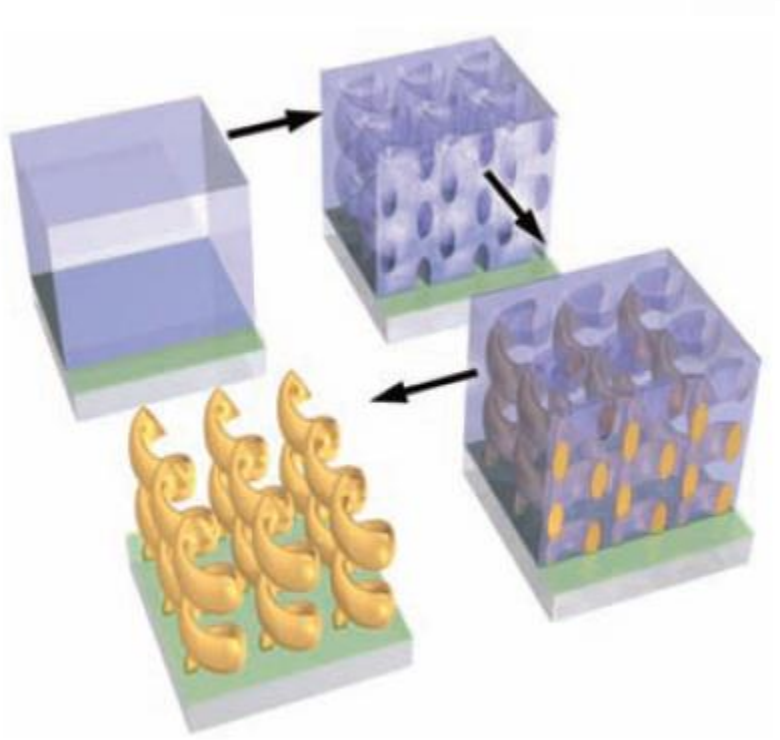
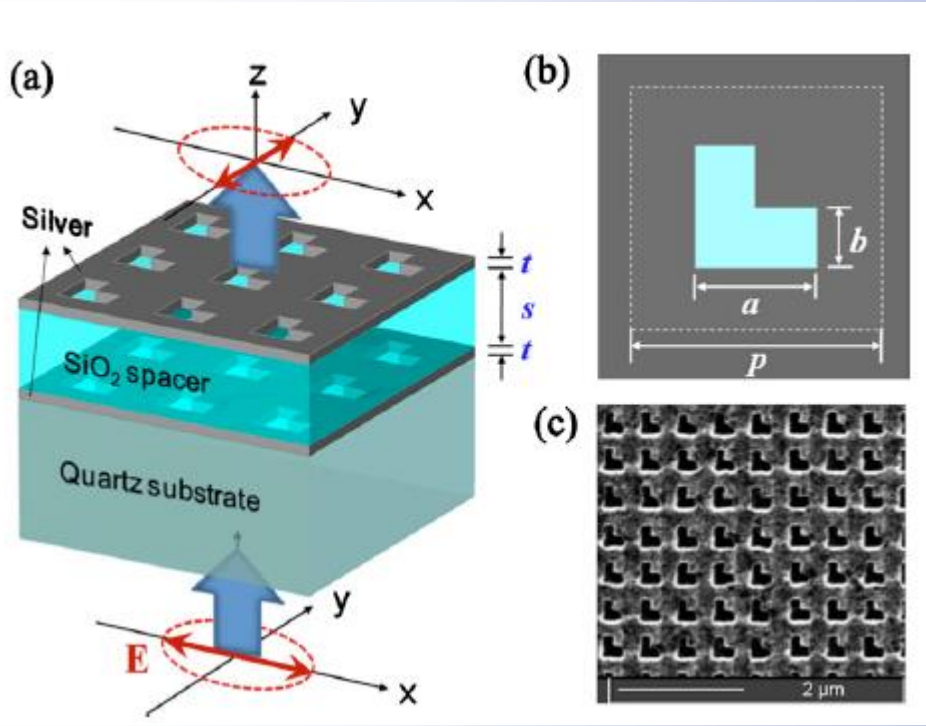
操控偏振与旋光性质





Chiral metamaterial

Science 325, 1513 (2009)

Plasmonic mode

T. Li, et al., APL 97, 261113 (2010)

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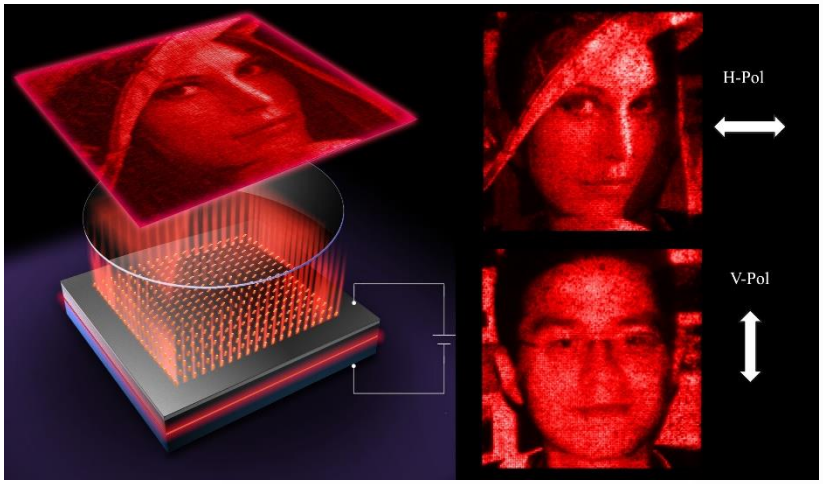
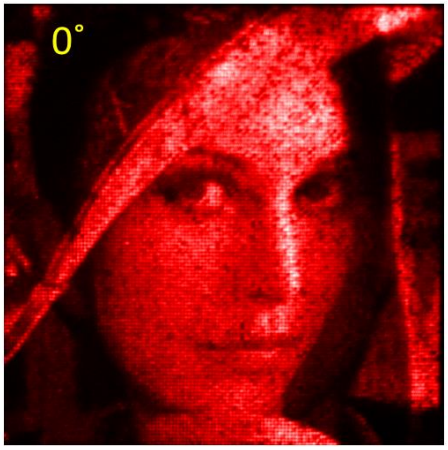
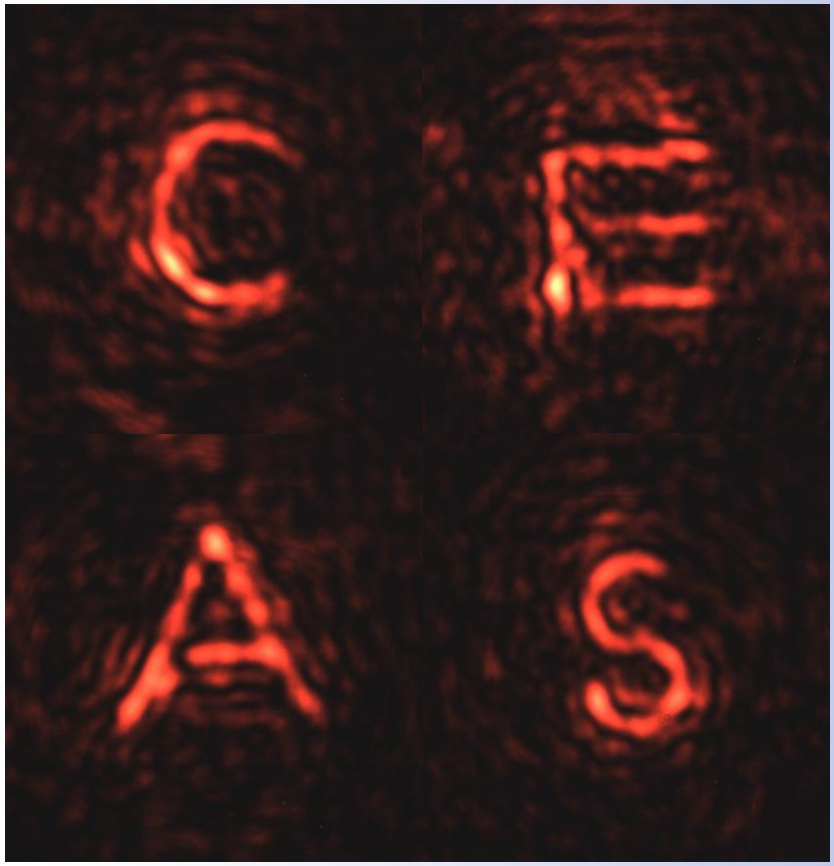
偏振复用显示与全息







Polarized Active display and Holography
Sci Rep 2, 2603 (2013) …. .
Tao LI group @ NJU.

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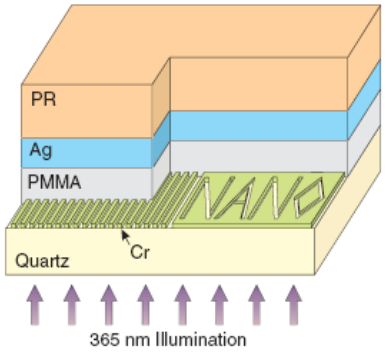
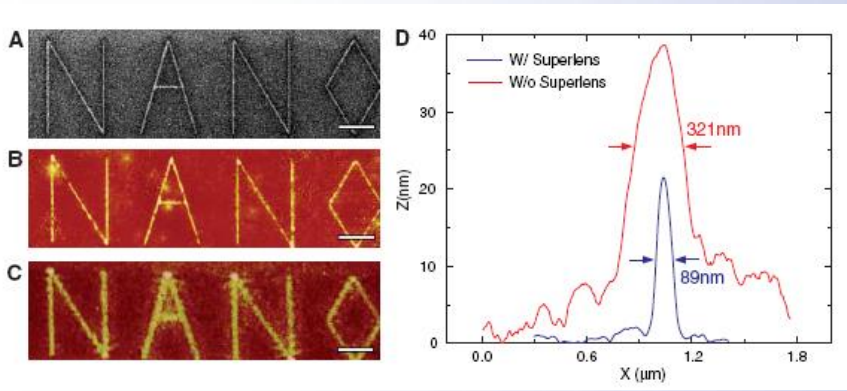
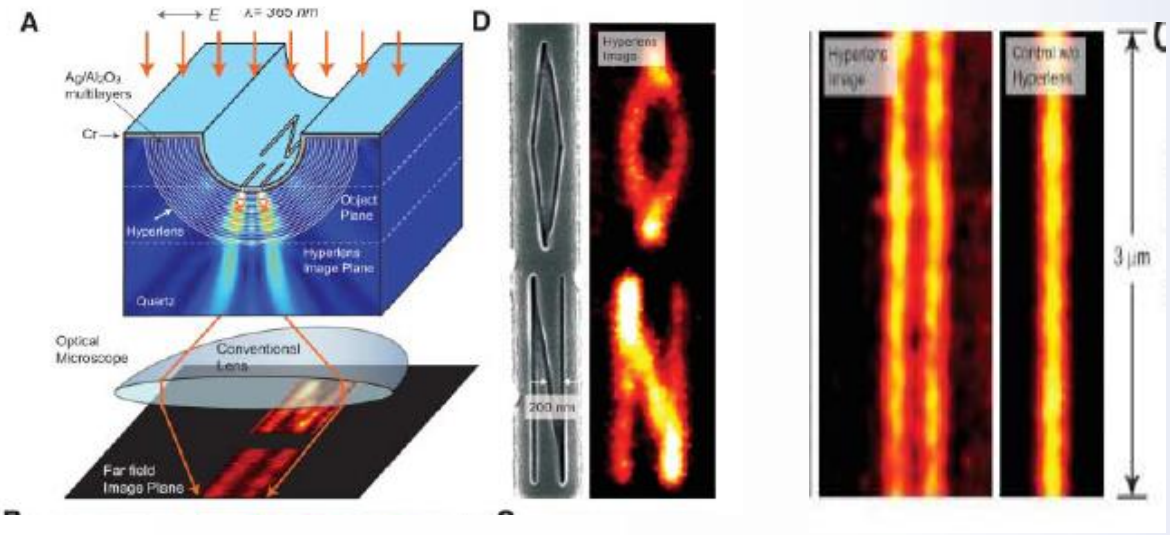
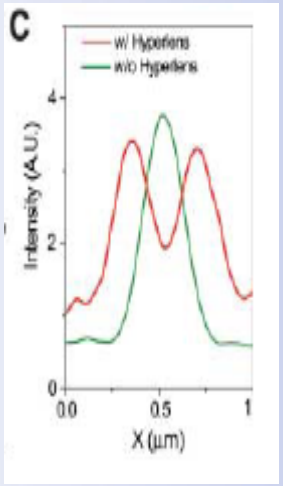
超透镜成像（突破衍射极限）









Science 308, 534 (2005), Science 315, 1686 (2007)
Xiang Zhang group, UC Berkeley.

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独特的色散关系、态密度及场增强效应

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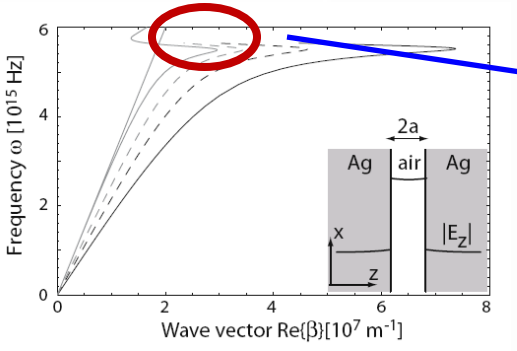
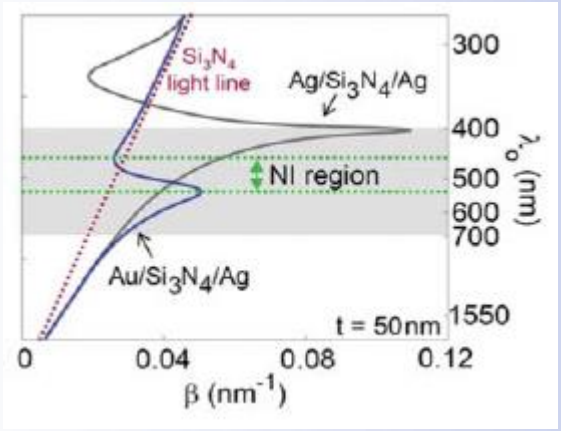
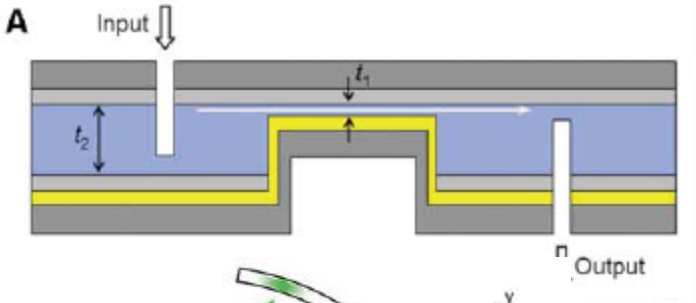
反常色散实现负折射

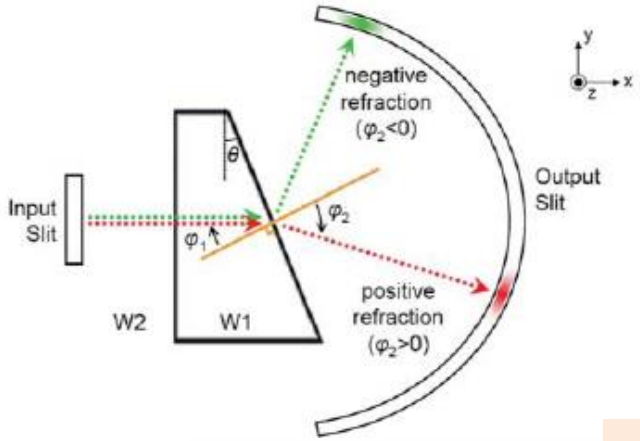
MIM结构

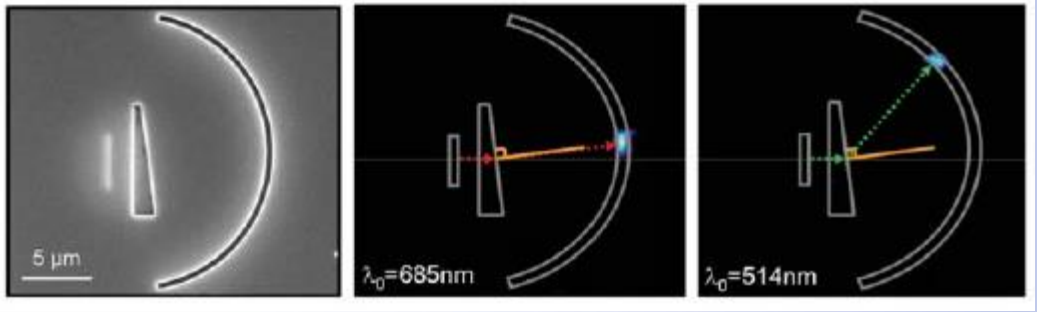


$$v_p = \frac{\omega}{k} > 0,\ v_g = \frac{\partial \omega}{\partial k} < 0$$









Science 316, 430 (2007)

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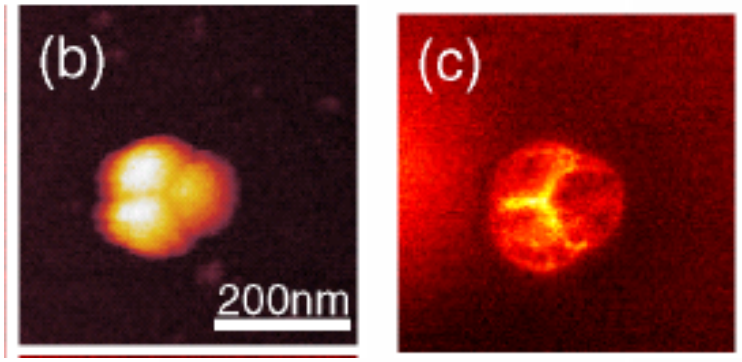
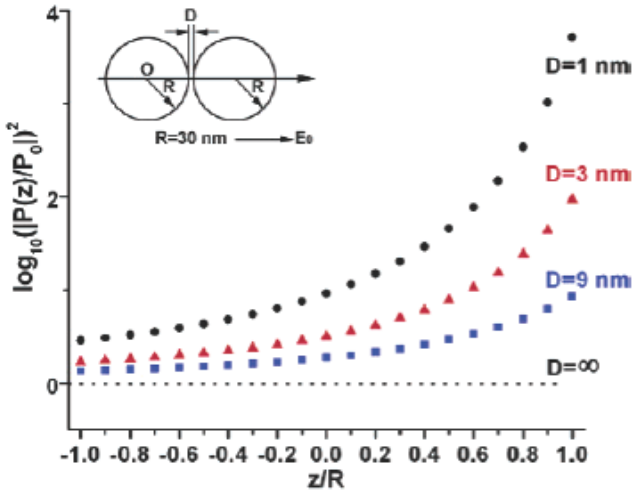
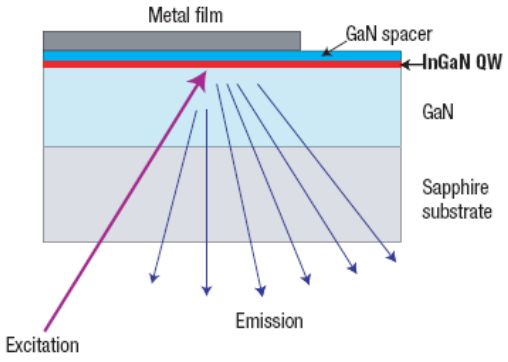
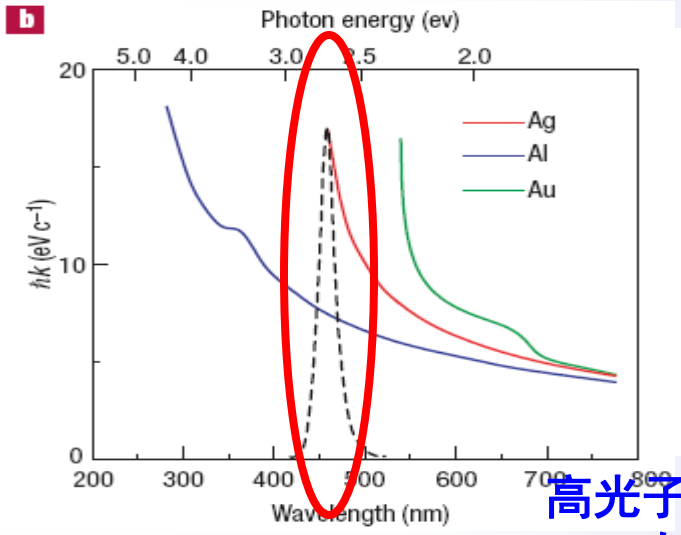
高局域场和高光子态密度

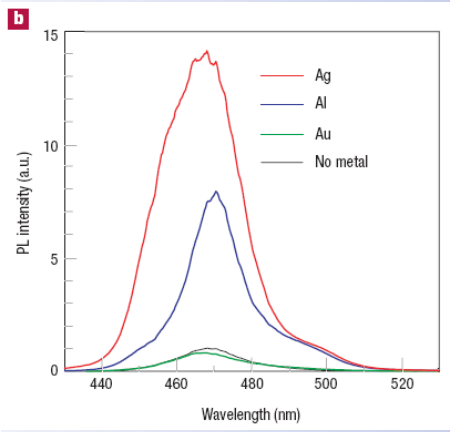


局域等离子共振——发光增强









高光子态密度提高光的自发辐射效率

Nat. Mater. 3, 601 (2004)

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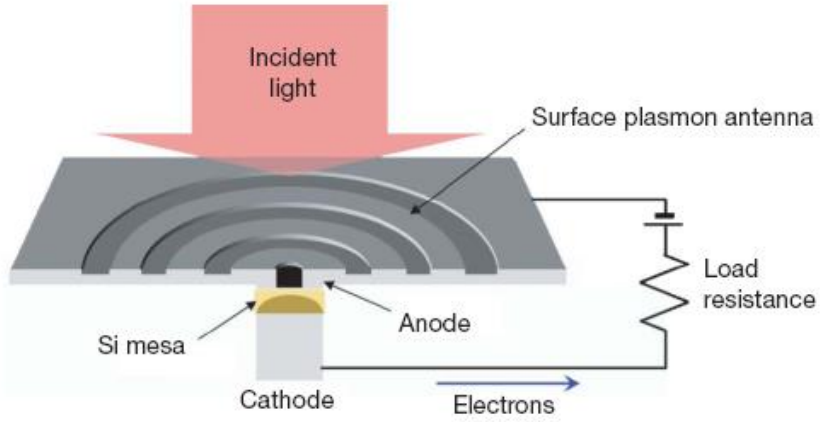
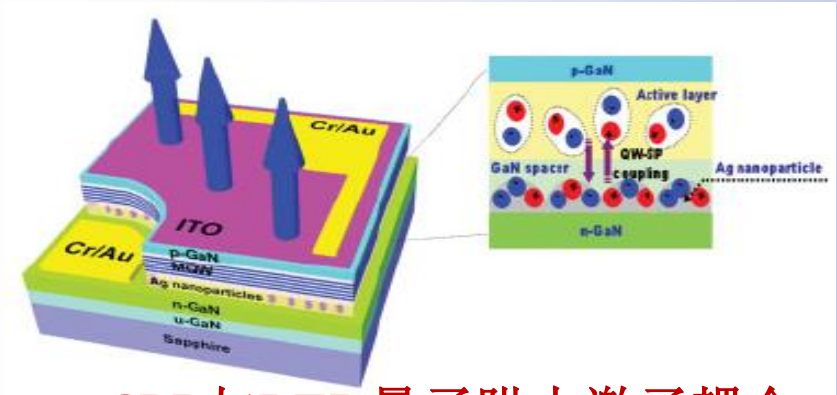
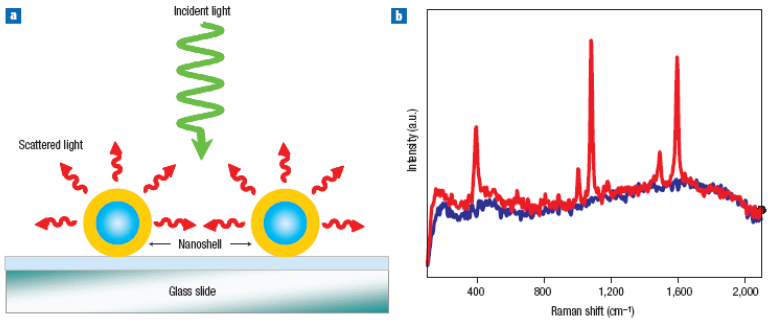
局域相互作用增强与应用



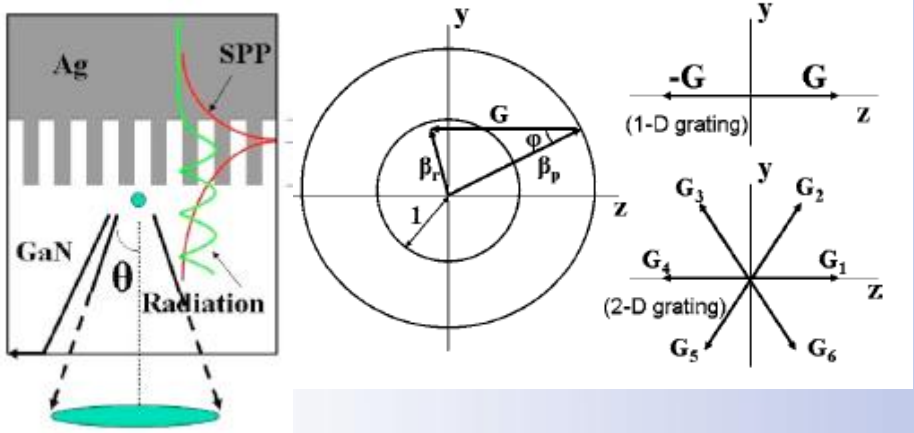
增强吸收与光电探测



SPP与LED量子阱中激子耦合
提高发光的量子转换效率



增强拉曼散射



周期结构中SPP提高LED光提取效率

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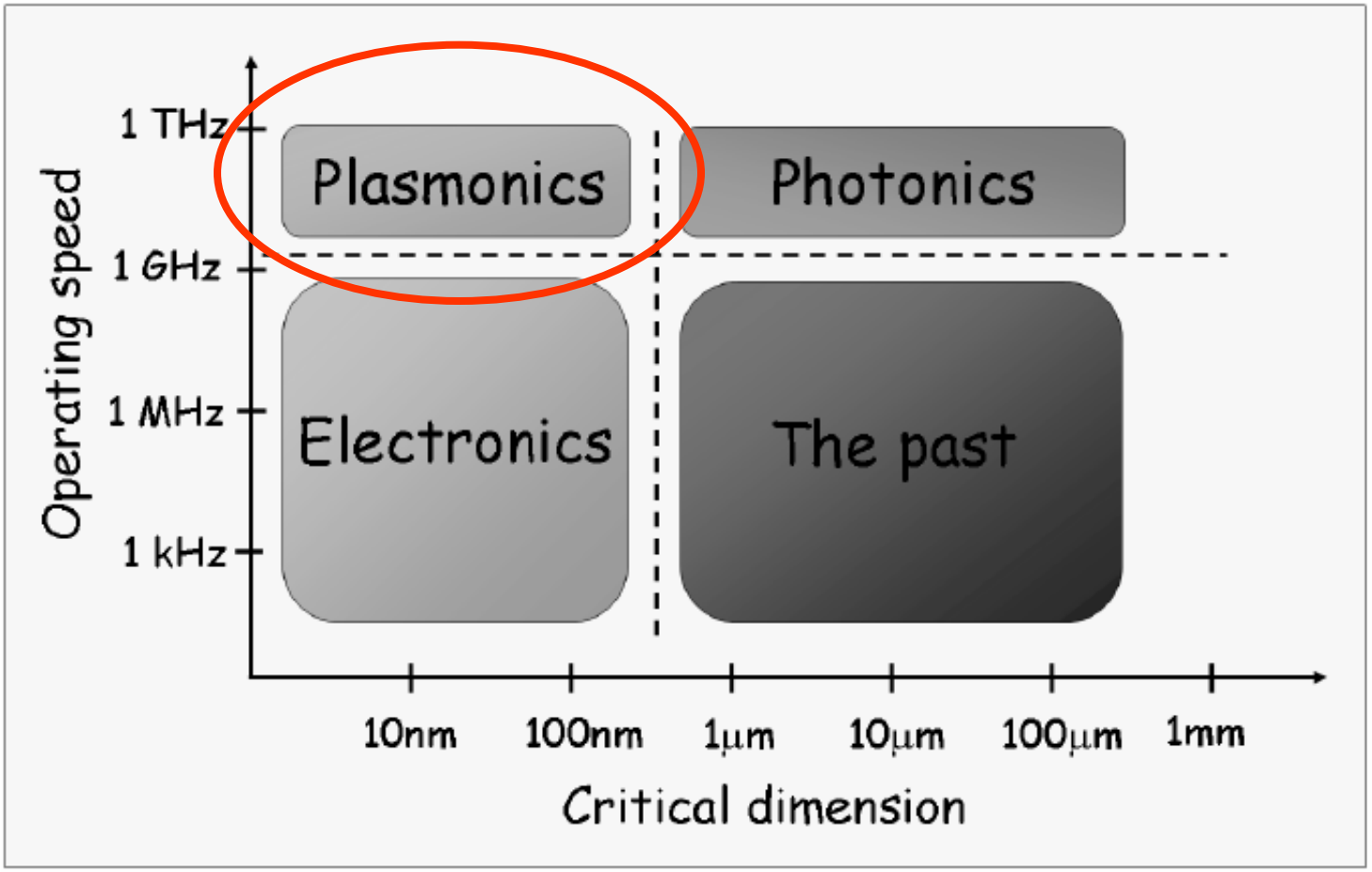
亚波长光约束效应
纳米光子学集成

Dielectric Superlattice Laboratory

Nat. Lab. Microstructures

Dr. Tao Li taoli@nju.edu.cn



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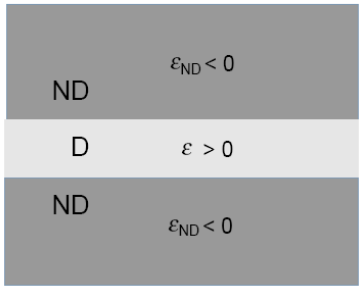
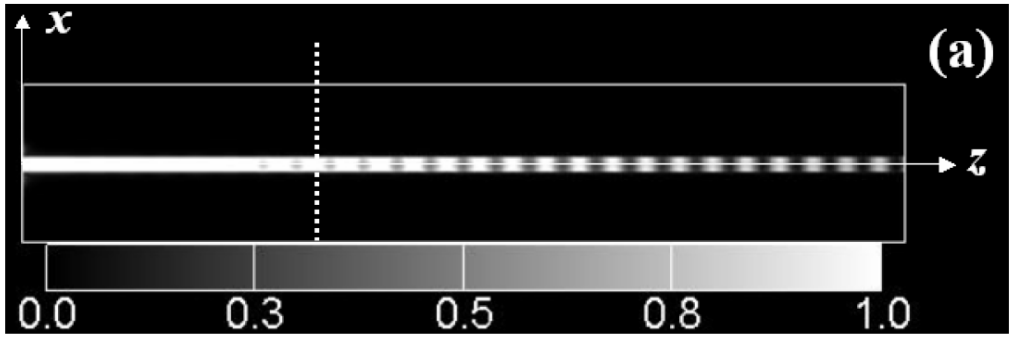
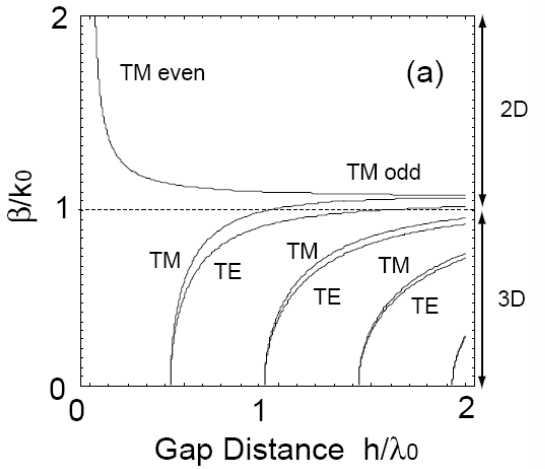
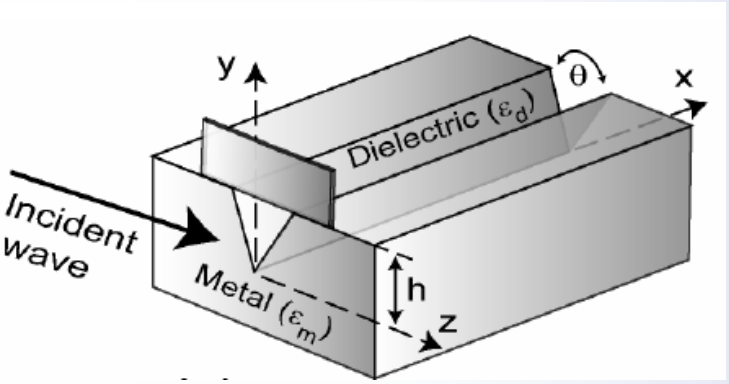
亚波长光波导

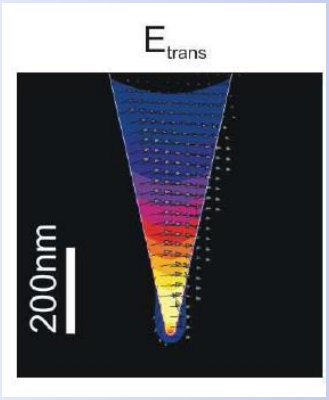
Sub-Wavelength Waveguide











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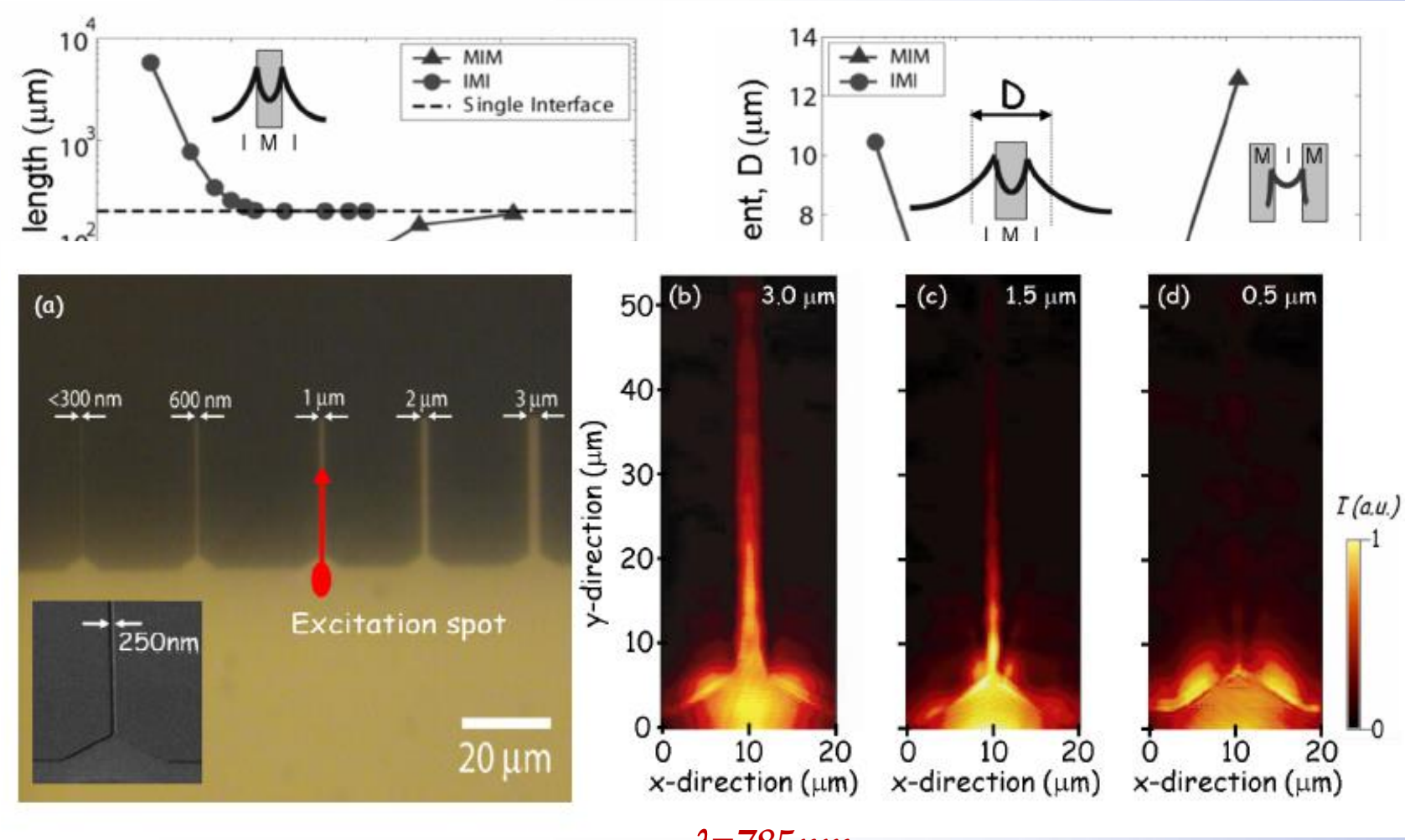
亚波长波导



λ=785nm

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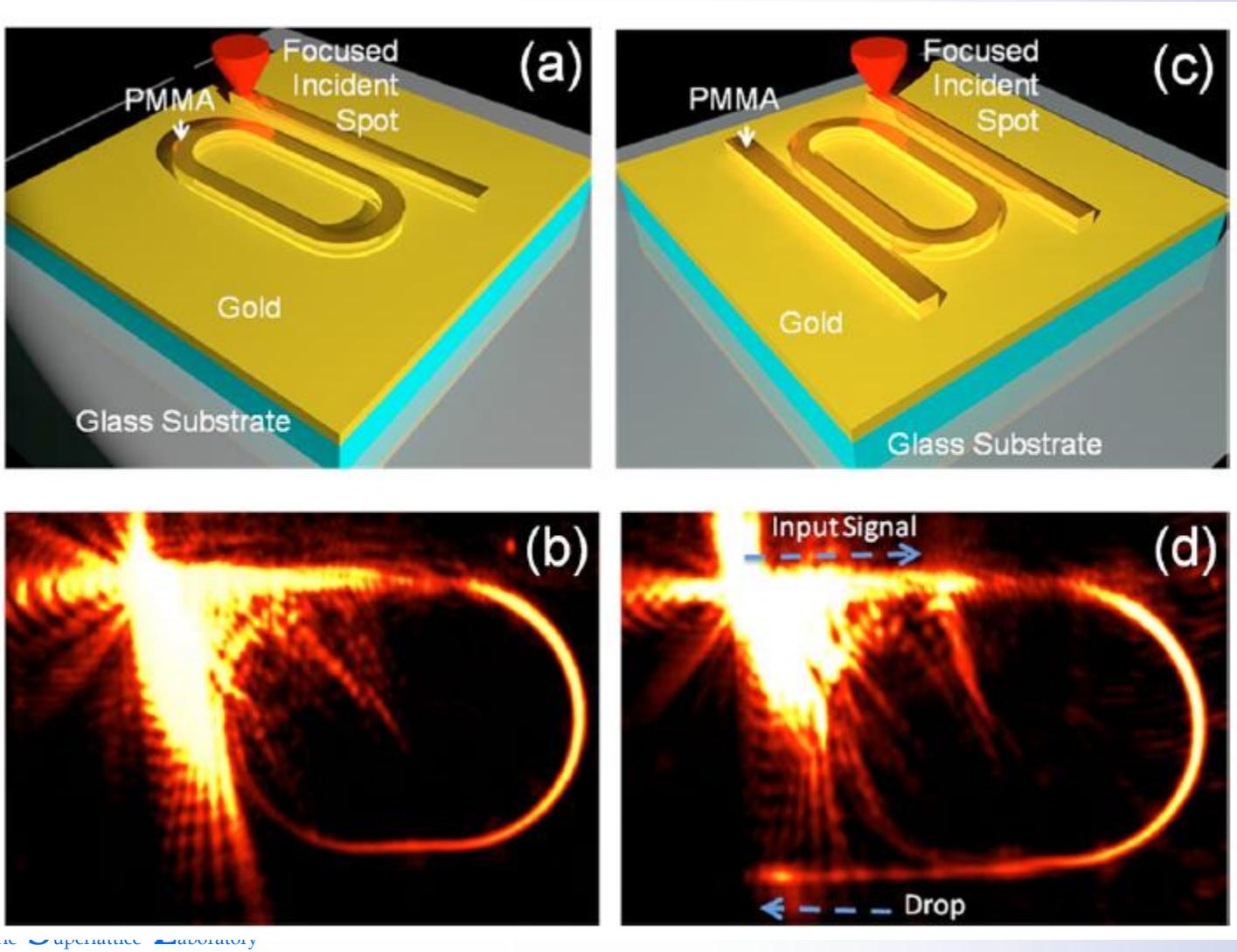
定向耦合器



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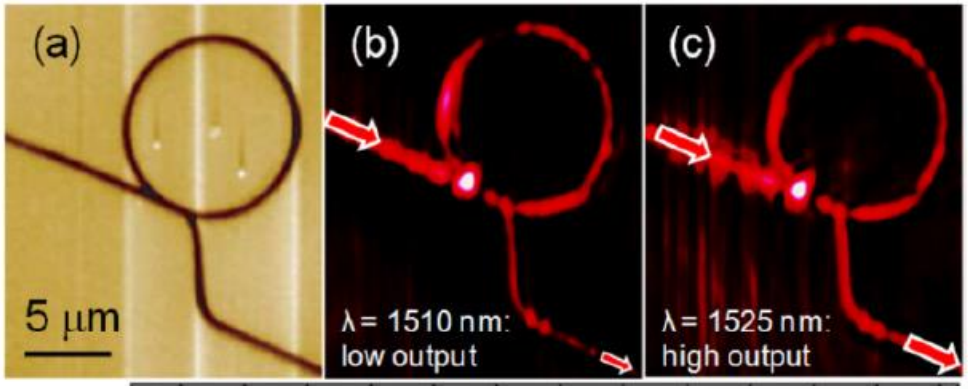
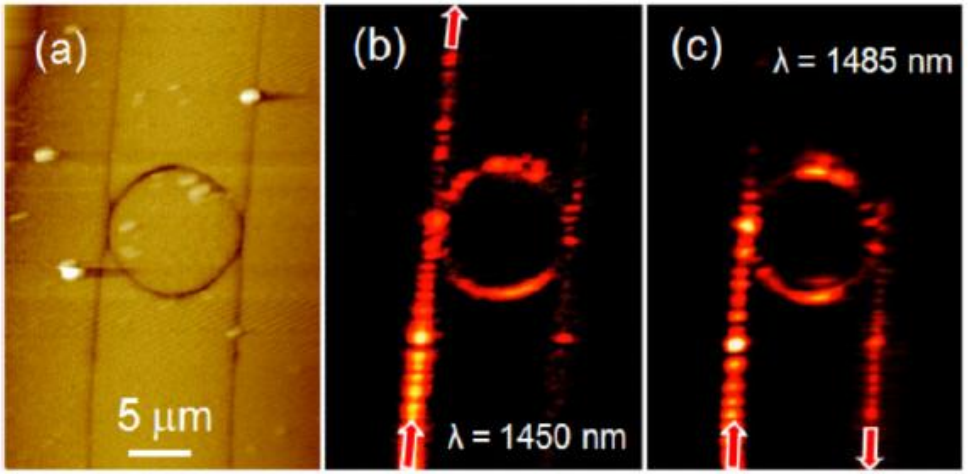
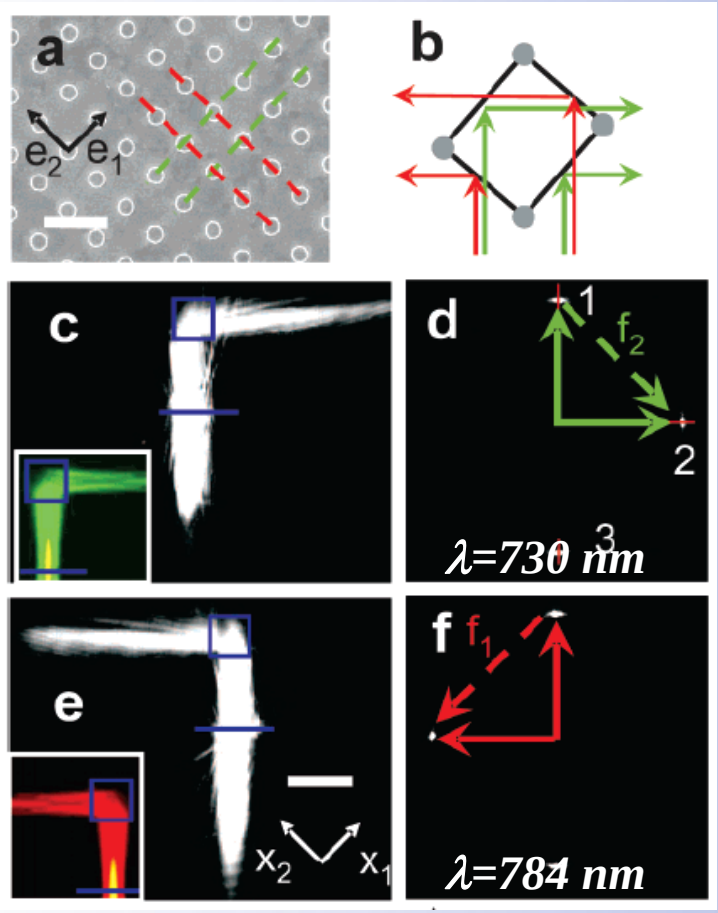
分插复用与波分复用







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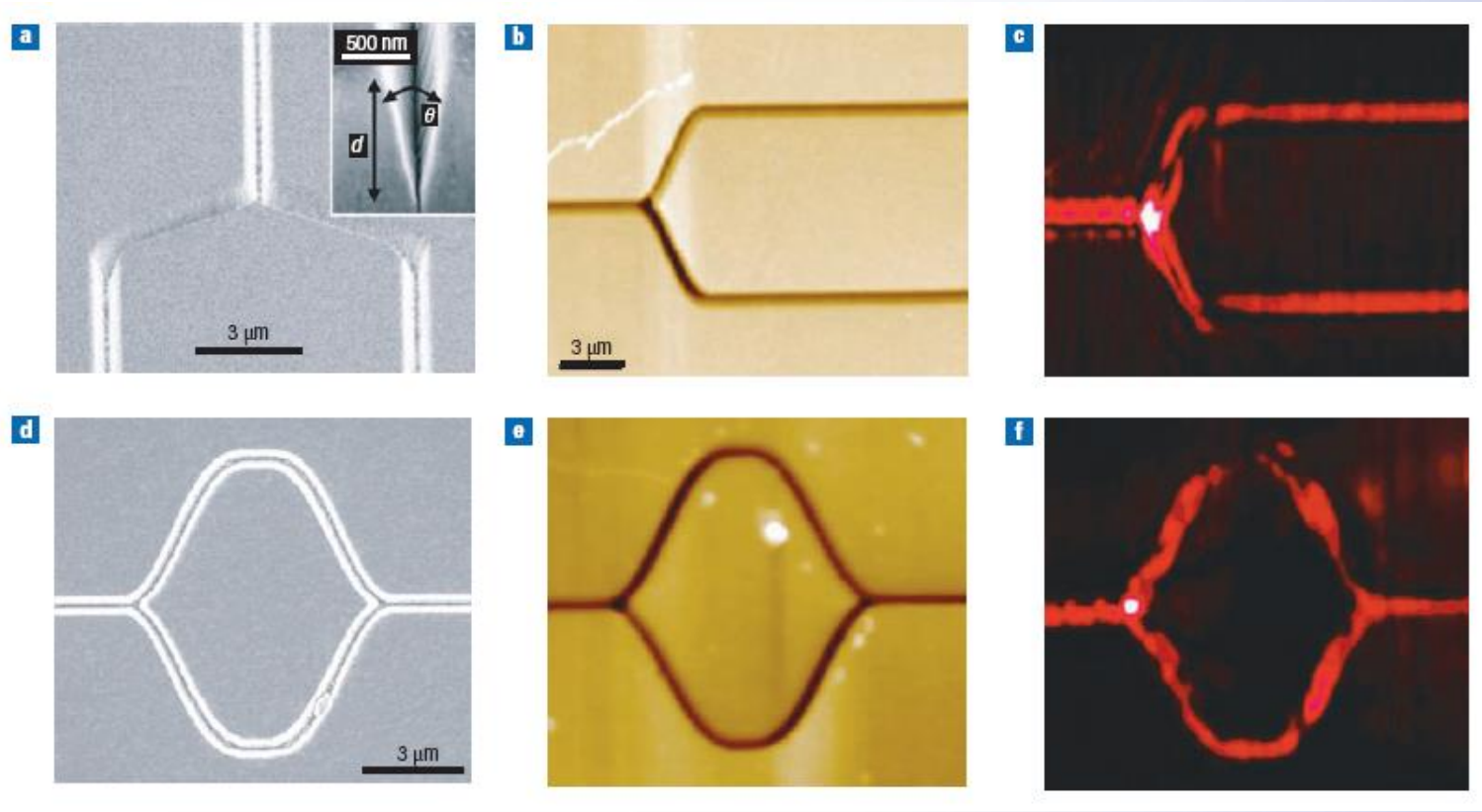
波导分束与MZ干涉



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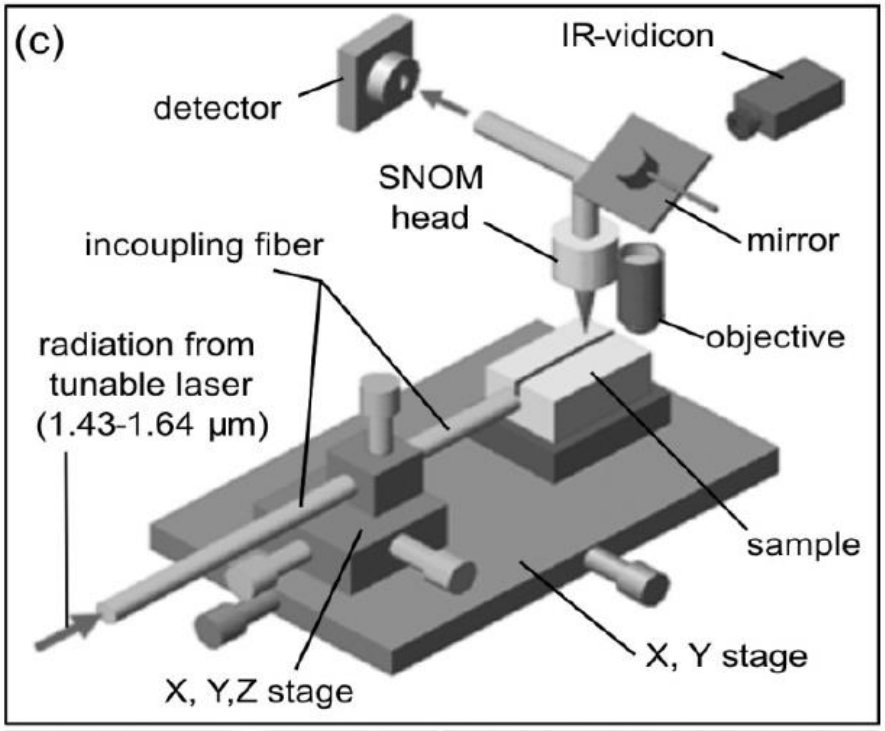
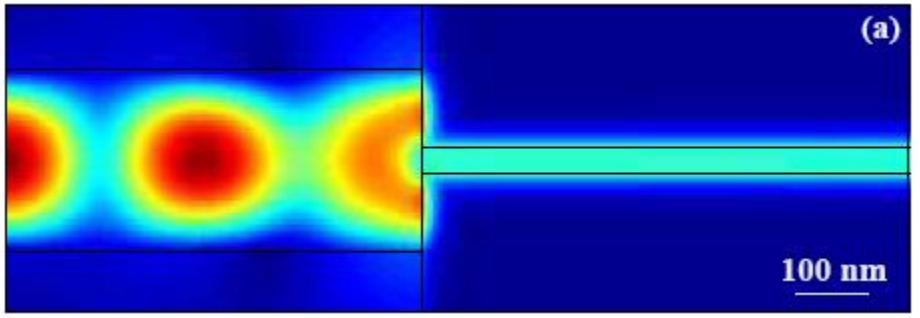
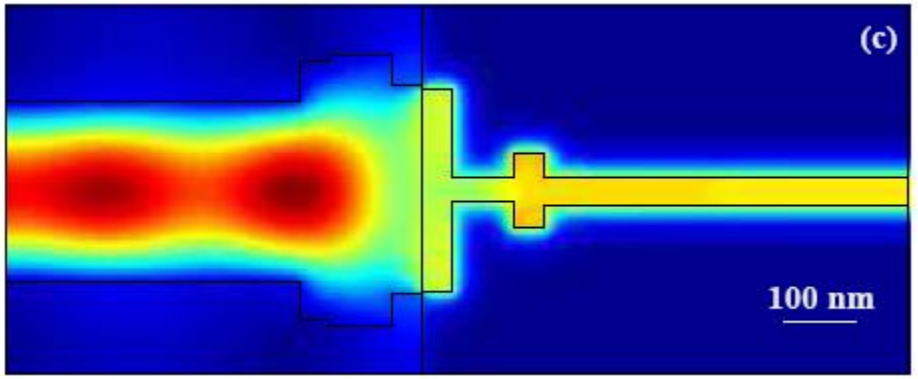
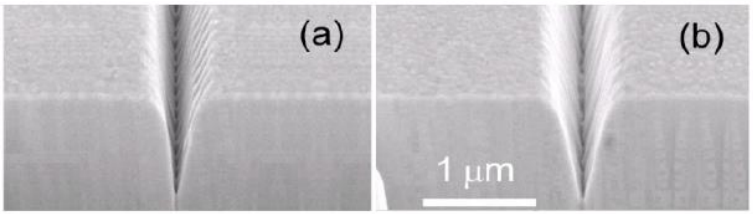
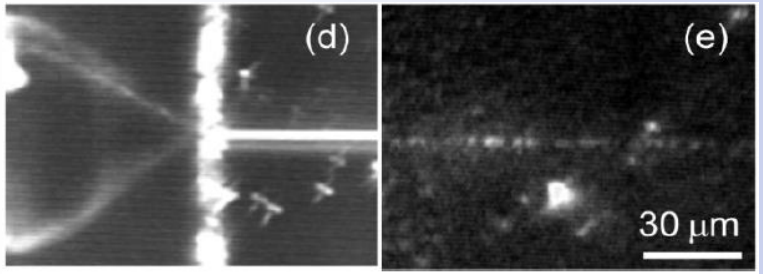
波导与光纤的对接











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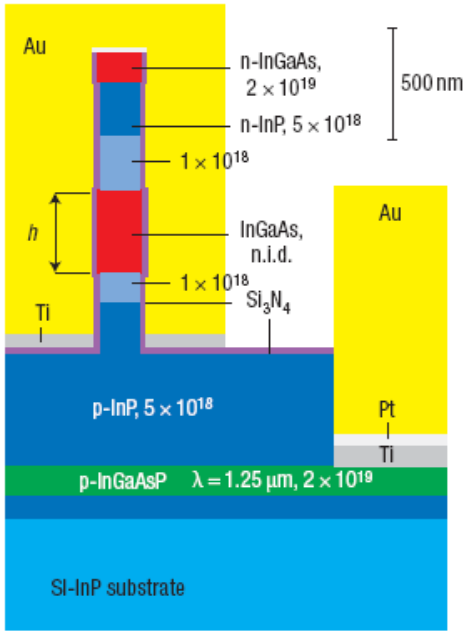
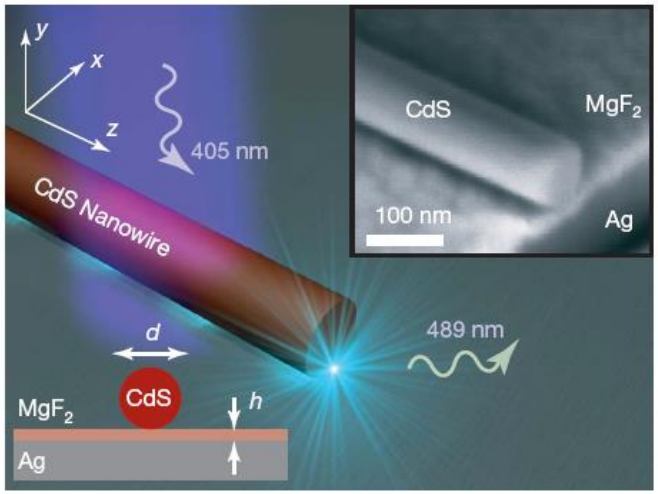
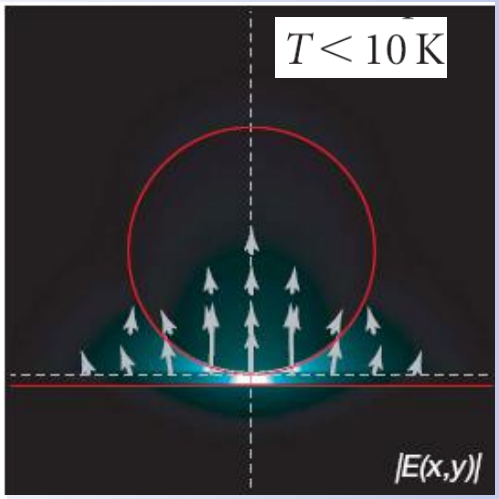
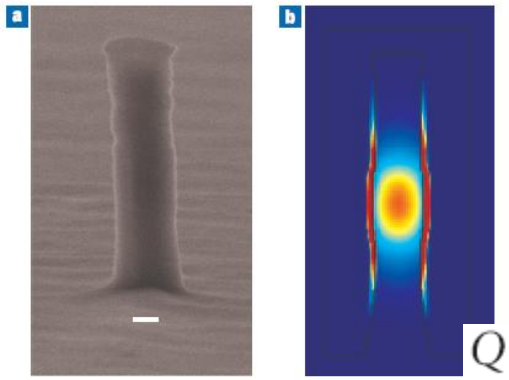
Plasmonic纳米激光器



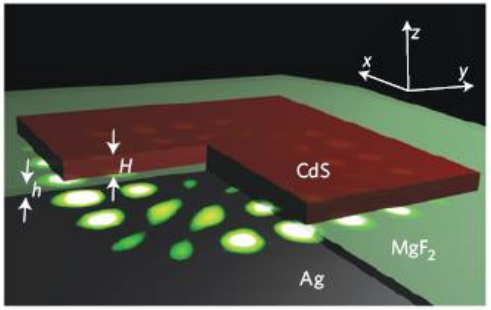


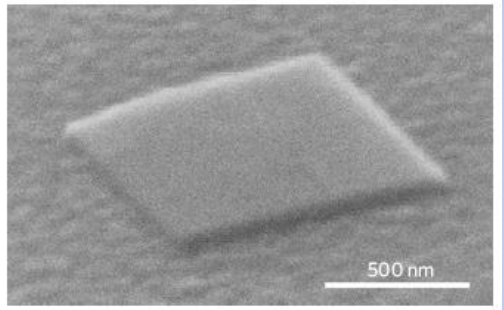


Deep subwavelength plasmon laser



Dielectric Golden Finger





$Q = 268$ for 10 K,
$Q = 144$ for 77 K

Room temperature plasmon laser

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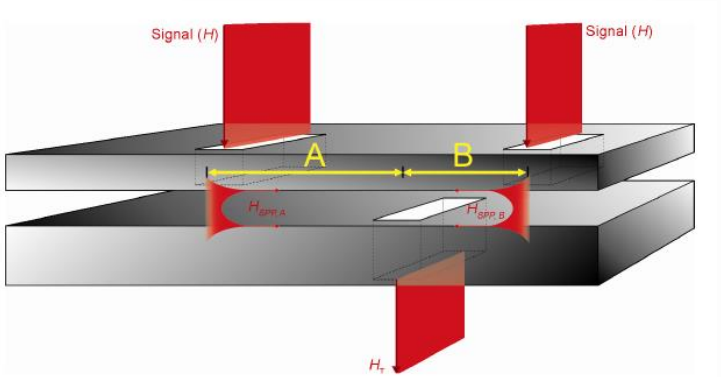
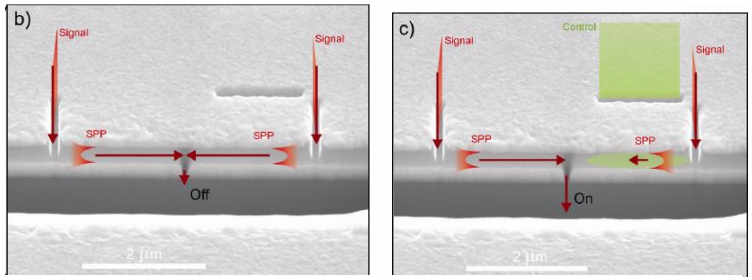
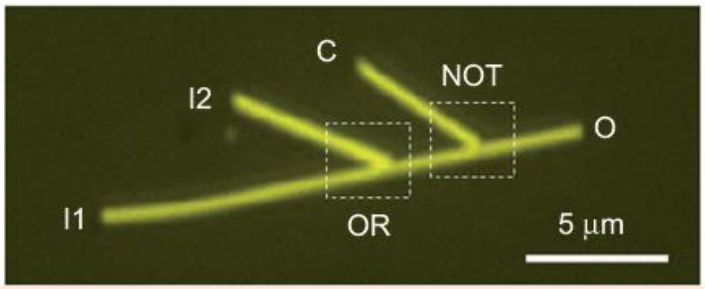
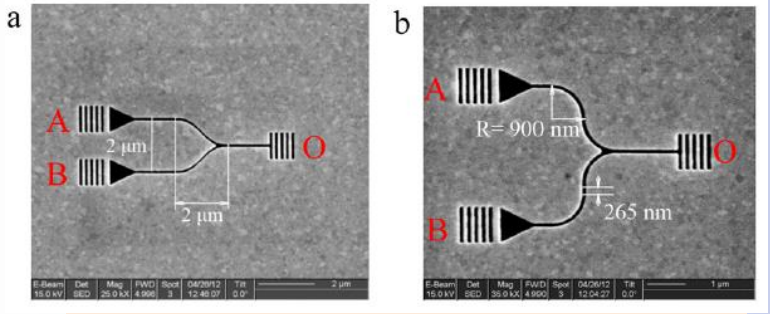
SPP动态调控



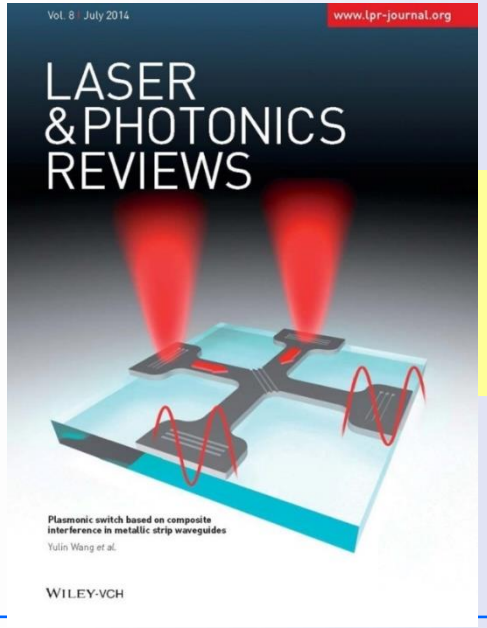




Prof. Xu HX group,
Nat. Comm. 2, 387 (2011)



Prof. Gong QH group,
Nano Lett. 12, 5784 (2012)

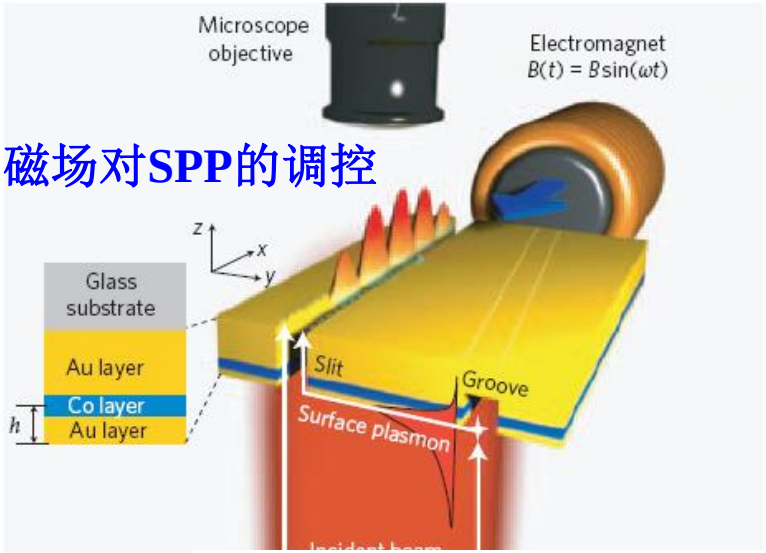


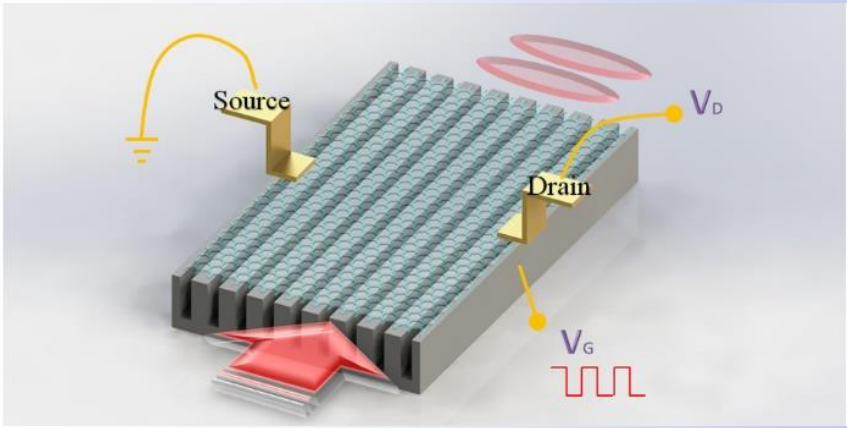
Plasmonic Switch，
LPR 8, L47 (2014).
Tao Li group @
NJU

Dr. Tao Li taoli@nju.edu.cn

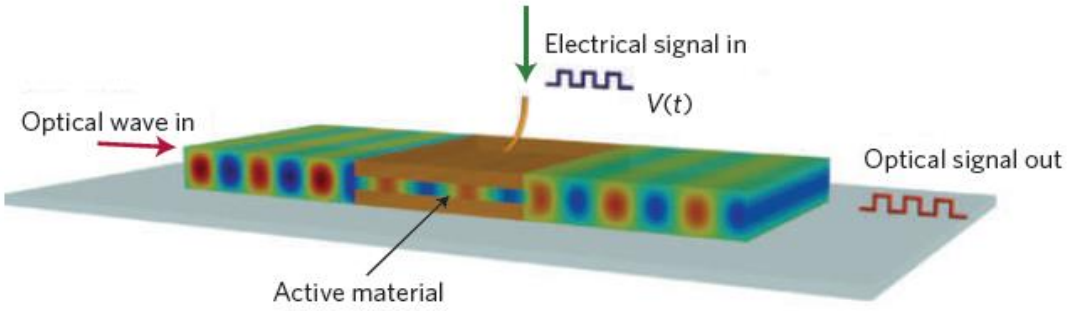
SPP动态调控

外磁场对SPP的调控



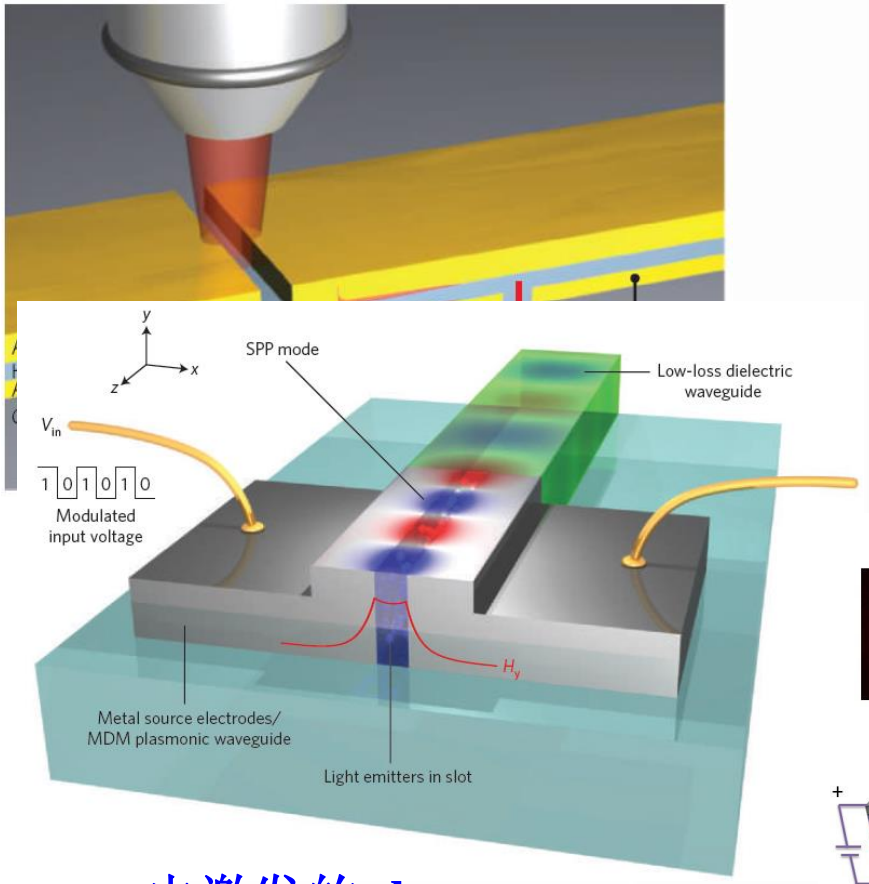


石墨烯加载SPP调制器，OL 42, 2247 (2017).
Tao Li group @ NJU

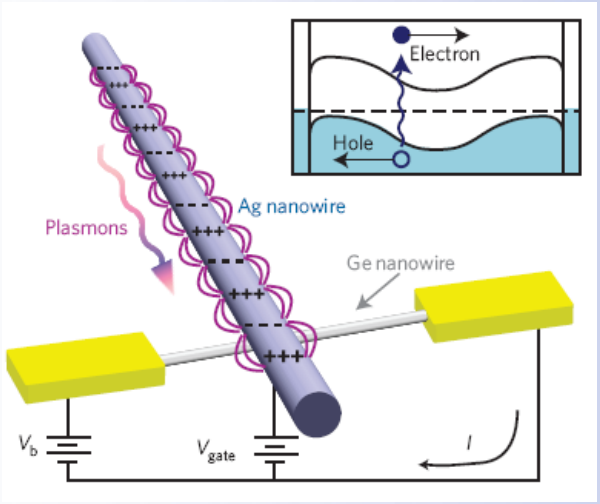


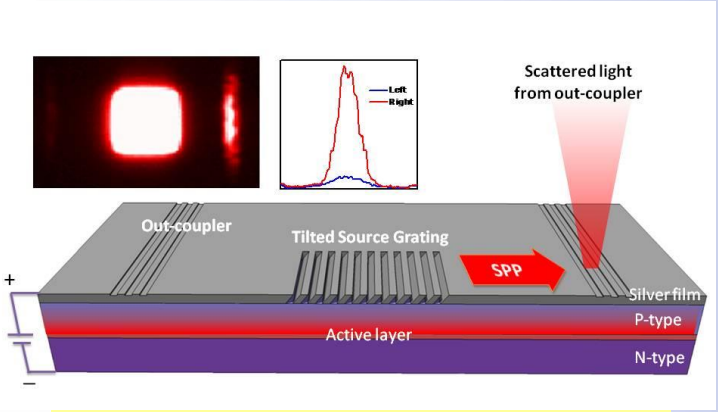
电场信号加载到SPP模式中

SPP的光电集成



电激发的plasmon





L. Wang, T. Li, et. al.
OE 20, 8710 (2012)

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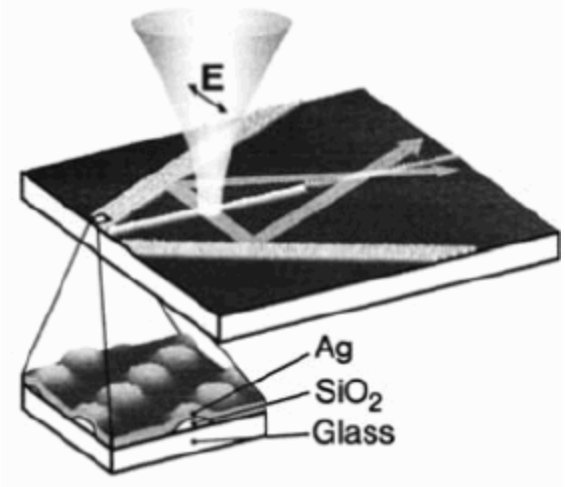
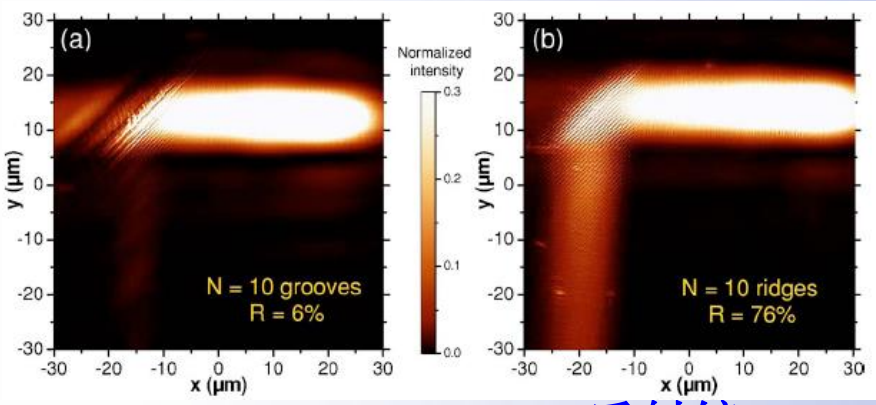
传统光学在二维平面的拓展与应用

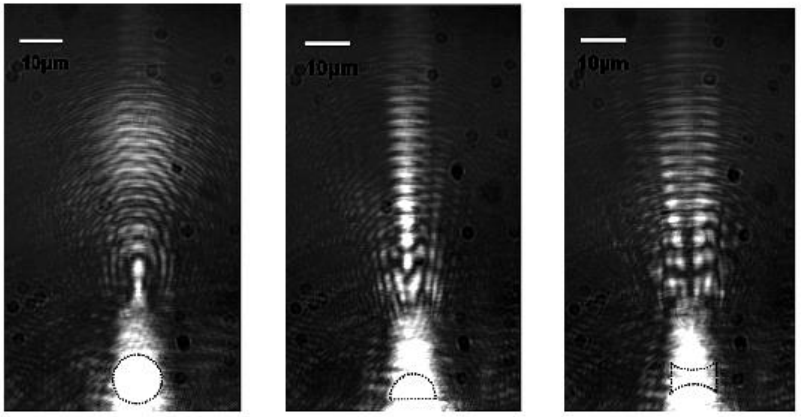
Dr. Tao Li taoli@nju.edu.cn

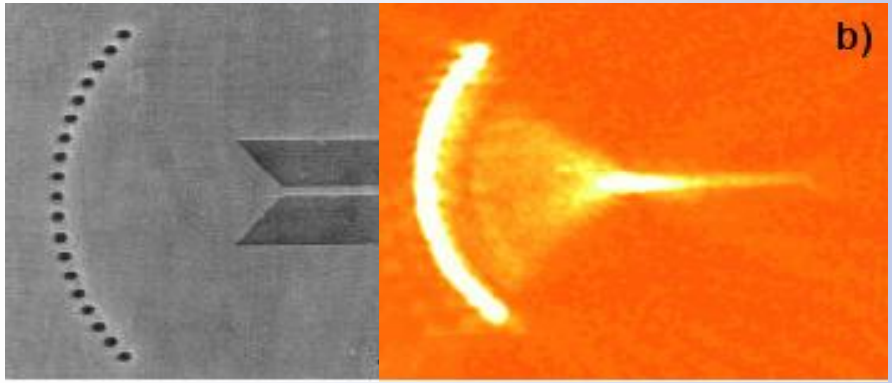
二维SPP光学元件





SPP Bragg反射镜





SPP透镜与聚焦

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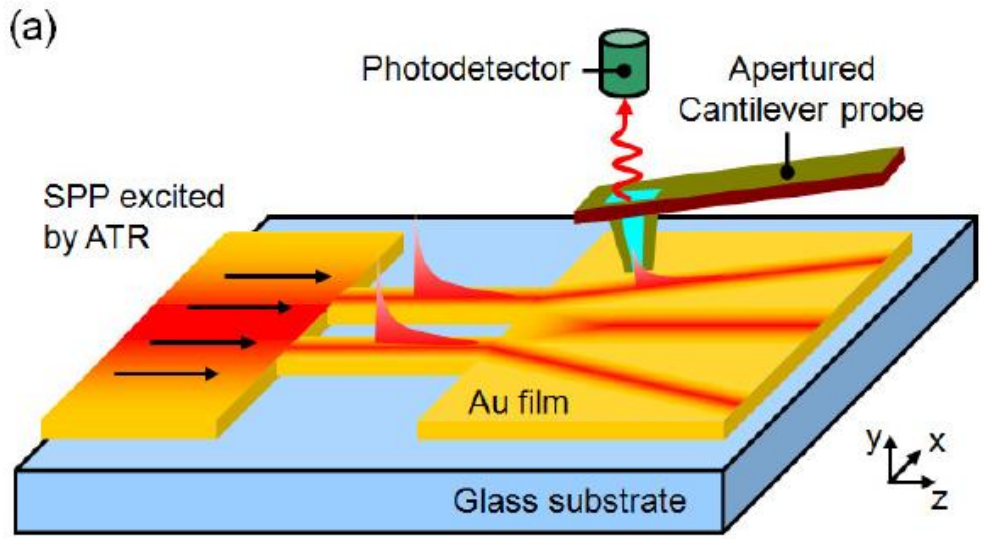
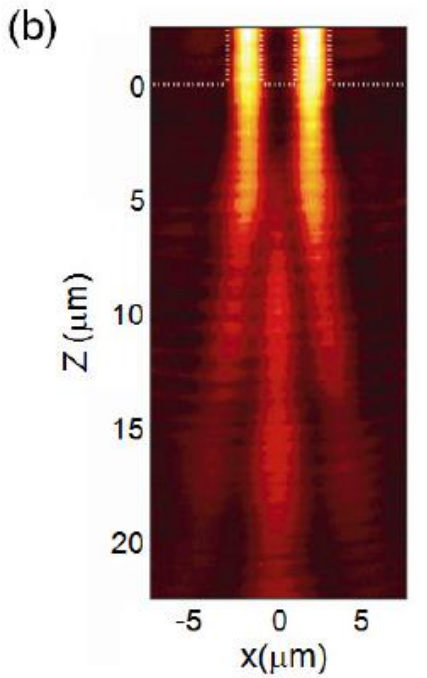
表面等离激元的“双缝衍射”





Nat. Nano. 2, 426 (2007)

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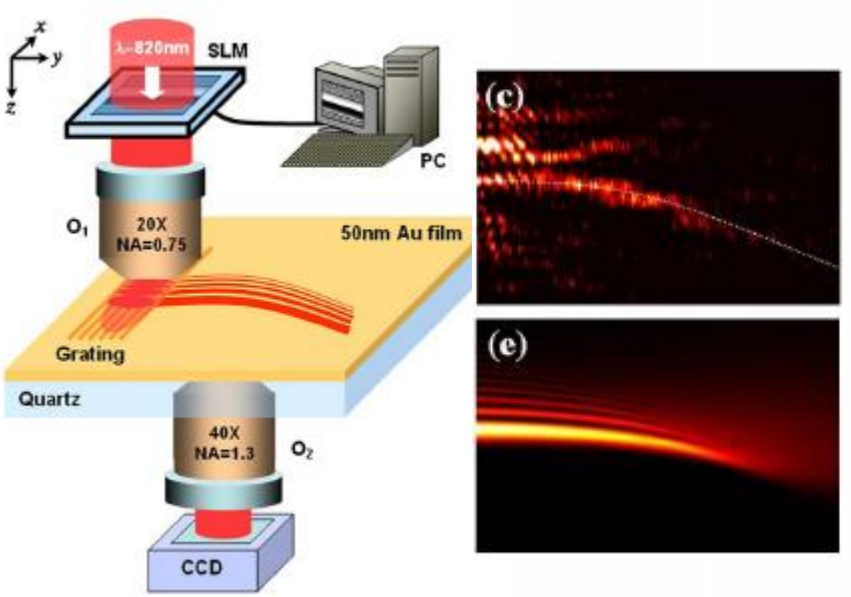
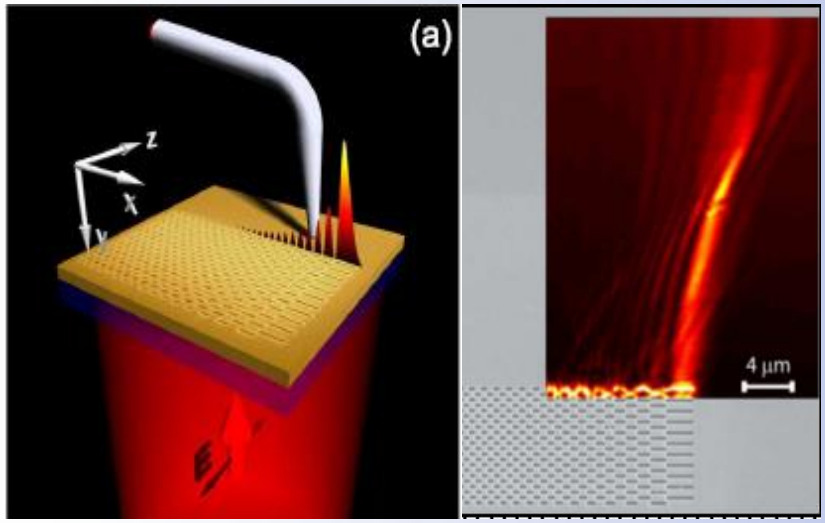
表面等离激元 Airy光束



X Zhang's group,
OL 36, 3191 (2011), August



Kivshar's group,
PRL 73, 155416 (2011), September, 9

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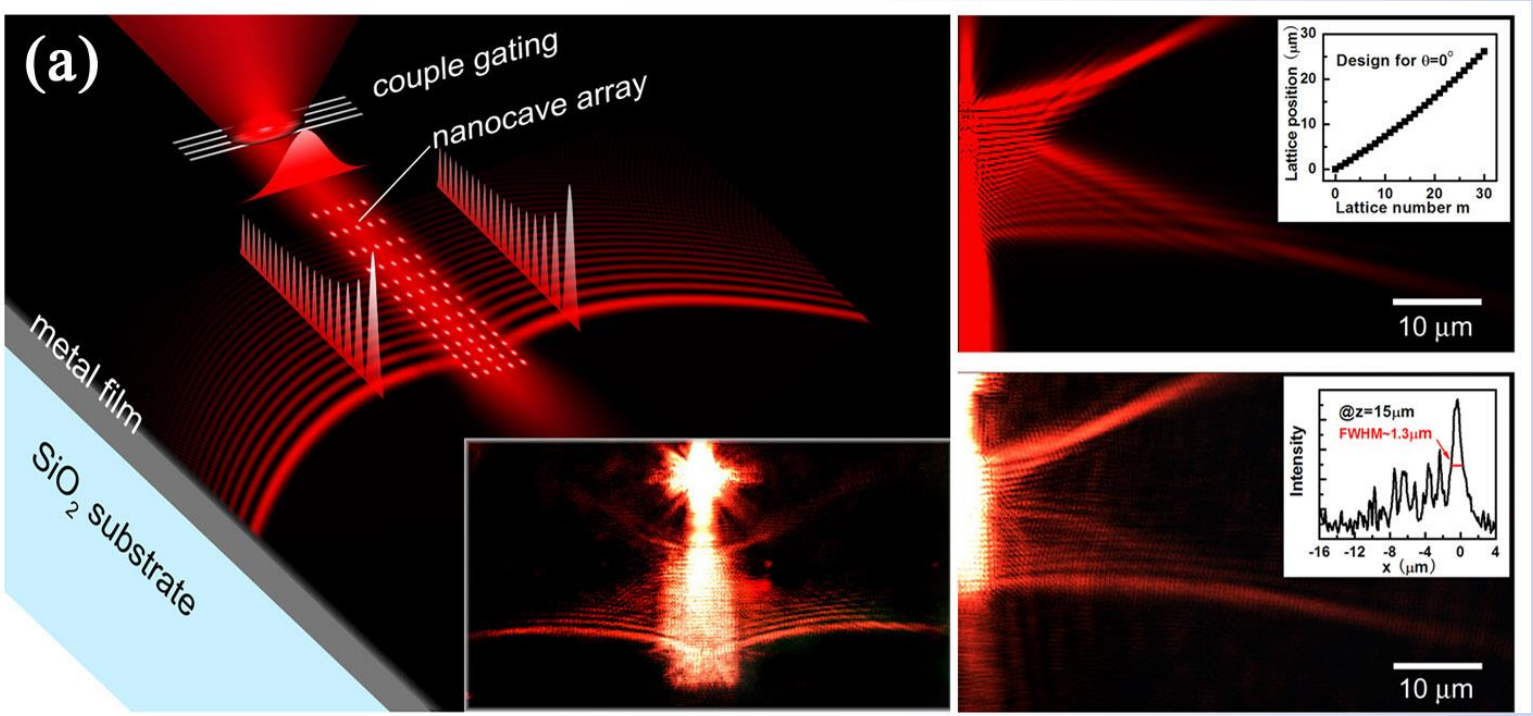
表面等离激元 Airy光束



L. Li, T. Li, et. al.
PRL 107, 126804 (2011), September, 16
Tao Li Group @ NJU

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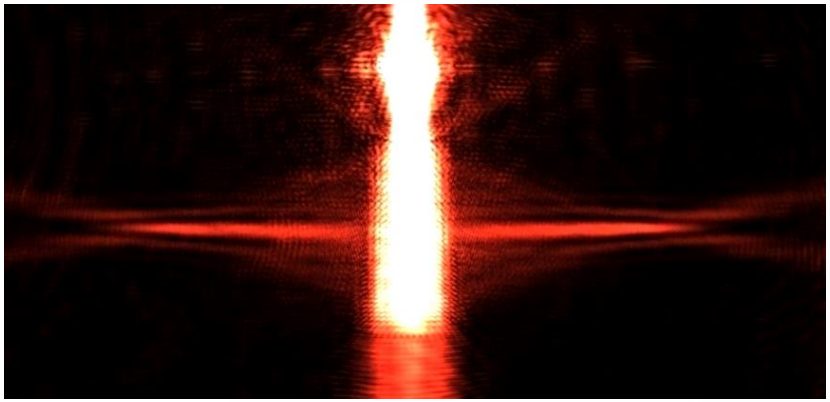
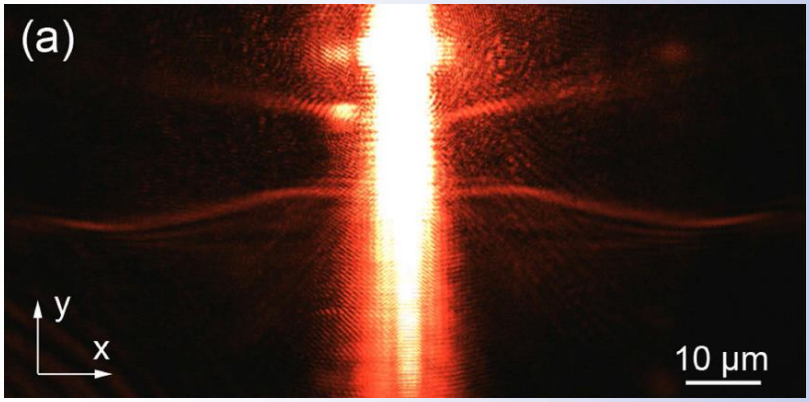
表面等离激元新颖波束调控



SPP准直无衍射波束



SPP弯曲振荡波束

L. Li, et. al. PRL 110, 046807 (2013).
J. Chen, et al. Sci. Rep. 6, 28926 (2016).
Tao Li Group @ NJU

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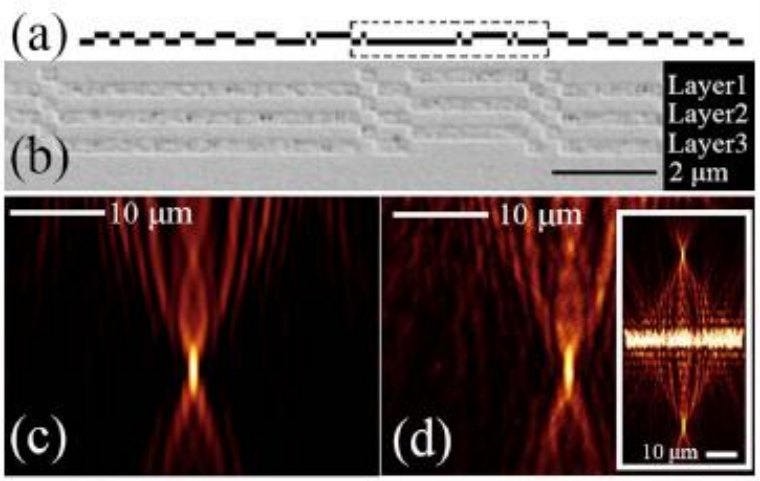
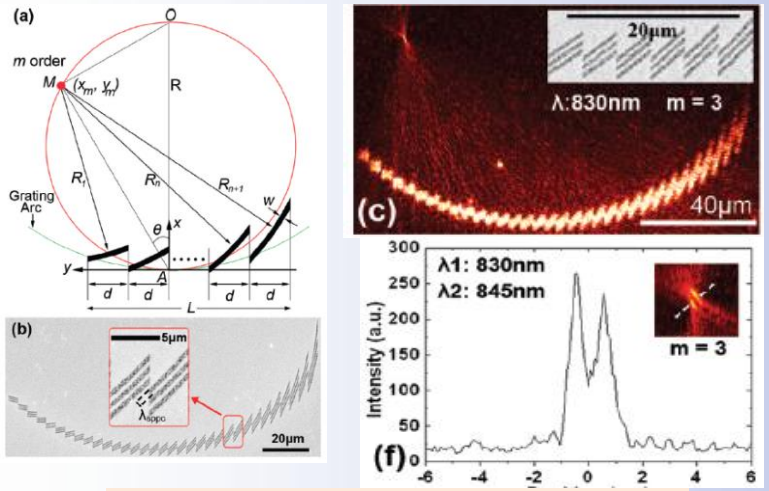
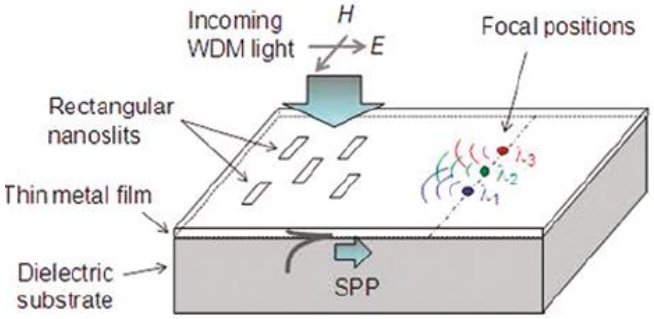
SPP平面内聚焦和波分复用

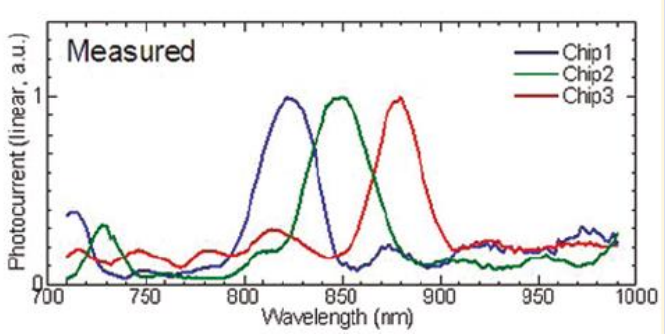


OL 16, 2417, APL 94, 081116 (2009)



ACS Nano 11, 6433 (2010)





Nano Lett. 11, 2693 (2011)

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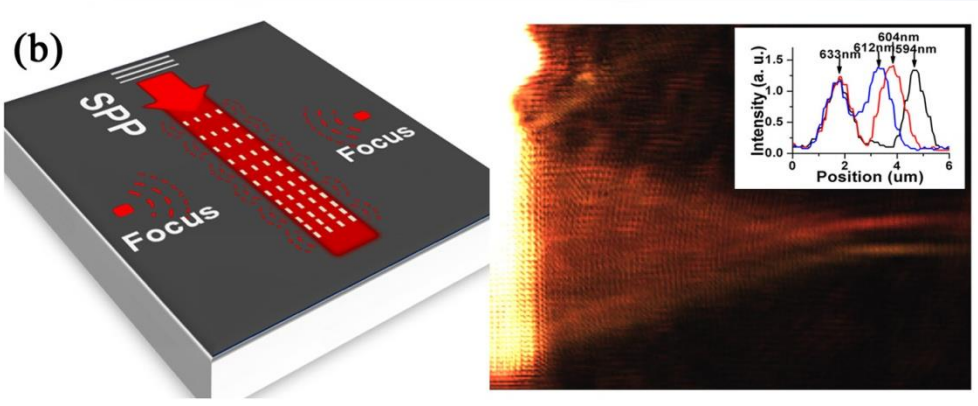
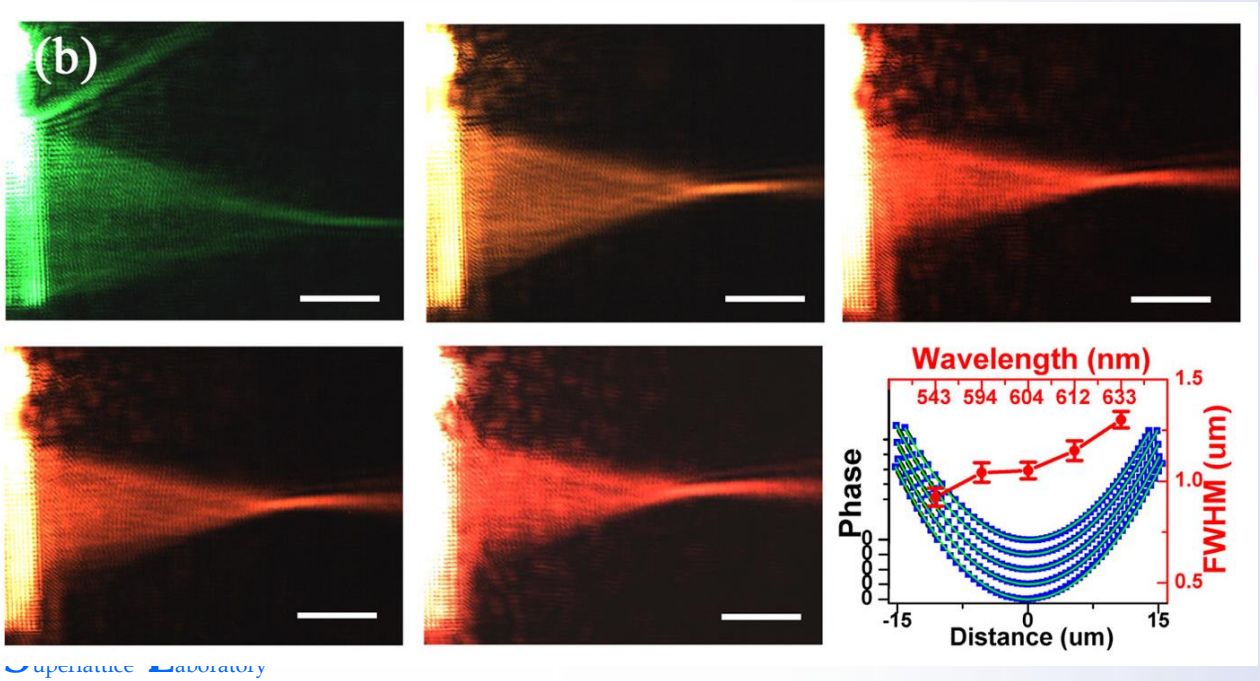
SPP平面内聚焦和波分复用



L. Li, T. Li, et. al.
Nano Lett. 11, 4357 (2011)
Tao Li Group @ NJU



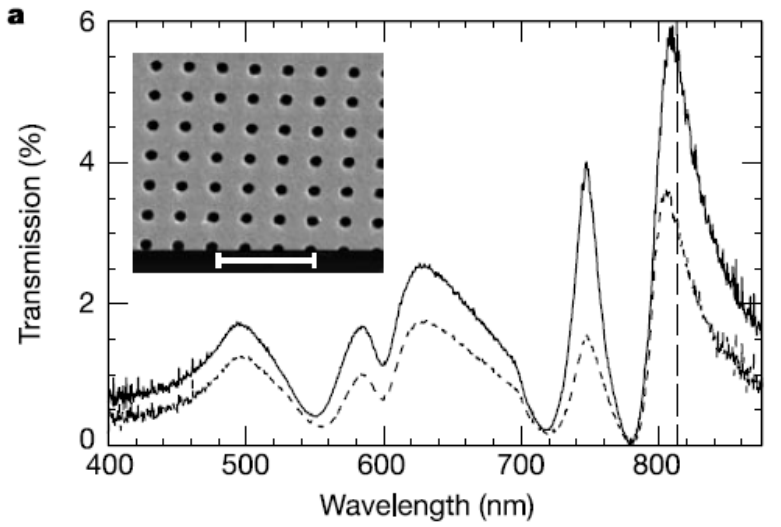
SPP量子特性的研究

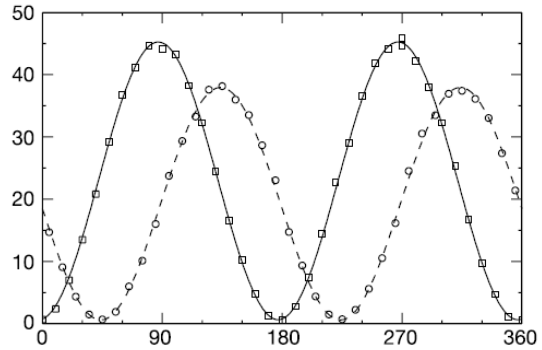
Dielectric Superlattice Laboratory

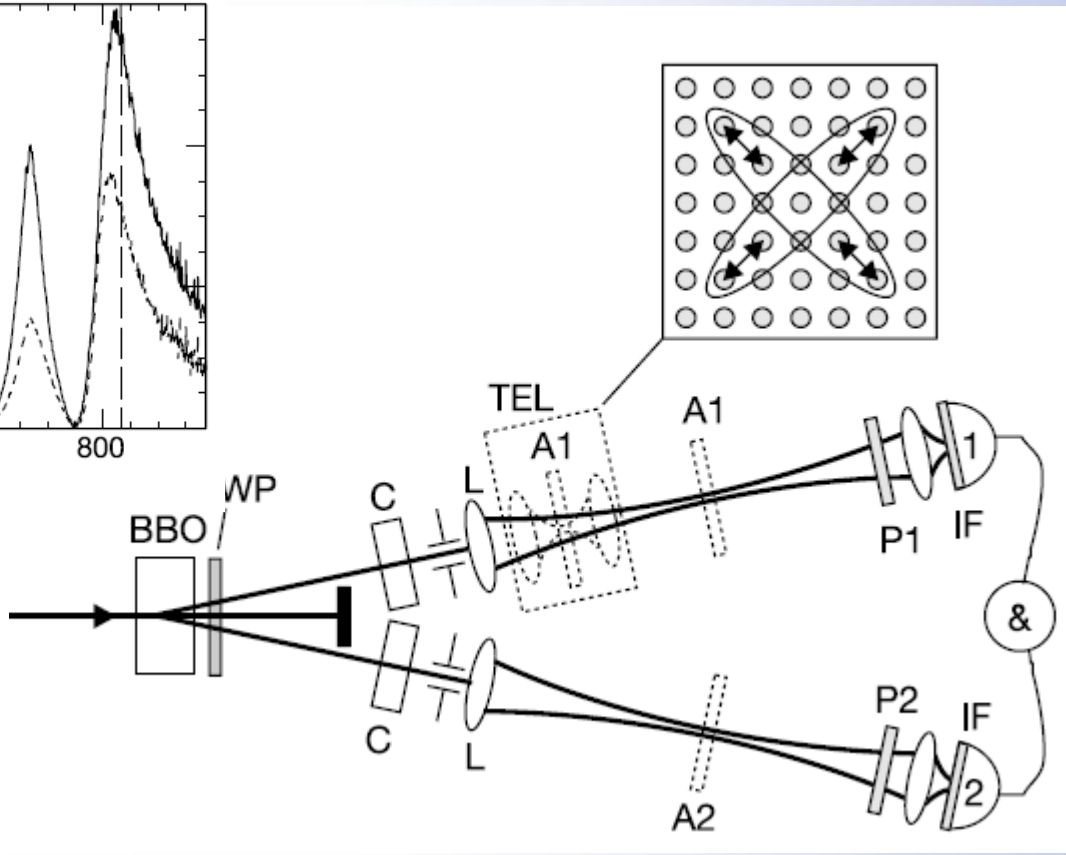
Nat. Lab. Microstructures

Dr. Tao Li taoli@nju.edu.cn

SPP对光子纠缠性质的保持



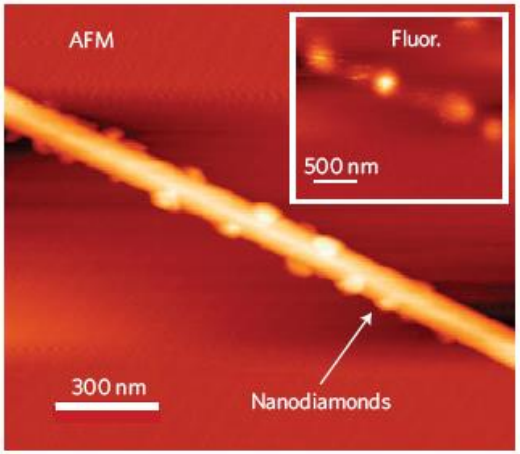


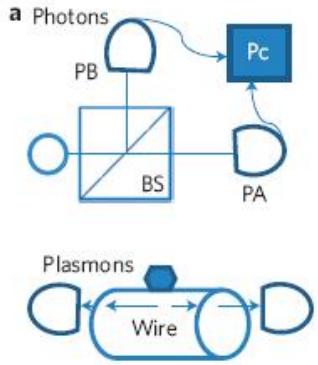


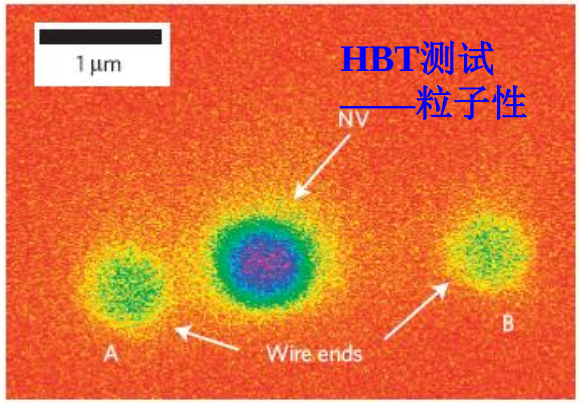
Nature 391, 667 (1998)

Dr. Tao Li taoli@nju.edu.cn

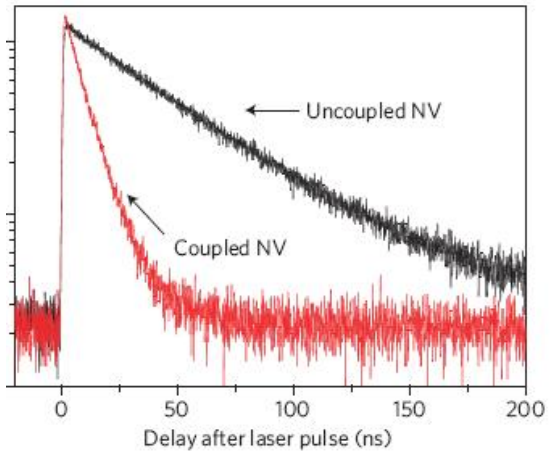
SPP的波粒二象性

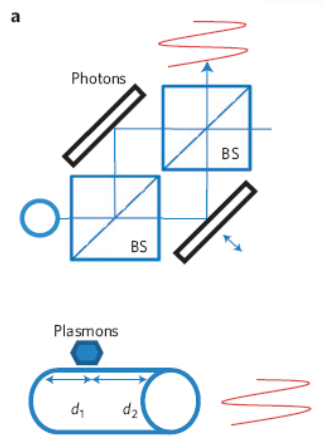


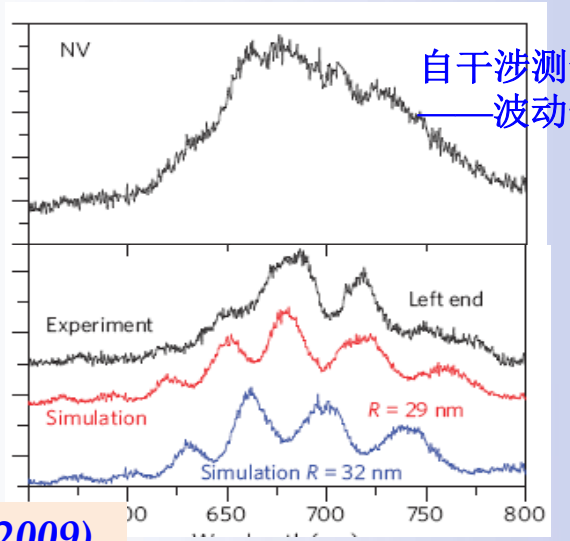




HBT测试
——粒子性







自干涉测试
——波动性

Nat. Physics 5, 470 (2009)

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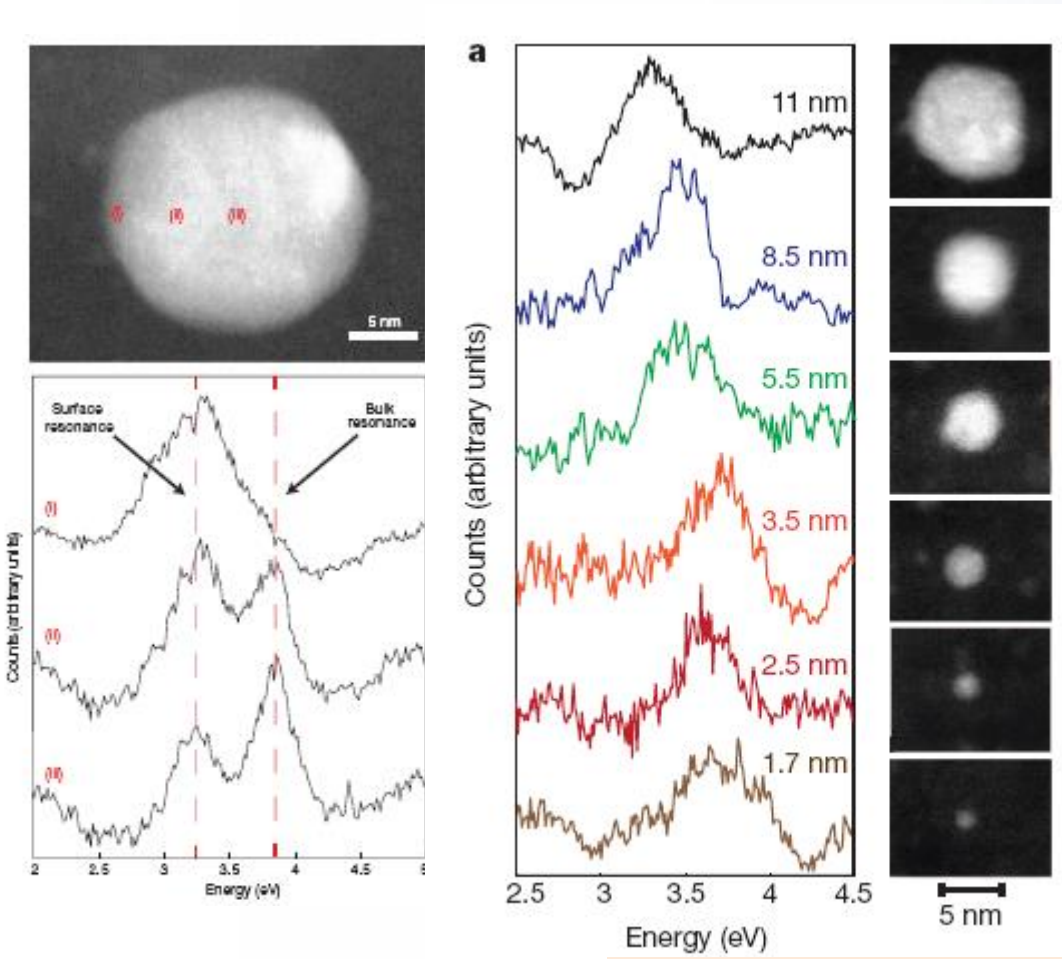
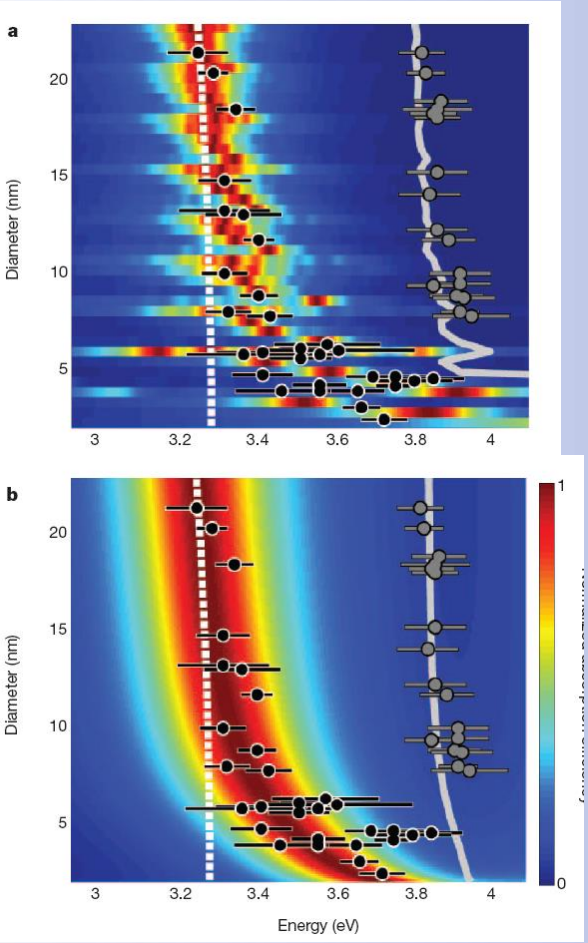
小颗粒中的SPP量子效应





Nature 483, 421 (2012)

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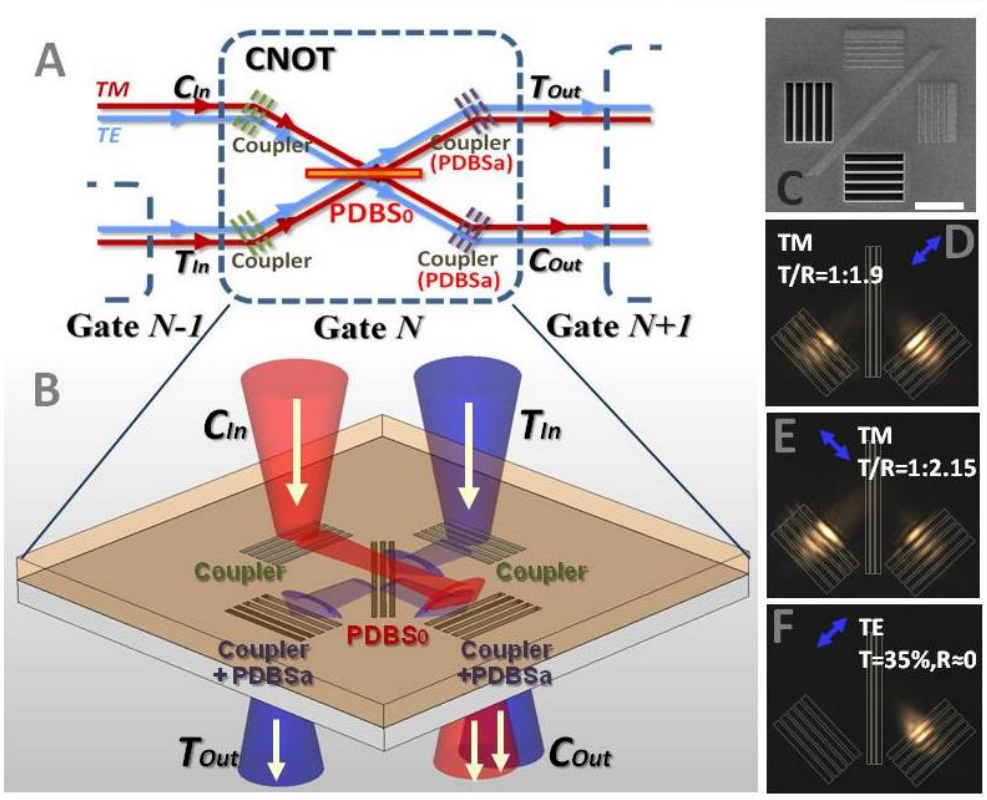
SPP量子逻辑门的研制

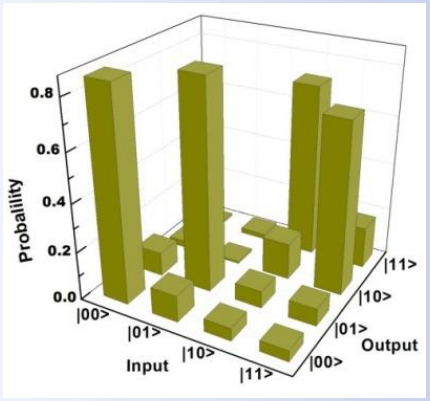


$$|0_{zz}\rangle_c \equiv |s\rangle_c$$

$$|1_{zz}\rangle_c \equiv |p\rangle_c$$

$$|0_{zz}\rangle_t \equiv |D\rangle_t = \left(|s\rangle_t + |p\rangle_t\right)/\sqrt{2}$$

$$|1_{zz}\rangle_t \equiv |A\rangle_t = \left(|s\rangle_t - |p\rangle_t\right)/\sqrt{2}$$



14×14 μm² Plasmonic CNOT gate.
S.M. Wang, et al, Nature Communications 7, 11490 (2016)
Tao Li Group @ NJU

Dr. Tao Li taoli@nju.edu.cn

超构材料

（metamaterial）

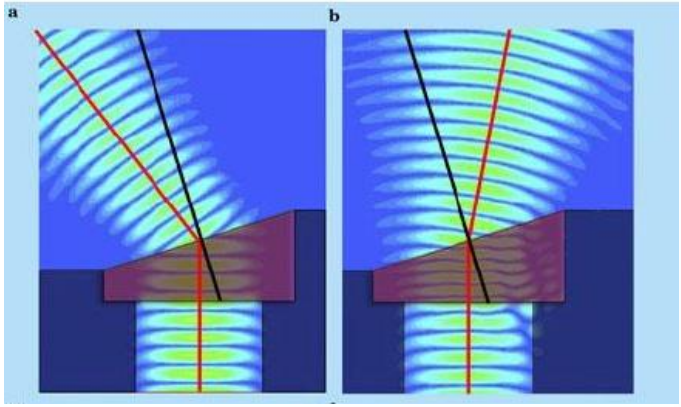
Dielectric Superlattice Laboratory

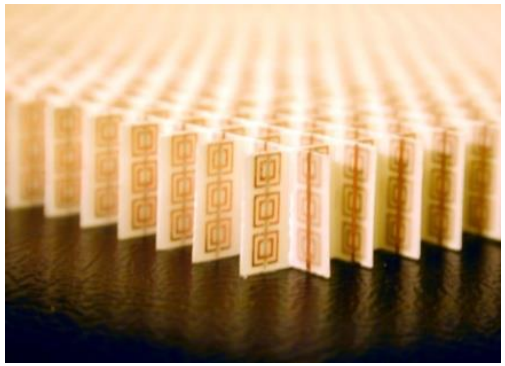
Nat. Lab. Microstructures

Dr. Tao Li taoli@nju.edu.cn

超构材料 —负折射效应

负折射现象



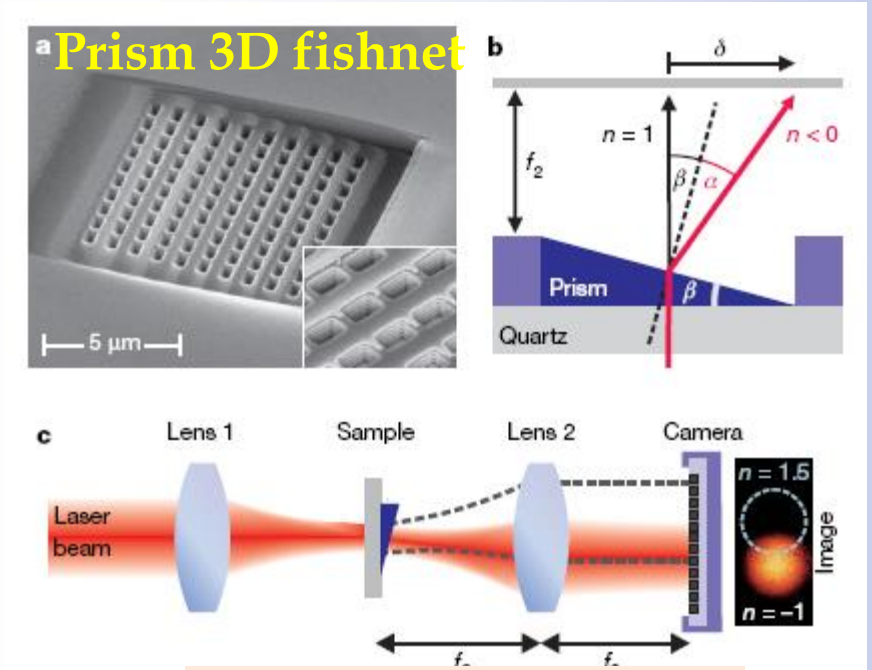


Science 292, 77 (2001)

metamaterial

$$n = \sqrt{\varepsilon} \cdot \sqrt{\mu}$$

$$\varepsilon < 0,\ \mu < 0 \Rightarrow n < 0$$



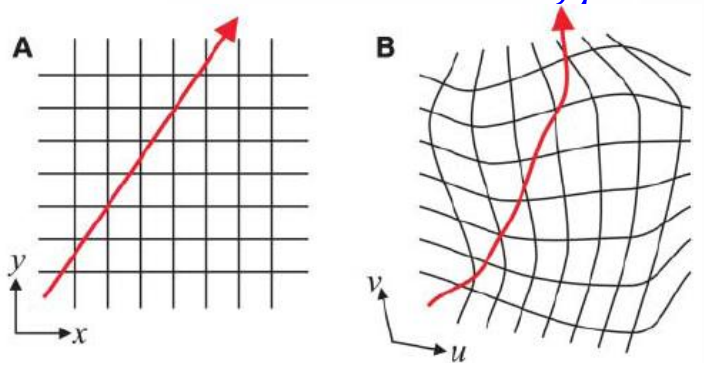
Nature 455, 379 (2008)

Dr. Tao Li taoli@nju.edu.cn

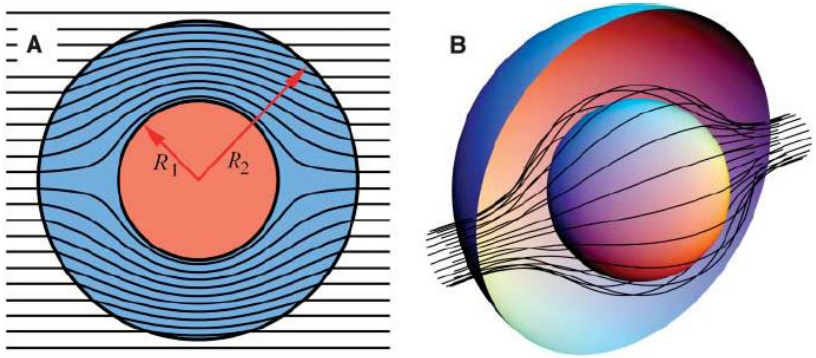
光学隐身衣（超构材料变换光学）
metamaterial

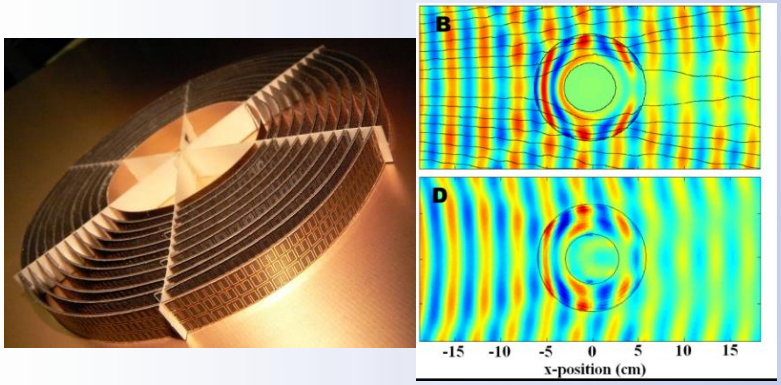
Cloaking隐身

在有效介质条件下，空间任意区域的
ε, μ 可以人为确定，n也就可以人为确定



人们就可以设计材料按照自
己意愿让光进行传播





Pendry rlattice] *Science 312, 1780 (2006)*

D. R. Smith, et al, Science (2006)

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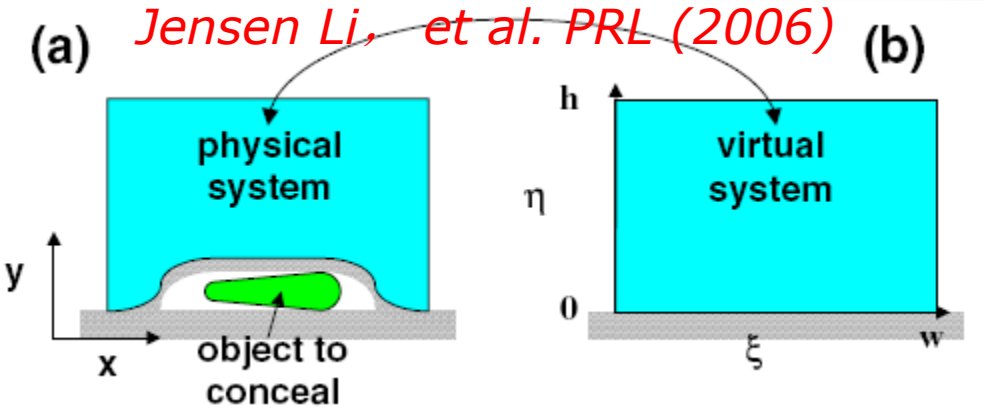
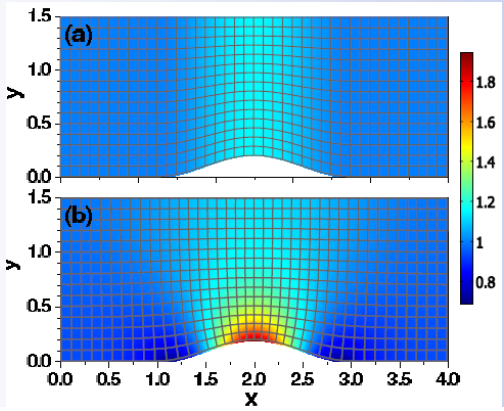
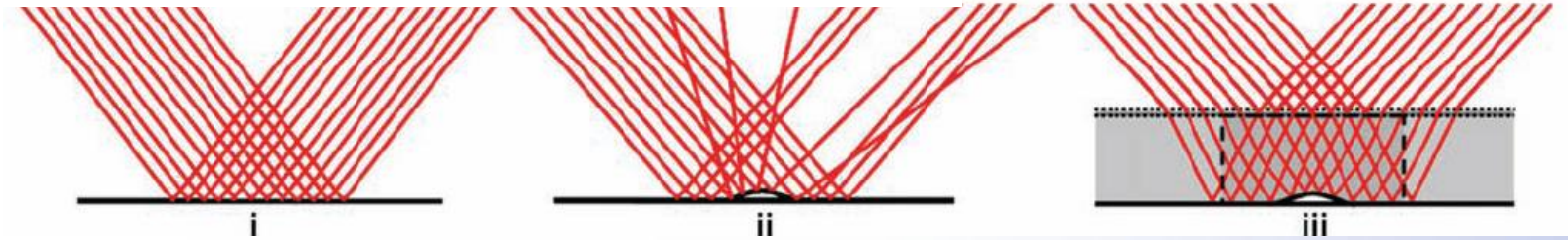
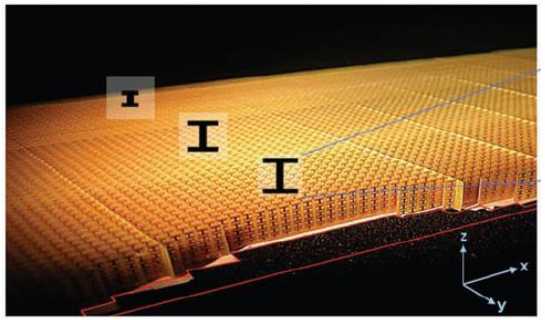
隐身地毯（及微波波段实现）

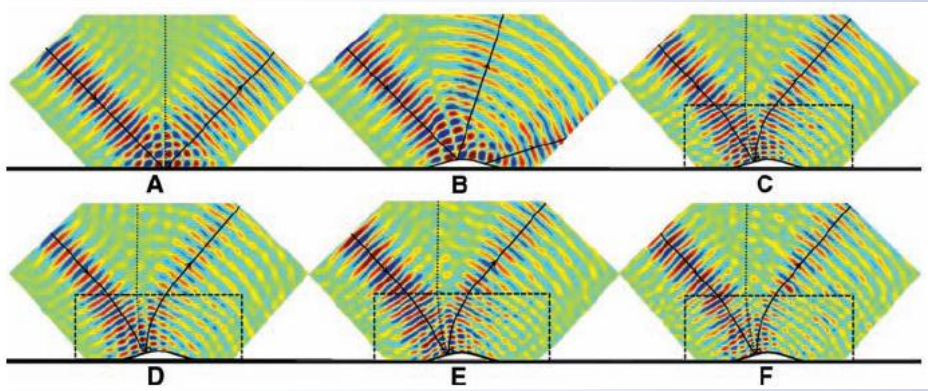
Jensen Li, et al. PRL (2006)









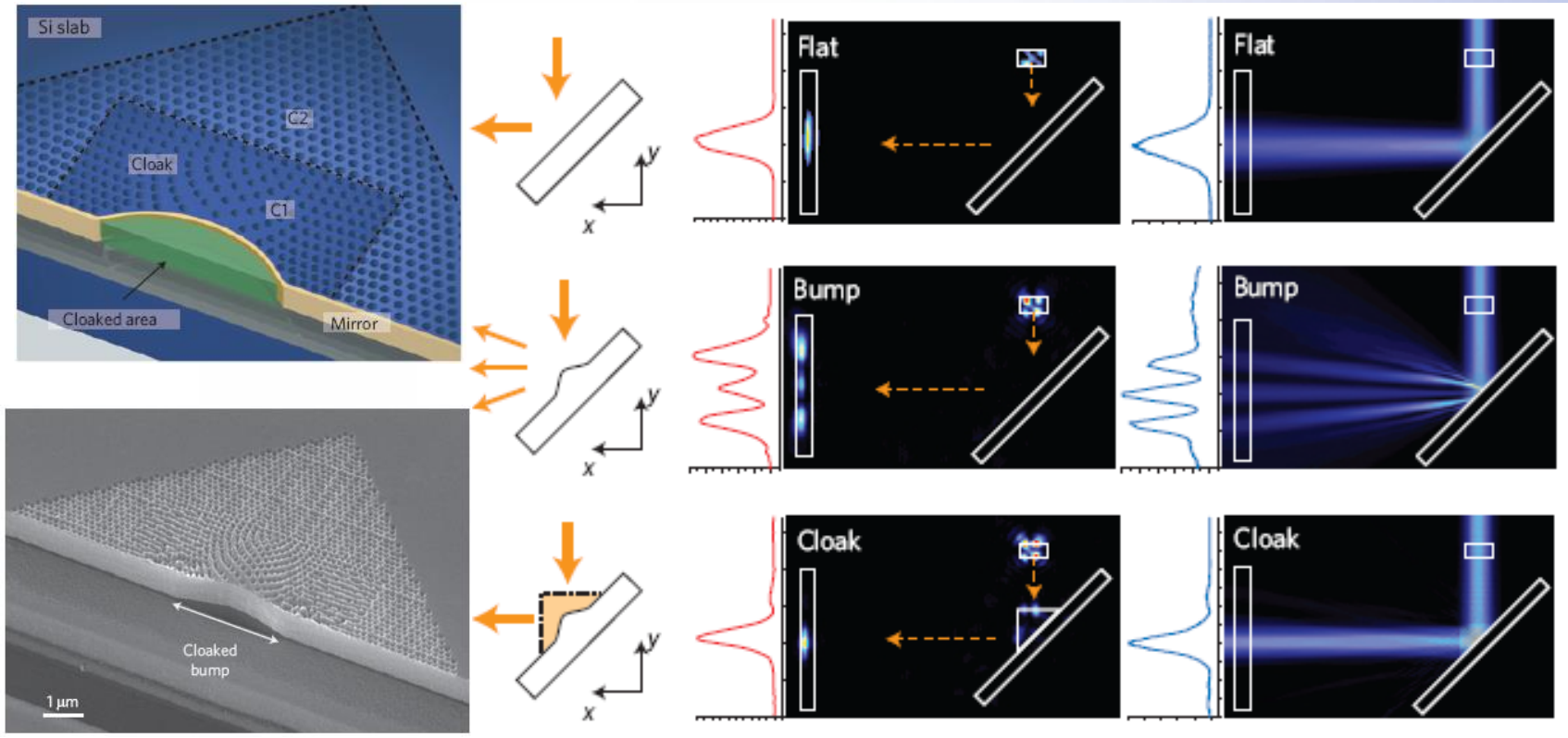


Science 323, 366 (2009)

Microwave region, by D. R. Smith group

Dr. Tao Li taoli@nju.edu.cn

隐身地毯（光波波段实现）



Nat. Mater. 8, 568 (2009)

1550 nm，By Xiang Zhang group (2009)

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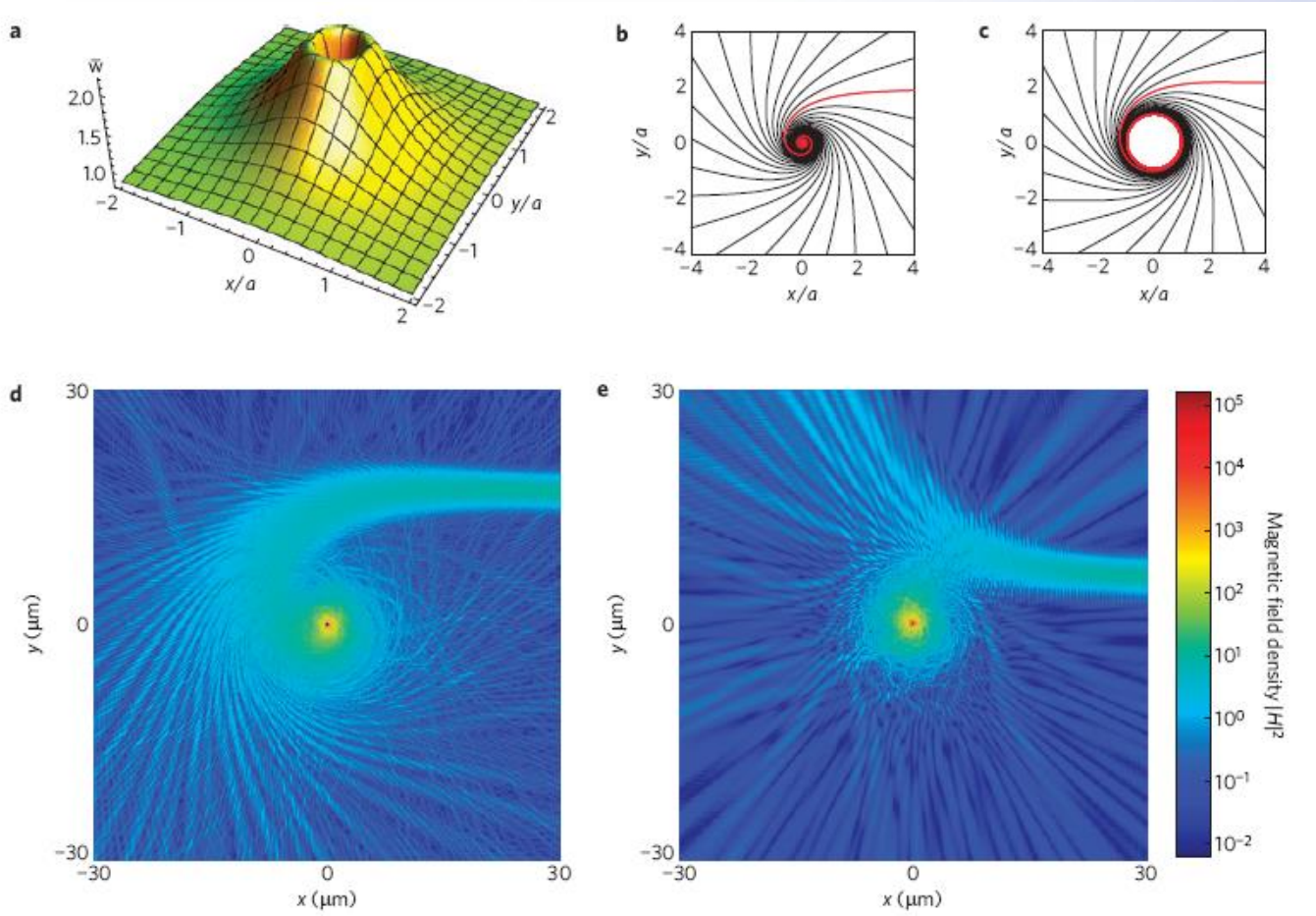
人造黑洞（变换光学）



Nat. Physics 5, 687 (2009)

By Xiang Zhang group (2009)

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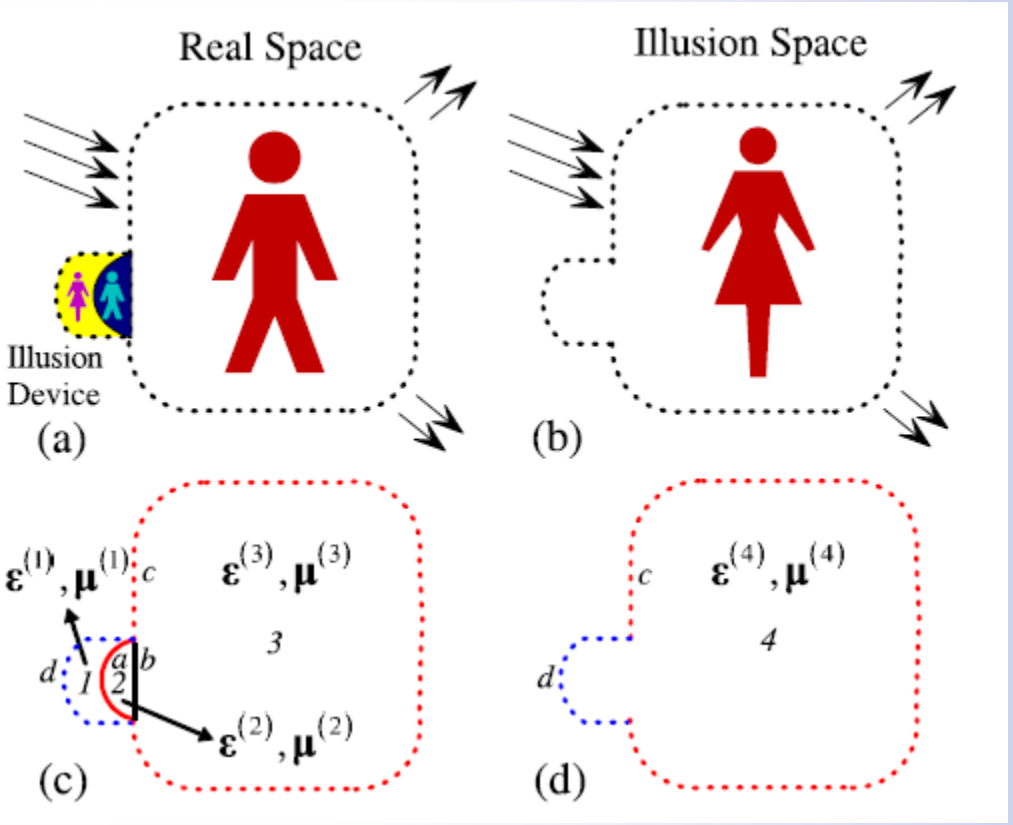
幻象光学 (*Illumination Optics*)

Illusion Optics:
The Optical Transformation of an Object into Another Object

A further development of ***Transformation Optics***

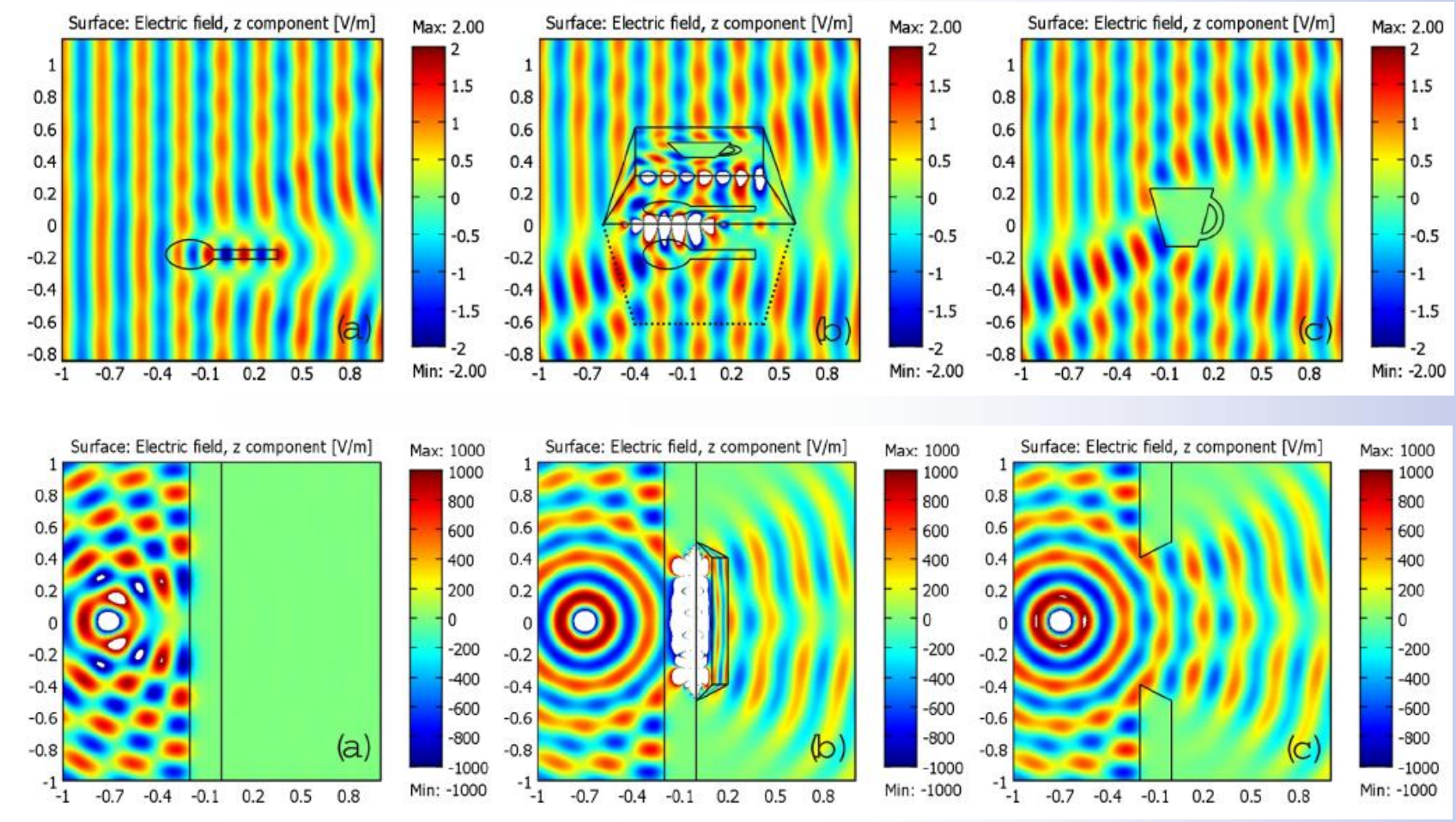


PRL 102, 253902 (2009)

By C.T. Chen group (2009)

Dr. Tao Li taoli@nju.edu.cn

幻象光学 (*Illumination Optics*)



By C.T. Chen group (2009)

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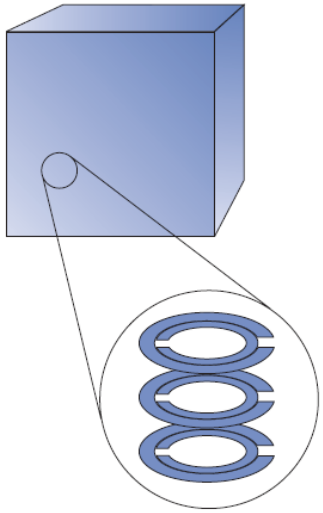
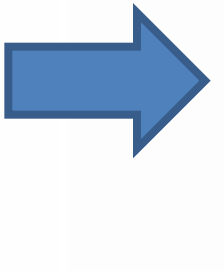
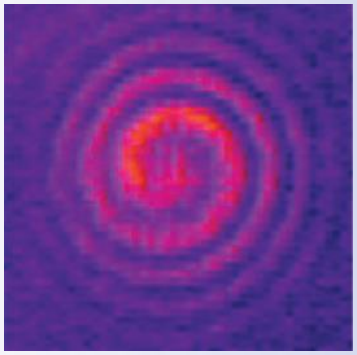
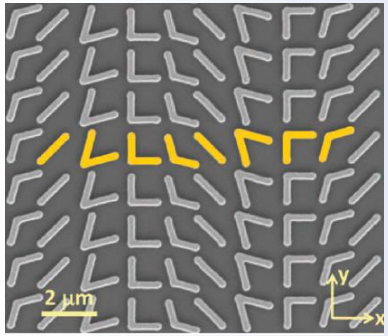
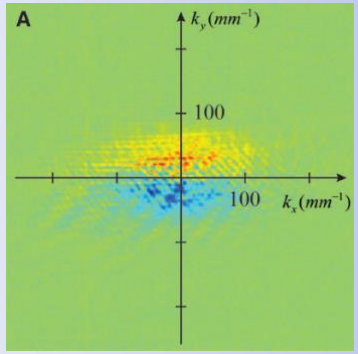
From metamaterial to metasurface

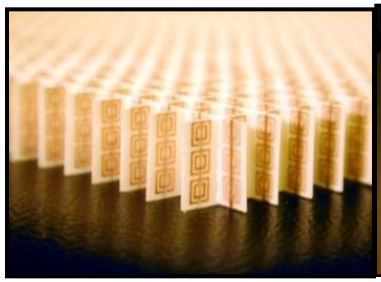


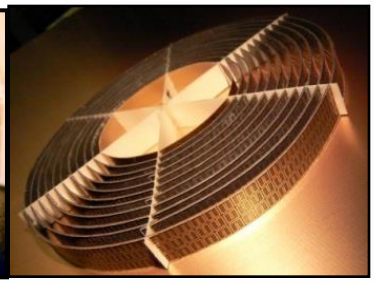


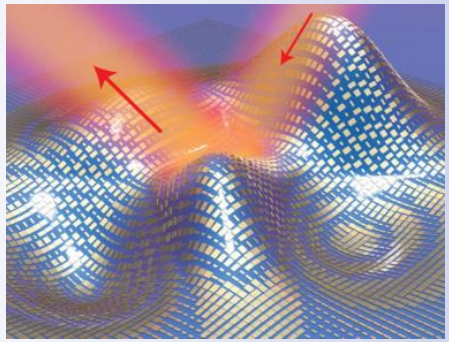










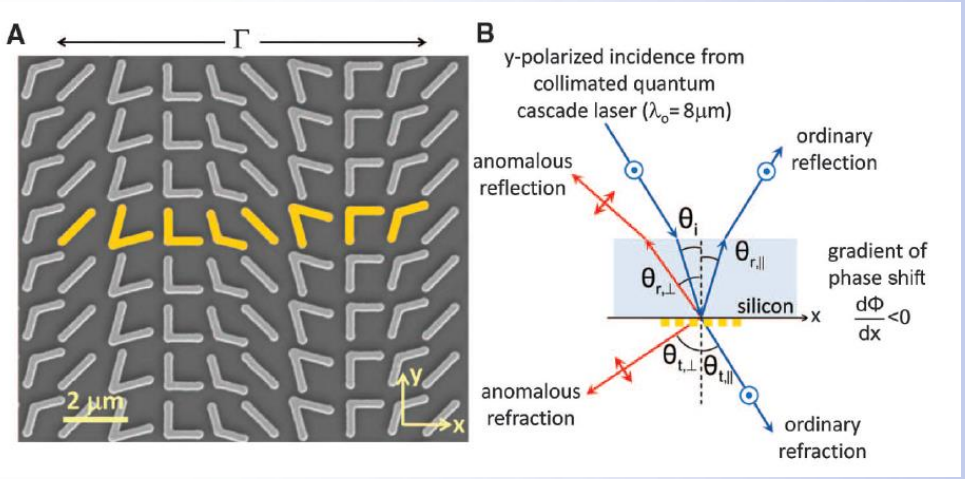


Metasurface (超构表面)

✓ **resonance**

Linear Polarization
wavelength-dependent

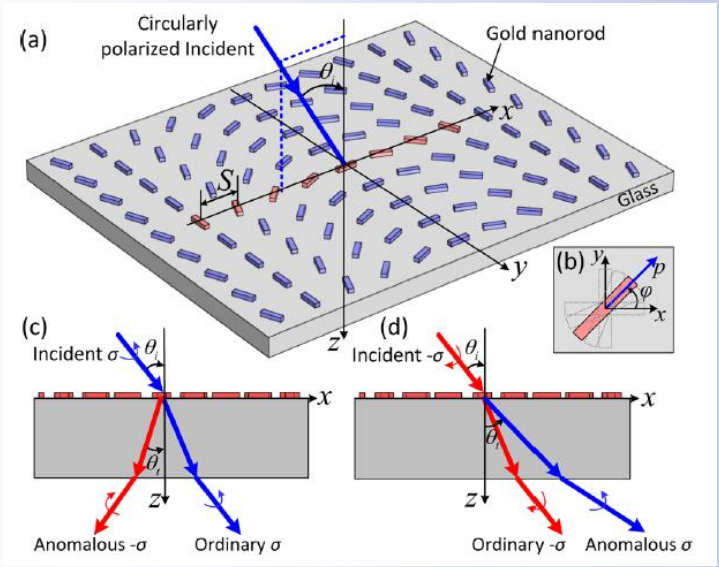
Science 334, 333 (2011)



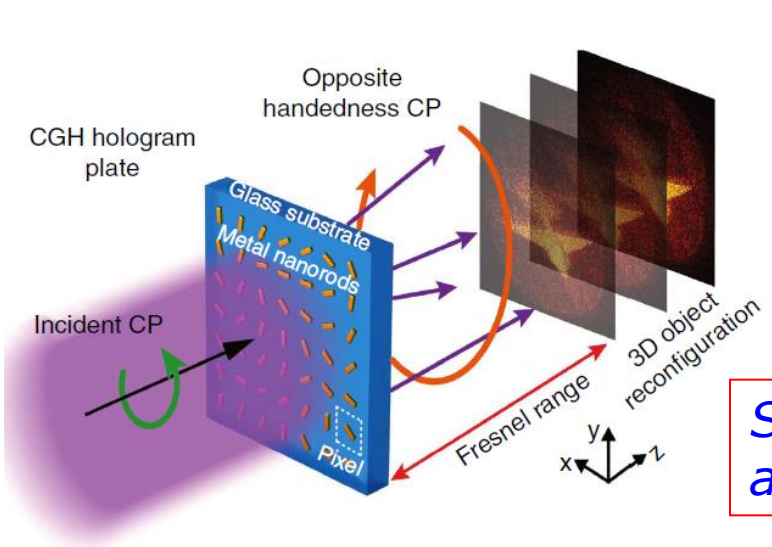
✓ **Geometric (PB) phase**

Broadband
Circular Polarization

Nano Lett. 12, 5750 (2012)

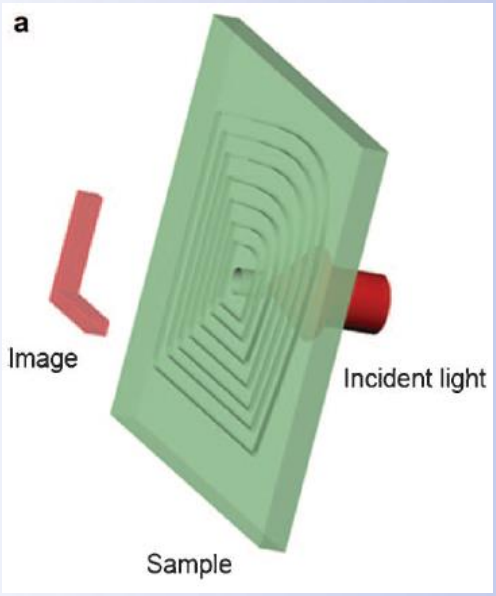


Hologram



Small pixel and large FOV

DOI: 10.1038/ncomms3808 (2013)

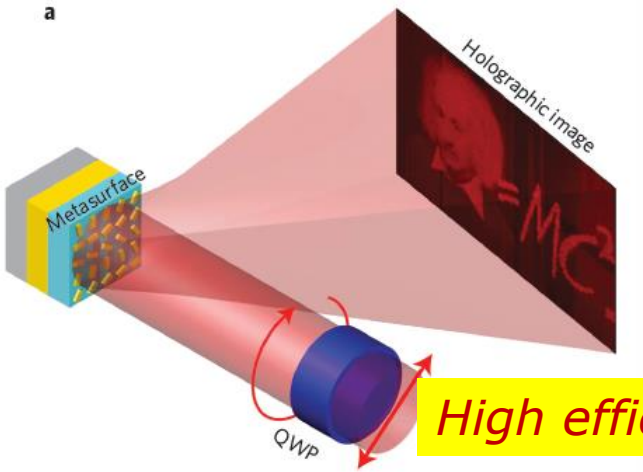


doi:10.1038/lsa.2012.26

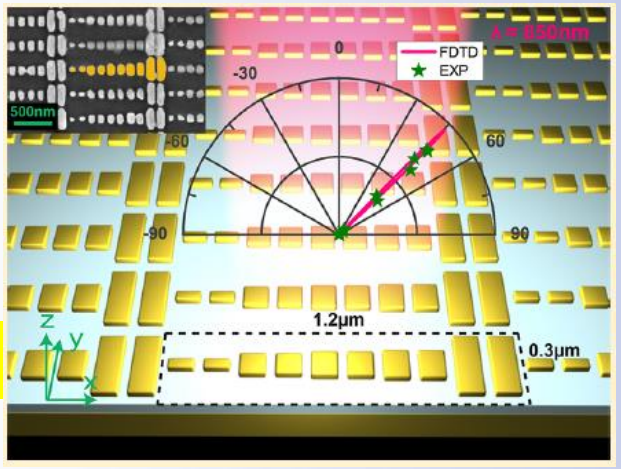
Conversion between far field and near field

DOI: 10.1038/ncomms3807 (2013)

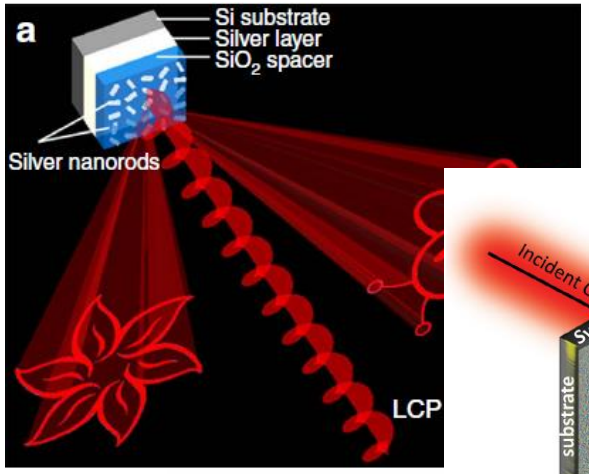
Meta-holograms

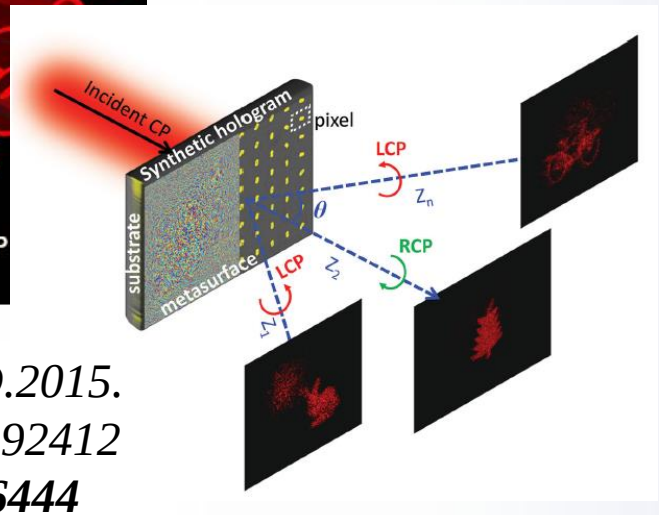


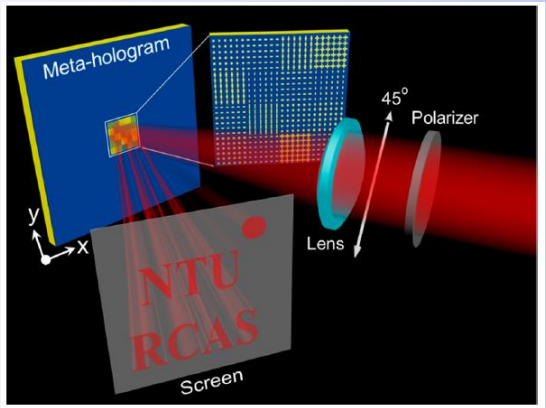
High efficiency > 80%



dx.doi.org/10.1021/nl3032668







DOI: 10.1038/NNANO.2015.
DOI: 10.1038/ncomms92412
Adv. Mater. ***2015, 27, 6444***

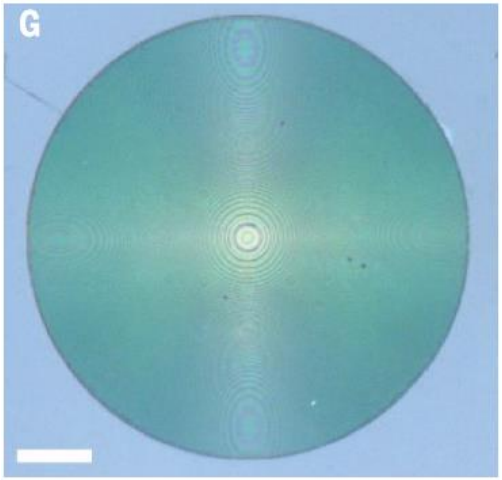
Nano Lett. 2014, 14, 225−230

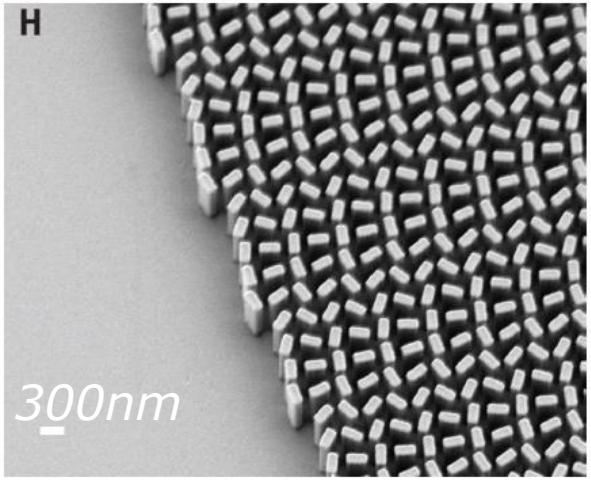
Metalens-超构透镜

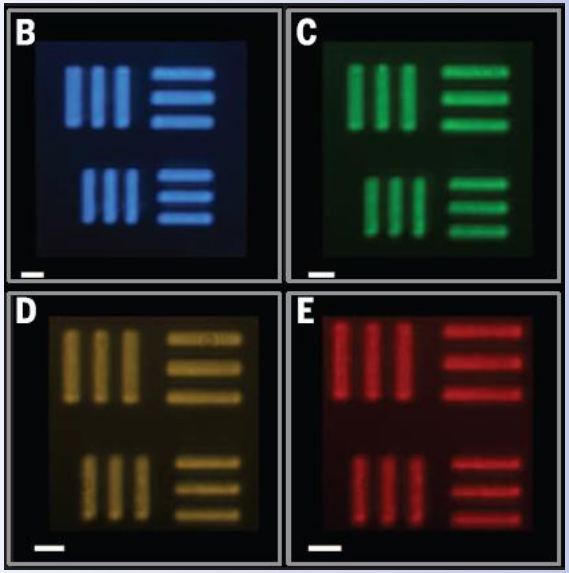
APPLIED OPTICS

Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging

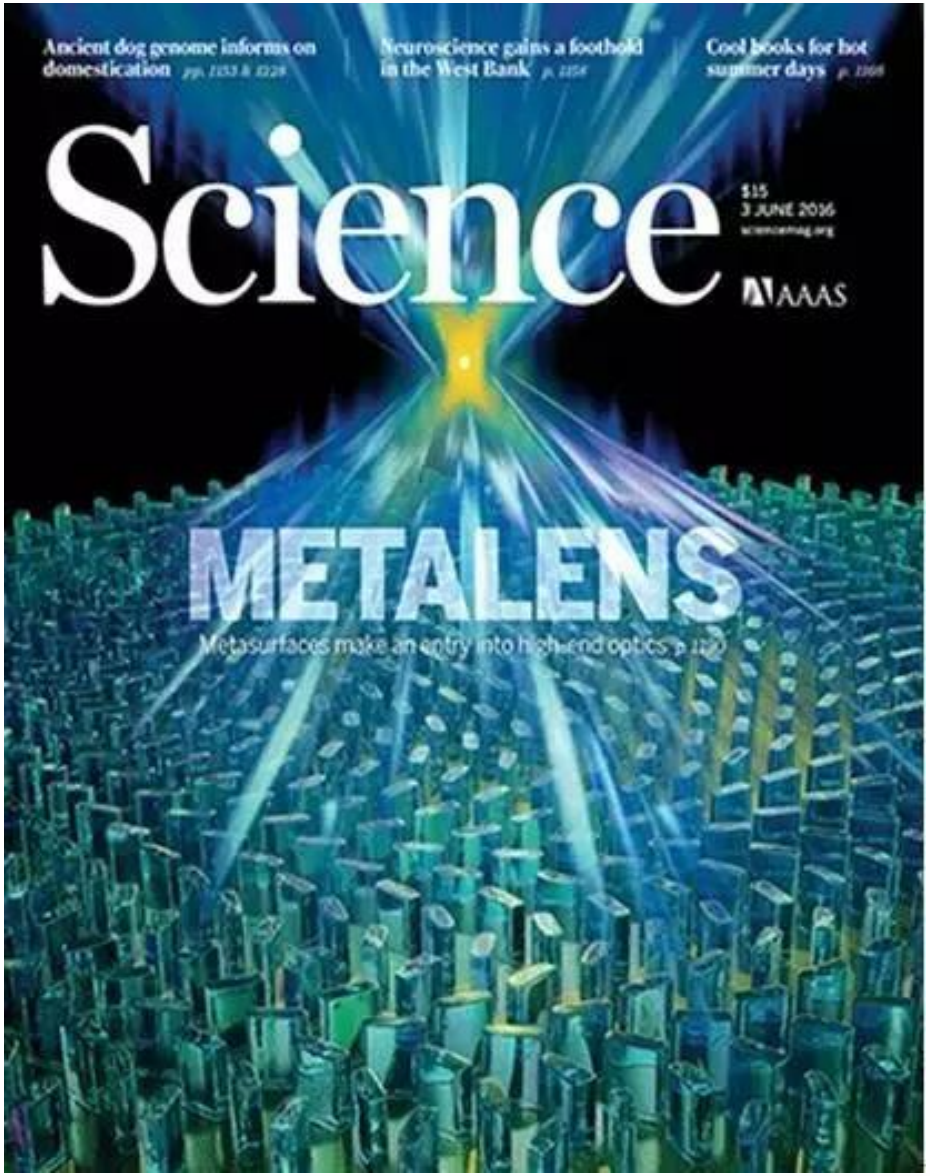
Mohammadreza Khorasaninejad,[1]* Wei Ting Chen,[1]* Robert C. Devlin,[1]* Jaewon Oh,[1,2]
Alexander Y. Zhu,[1] Federico Capasso[1]†

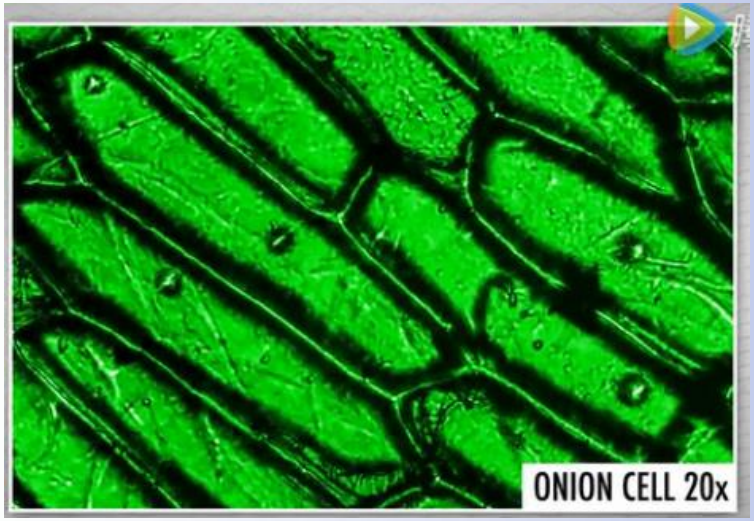






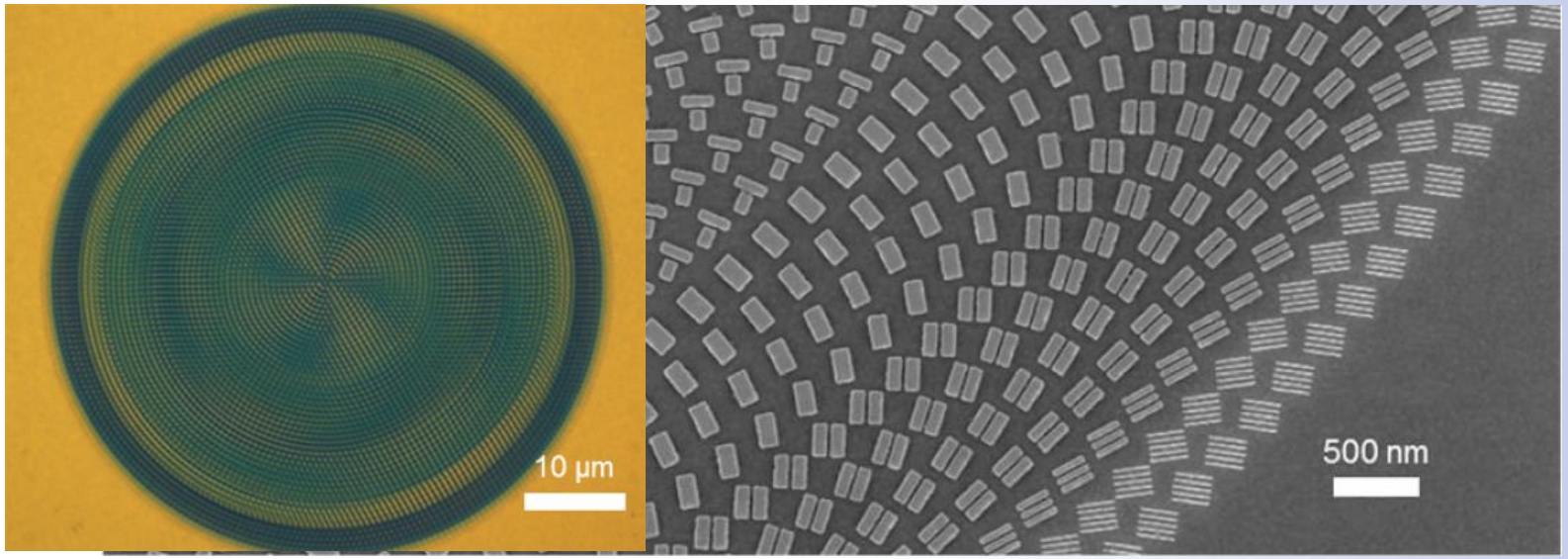
5 um **170**×

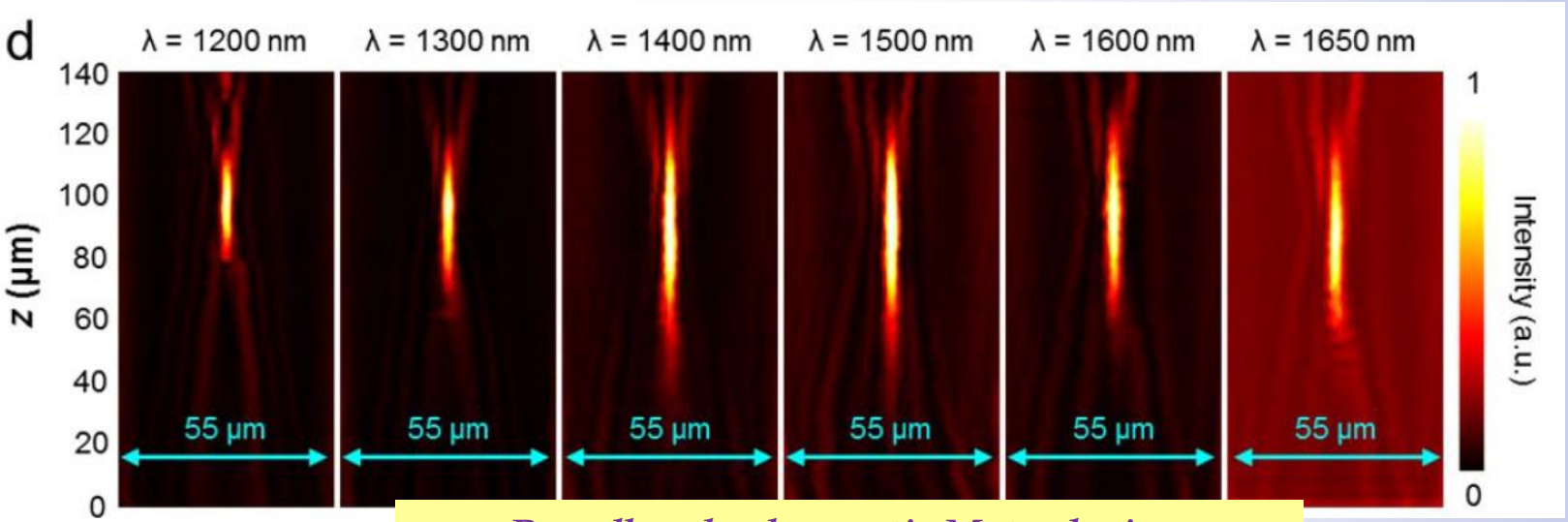




也许有一天，智能手机就可以当作显微镜，而隐形眼镜可以当作望远镜，那将是个怎样的世界？

Achromatic metalens





Broadband achromatic Meta-devices
Nature Communications (2017), accepted
Tao Li Group @ NJU

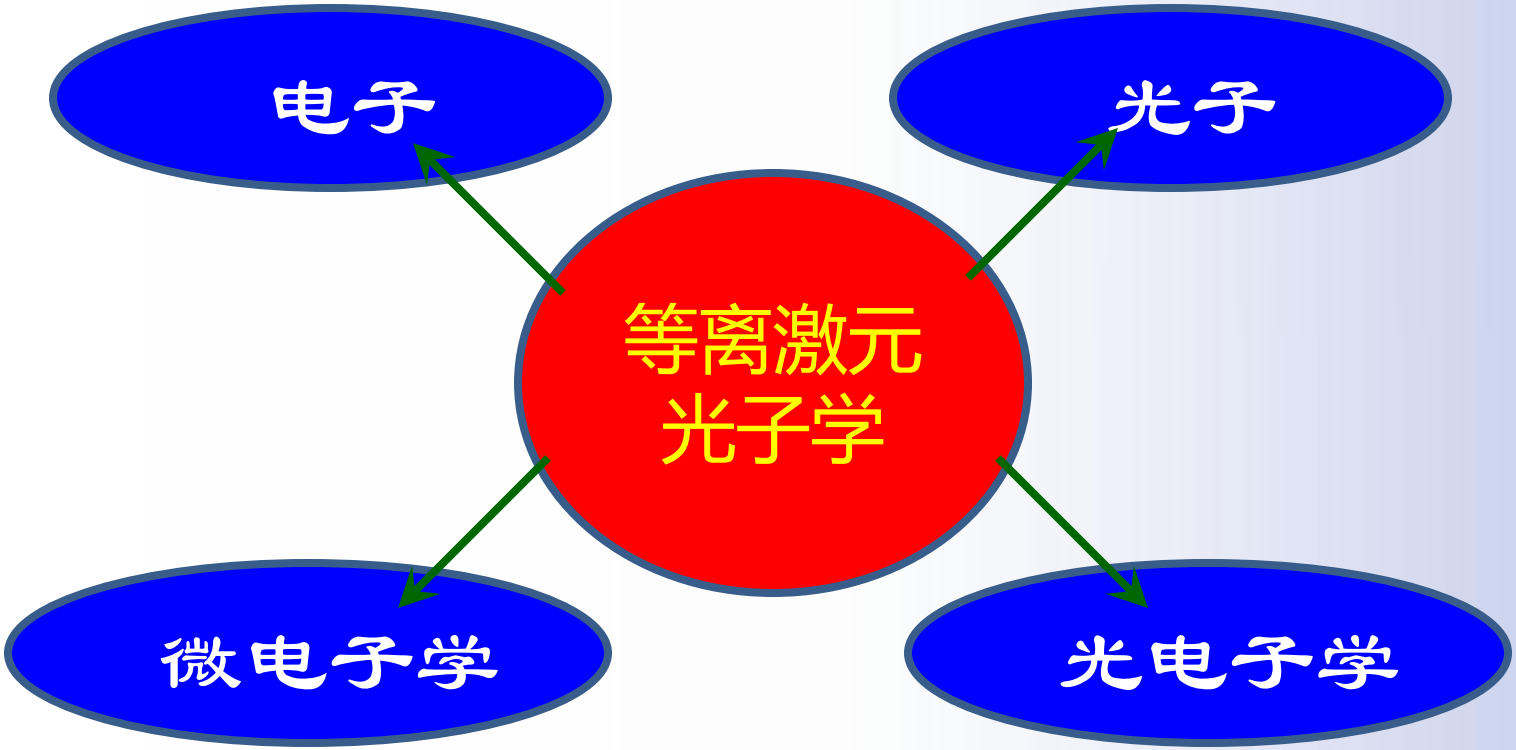
结论与展望

By using metallic nanostructures as a bridge between photonics and electronics, one plays to the strengths of the metallic nanostructures (concentrating fields and subwavelength guiding), the dielectric waveguides (low loss information transport) and the nanoscale electronic components (high speed information processing).

——Mark L. Brongersma

Dr. Tao Li taoli@nju.edu.cn

结论与展望



充满希望，充满机遇！

Dr. Tao Li taoli@nju.edu.cn

谢谢大家！

相关资料请登陆
http://dsl.nju.edu.cn/litao/res/

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