旋光特性在SP中的应用

——电动力学研习汇报

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OUTLINE

- 表面等离激元简介:LSP/SPP
- 旋光特性在LSP中的体现
- 旋光特性在SPP中的体现

表面等离激元
Surface Plasmon

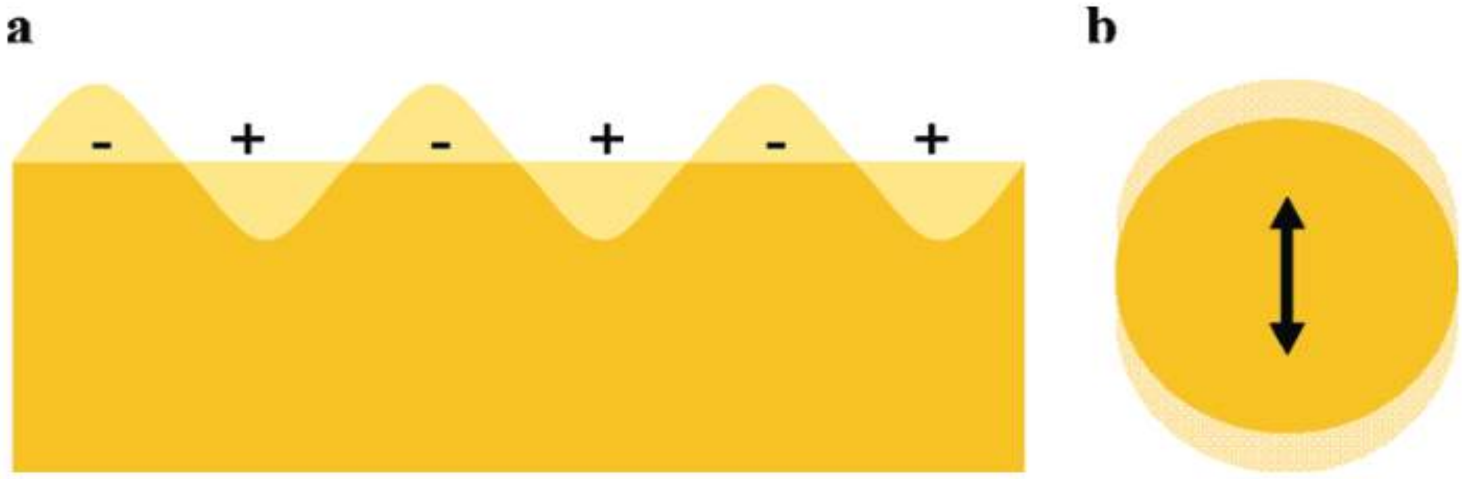
- SPP的基本原理
- LSP的基本原理
- 透射增强现象
- Plasmonic Metasurface

SP SP的历史

- 1902 Wood 金属光栅反射光出现明暗条纹（Wood异常）
- 1957 Ritchie 理论预测金属表面存在等离子体模式
- 1968 Otto, Kretschmann 实验上激发SP

Plasmon原理

- 等离子体振荡 Bulk Plasmon
- 表面等离(极化)激元 Surface Plasmon (Polaritons)
- 局域表面等离激元 Localized Surface Plasmon



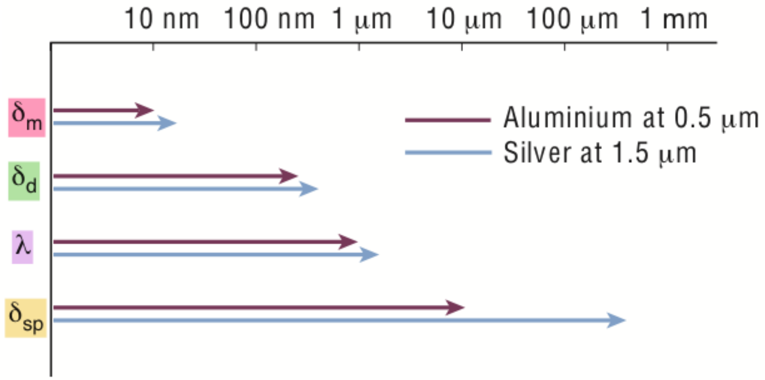
SP

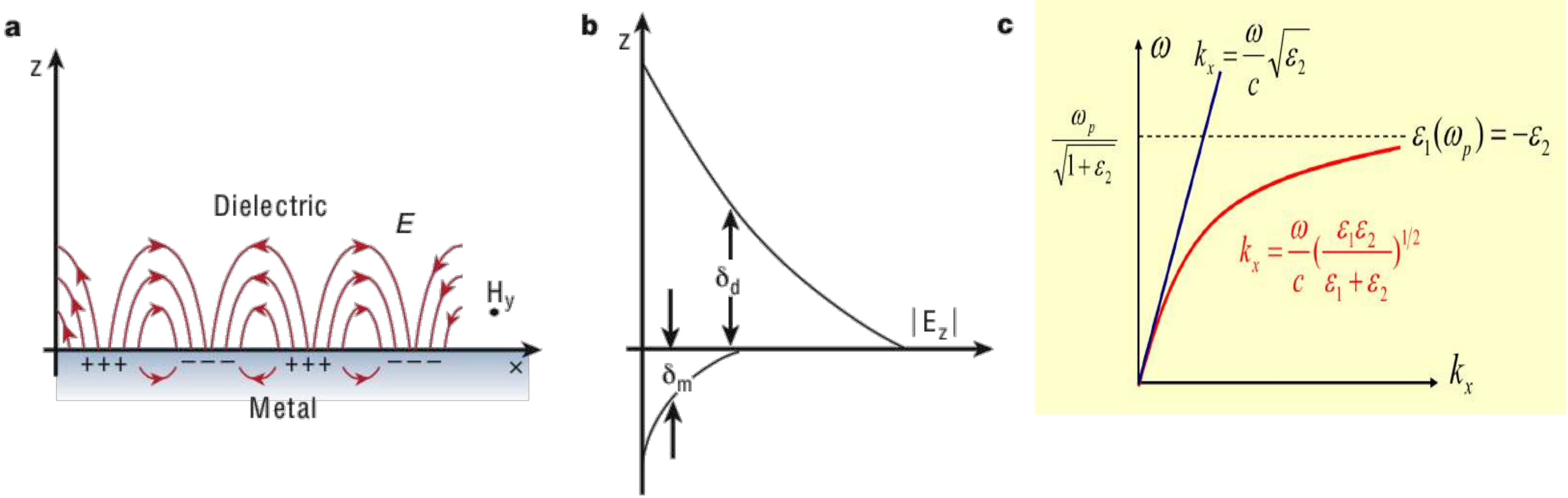
SPP基本原理：基本性质

$$k_{sp}=k_0\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}}+ik_0\left(\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}\right)^{3/2}\frac{\varepsilon'_m}{2(\varepsilon_m)^2}$$

$$k_{zj}=ik_0\sqrt{\frac{\varepsilon_j^{\,2}}{\varepsilon_1+\varepsilon_2}}$$

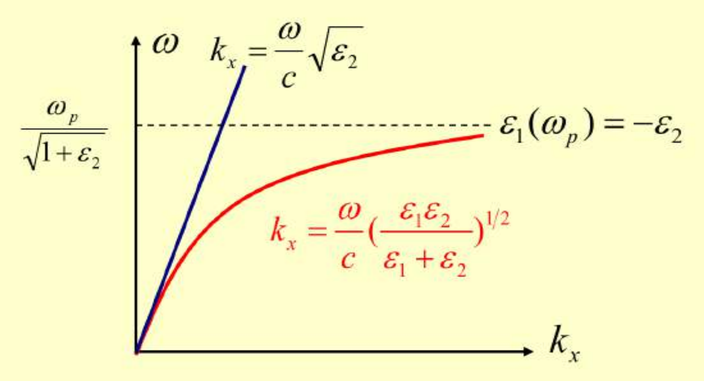
$$l_{sp}=\frac{2}{[\mathrm{Re}(k_{sp})]^3}\,\frac{[2\pi\,\mathrm{Re}(\varepsilon_m)]^2}{\lambda^2\,\mathrm{Im}(\varepsilon_m)}$$

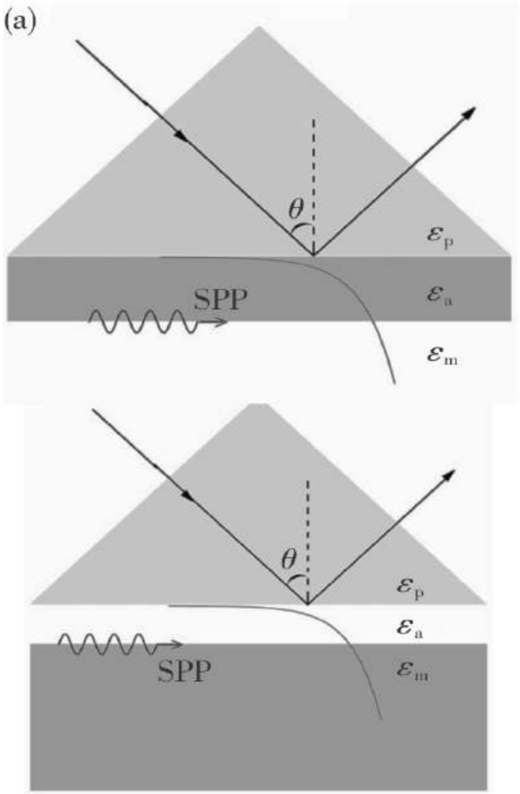


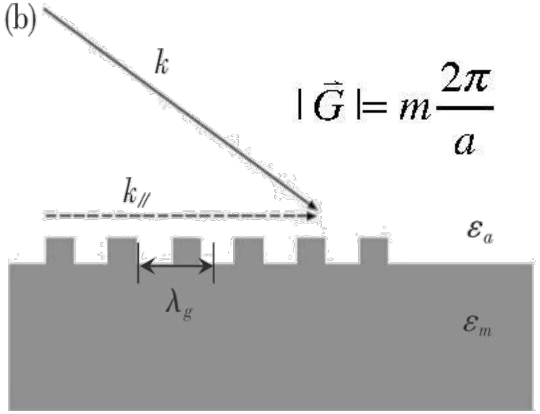


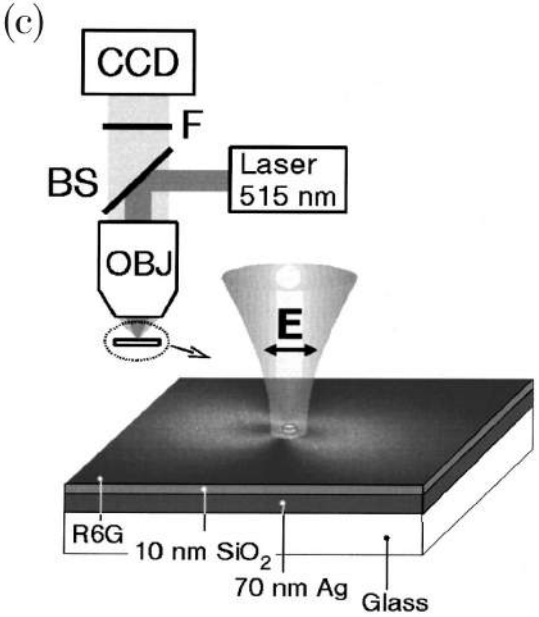
SPP基本原理：激发

a) 棱镜耦合：Kretschmann\Otto
b) 周期性处理：光栅结构
c) 几何缺陷：亚波长突起



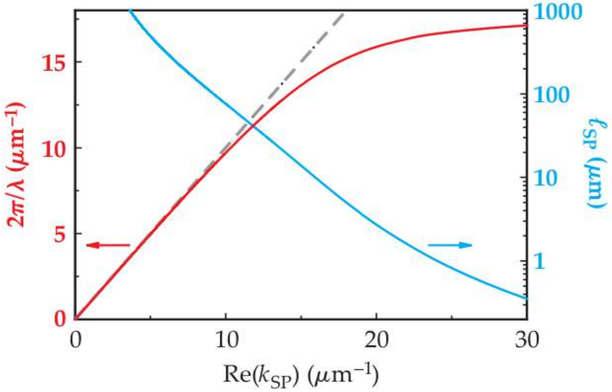




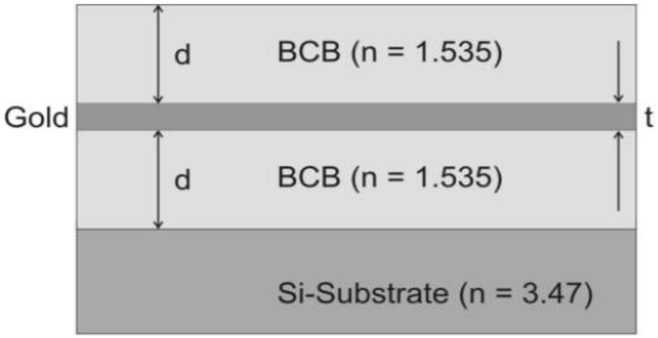


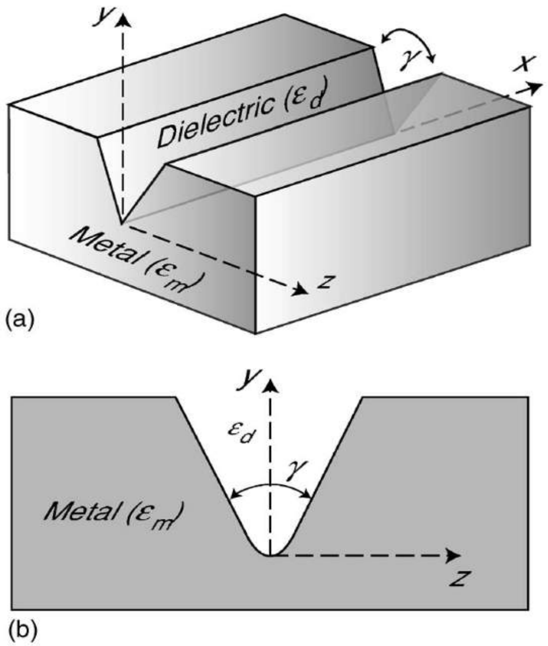
SPP基本原理：传播

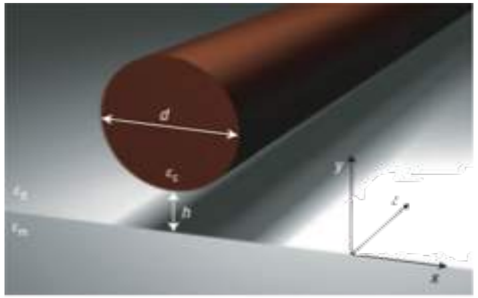
- 多层结构：DMD（LRSP）、MDM
- 脊/槽型结构：CPP、WPP
- 杂化结构：HPP

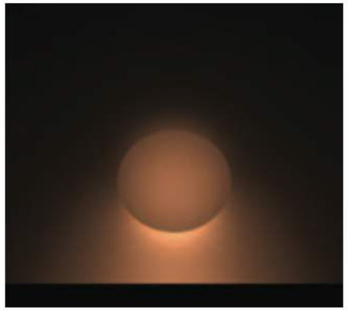


$$l_{sp} \propto [\mathrm{Re}(k_{sp})]^{-3}$$



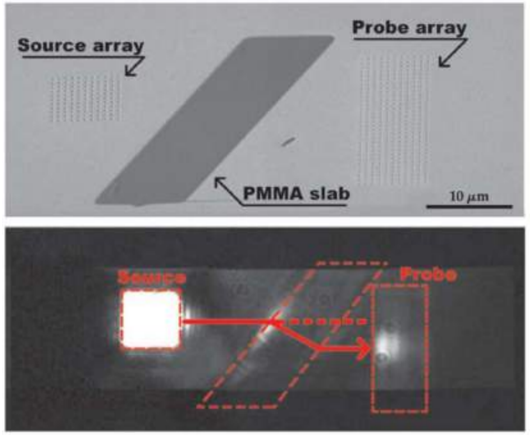


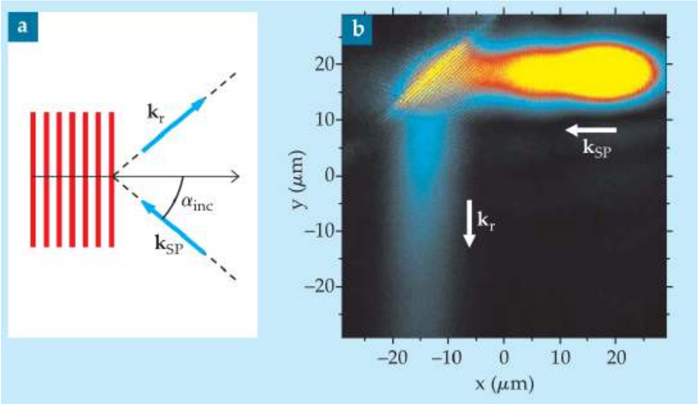


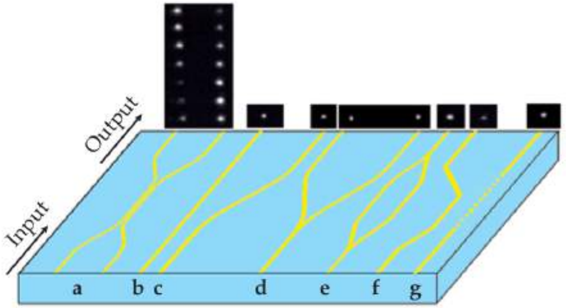


SPP基本原理：控制

- 被动元件
  - 折射元件
  - Bragg反射镜
  - 波导
- 主动元件
  - 电光元件
  - 热光元件
  - ……



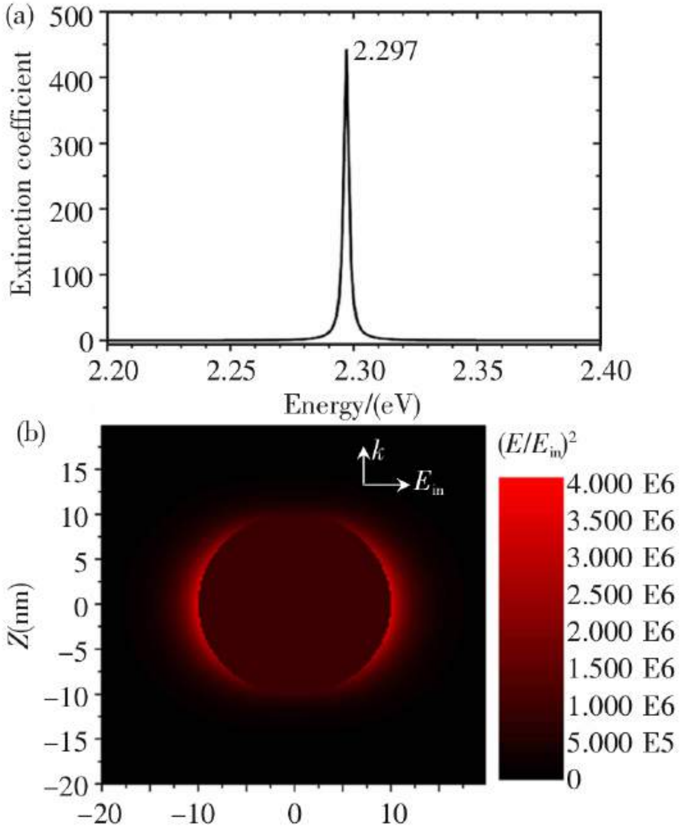




SP

LSP基本性质

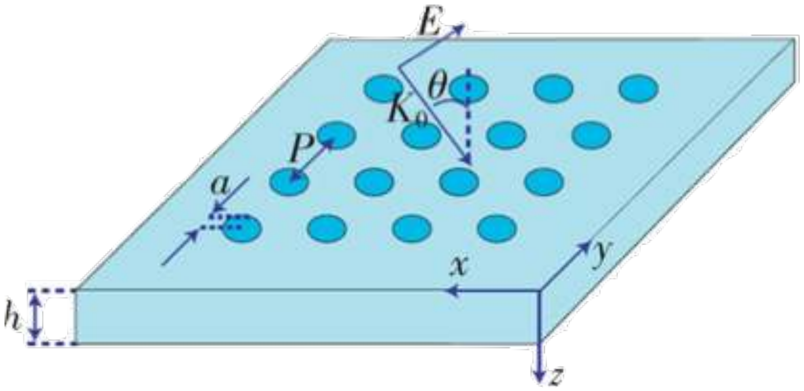
- 消光谱峰与局域介质折射率有关
- 局域范围内强烈的场增强

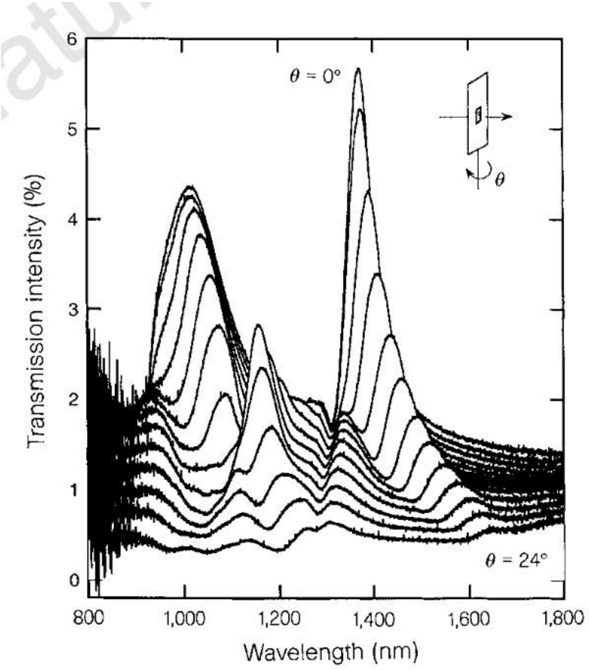


SP 透射增强现象（ EOT ）

- 1998 Ebbesen 金属膜中的透射现象（EOT）
- 透射波长的周期依赖关系 $\lambda_{max} = \frac{a_0}{\sqrt{i^2+j^2}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}}$
- 透射波长的角度依赖关系

→SPP起作用



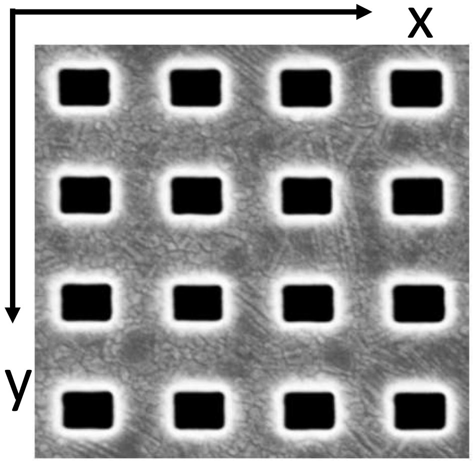


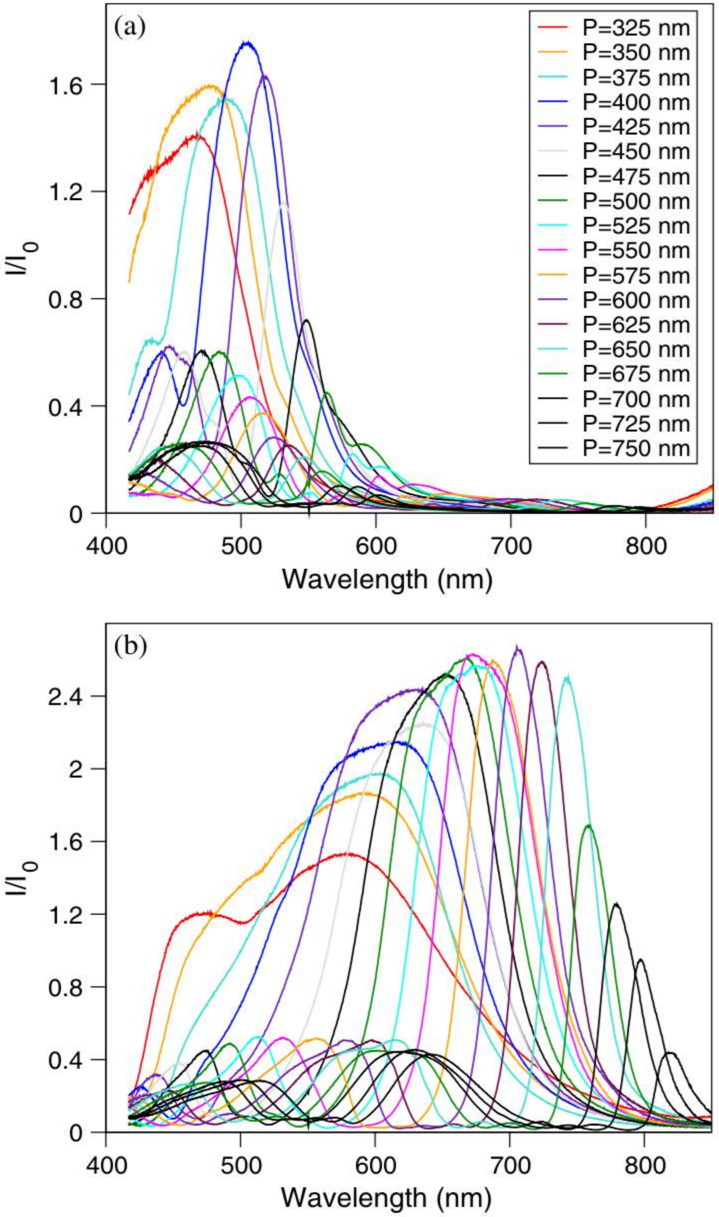
Ebbesen T W et al. Extraordinary optical transmission through sub-wavelength hole arrays[J]. Nature, 1998, 391(6668): 667-669

SP 透射增强现象（EOT）

- 孔形状引起**透射峰位置**和**形状**改变

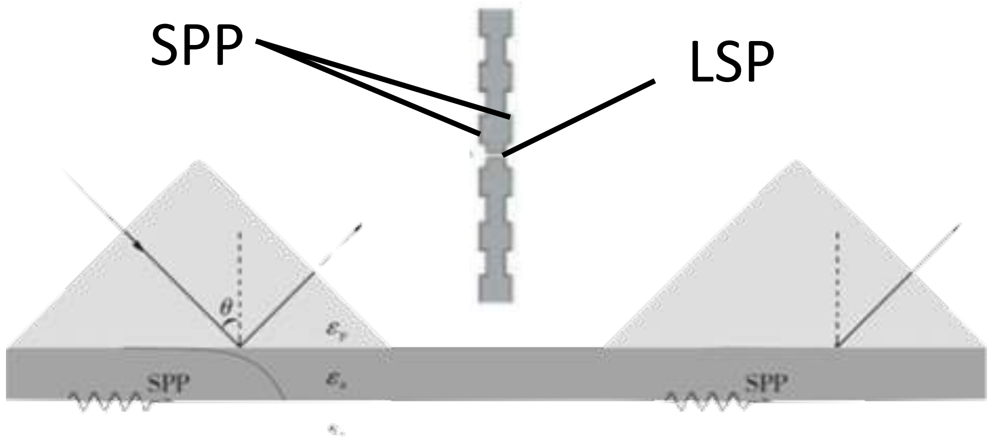
  →LSP起作用

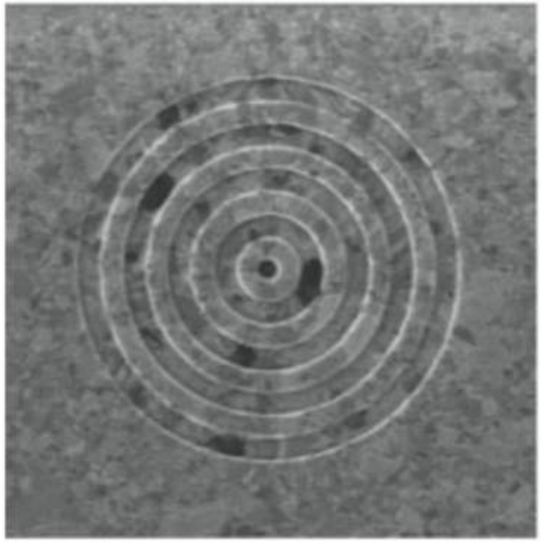


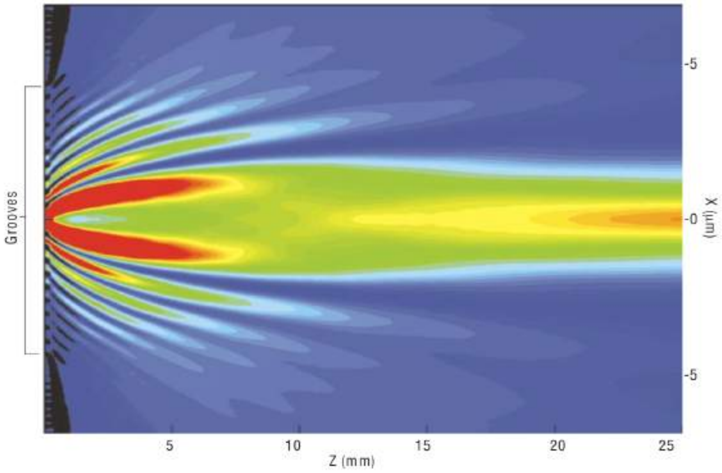


Degiron A et al. Journal of Optics A: Pure and Applied Optics, 2005, 7(2): S90.

SP 透射增强现象：从孔阵列到单孔







Lezec H J, et al. Beaming light from a subwavelength aperture[J]. Science, 2002, 297(5582): 820-822.

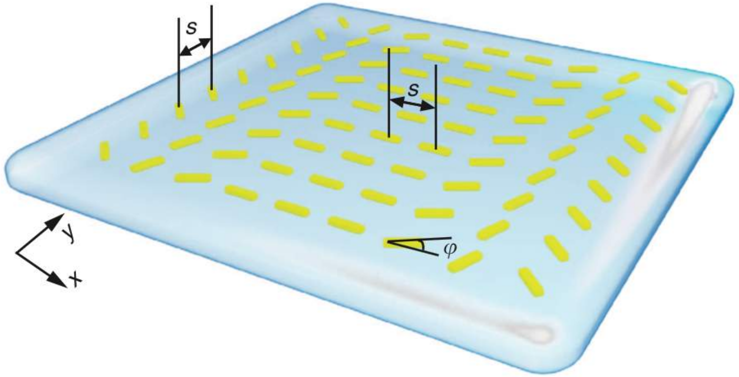
LSP中的旋光特性
Helicity in LSP

- 超构等离激元透镜
- 等离激元表面实现全息

RL

超构等离激元透镜 Plasmonic Lenses

- 透镜：重塑波前
- 传统透镜：相位连续改变
  - 改变透镜表面的形状
  - 改变透镜内部折射率分布
- 等离激元透镜：在薄层内不连续改变相位



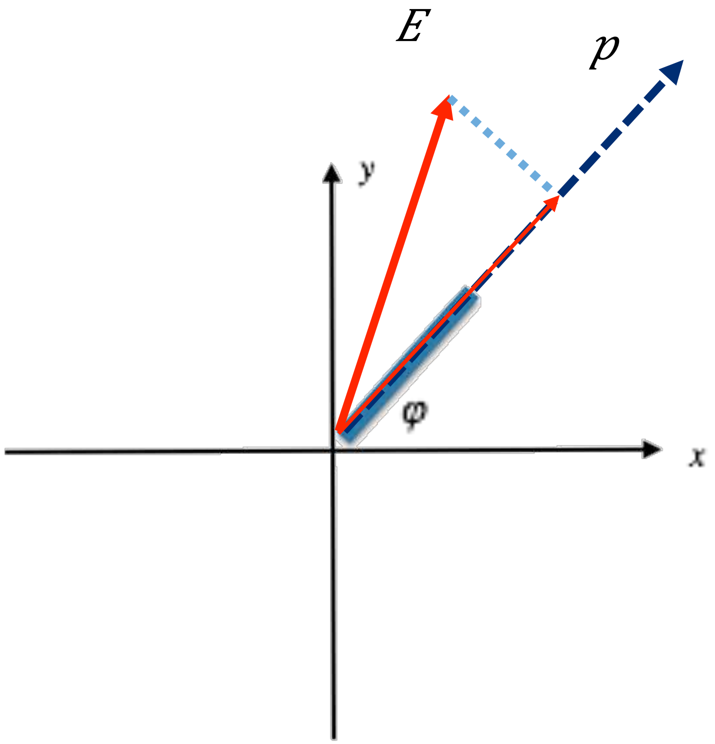
Chen X et al. Dual-polarity plasmonic metalens for visible light[J]. Nature communications, 2012, 3: 1198.

RL 超构等离激元透镜

- 光通过单个小金属棒

$$L \rightarrow L \,\&\, e^{i2\varphi} R$$

$$R \rightarrow R \,\&\, e^{-i2\varphi} L$$



Proof:

$$\begin{pmatrix} p_x \\ p_y \end{pmatrix} = \alpha_e \begin{pmatrix} \cos^2\varphi & \sin\varphi\cos\varphi \\ \sin\varphi\cos\varphi & \sin^2\varphi \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

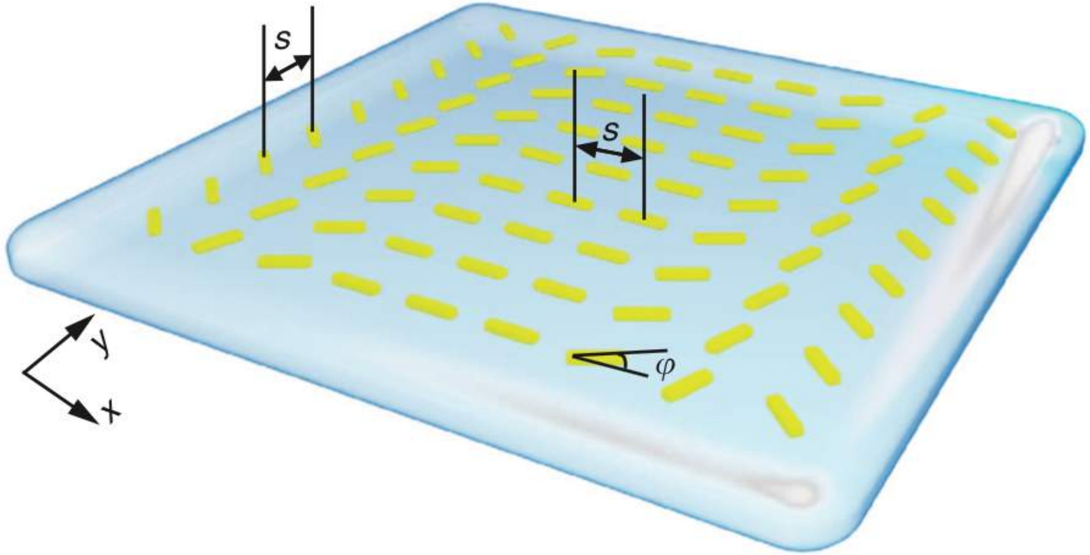
$$P_{L(R)} = \frac{1}{2}\alpha_e(e_x \pm ie_y) + \frac{1}{2}\alpha_e e^{\pm i2\varphi}(e_x \mp ie_y)$$

$$= \frac{1}{\sqrt{2}}\alpha_e(e_{L(R)} \pm e^{\pm i2} e_{R(L)})$$

Chen X et al. Dual-polarity plasmonic metalens for visible light[J]. Nature communications, 2012, 3: 1198.

超构等离激元透镜

- 排列金属棒 形成透镜

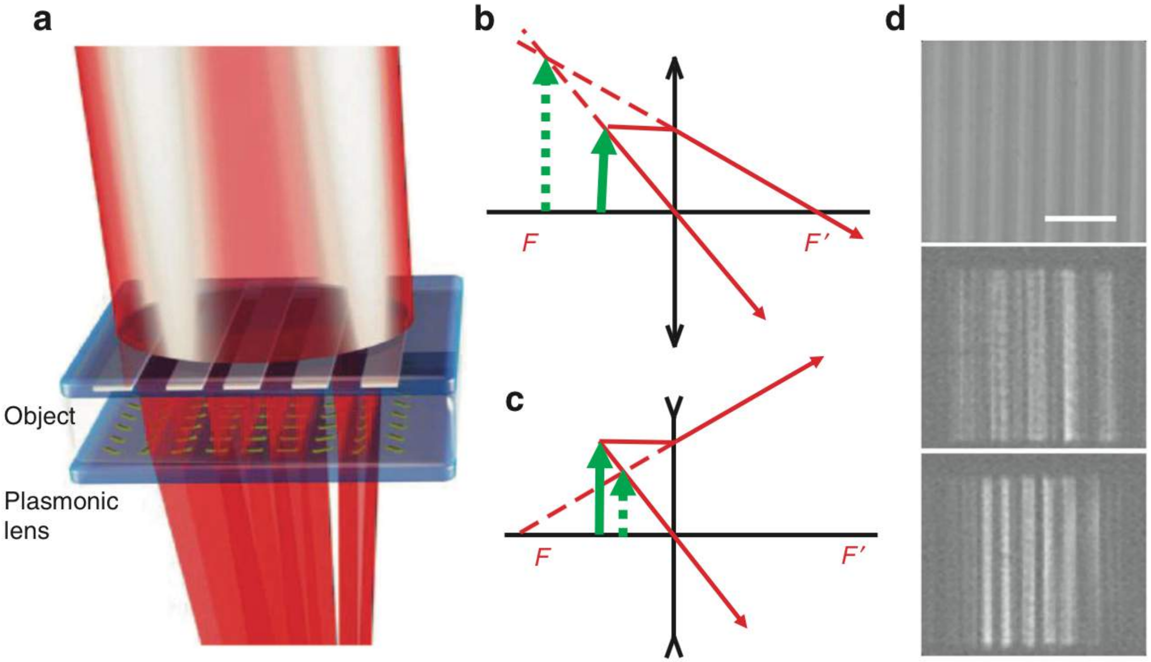


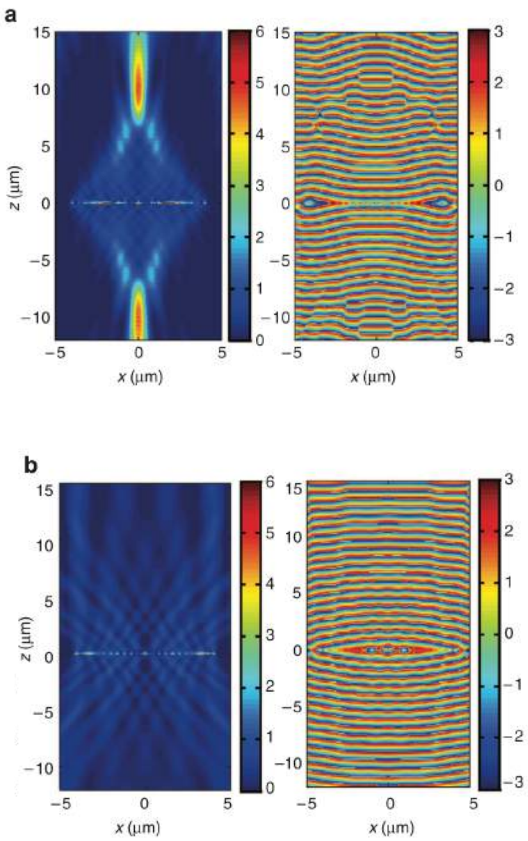
$$\varphi(x)=\pm 0.5k_0\left(\sqrt{f^2+x^2}-|f|\right)$$

Chen X et al. Dual-polarity plasmonic metalens for visible light[J]. Nature communications, 2012, 3: 1198.

超构等离激元透镜

- 实现透镜功能

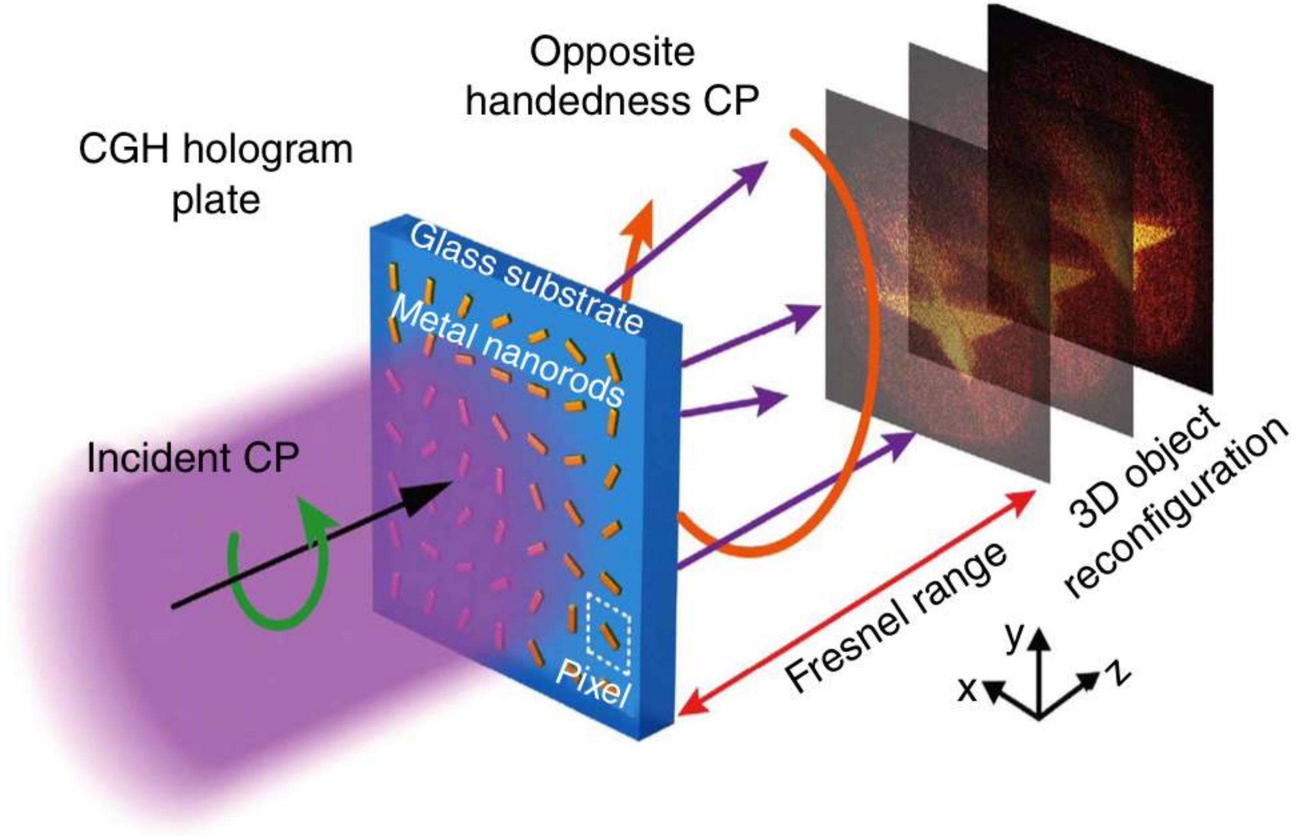




Chen X et al. Dual-polarity plasmonic metalens for visible light[J]. Nature communications, 2012, 3: 1198.

RL

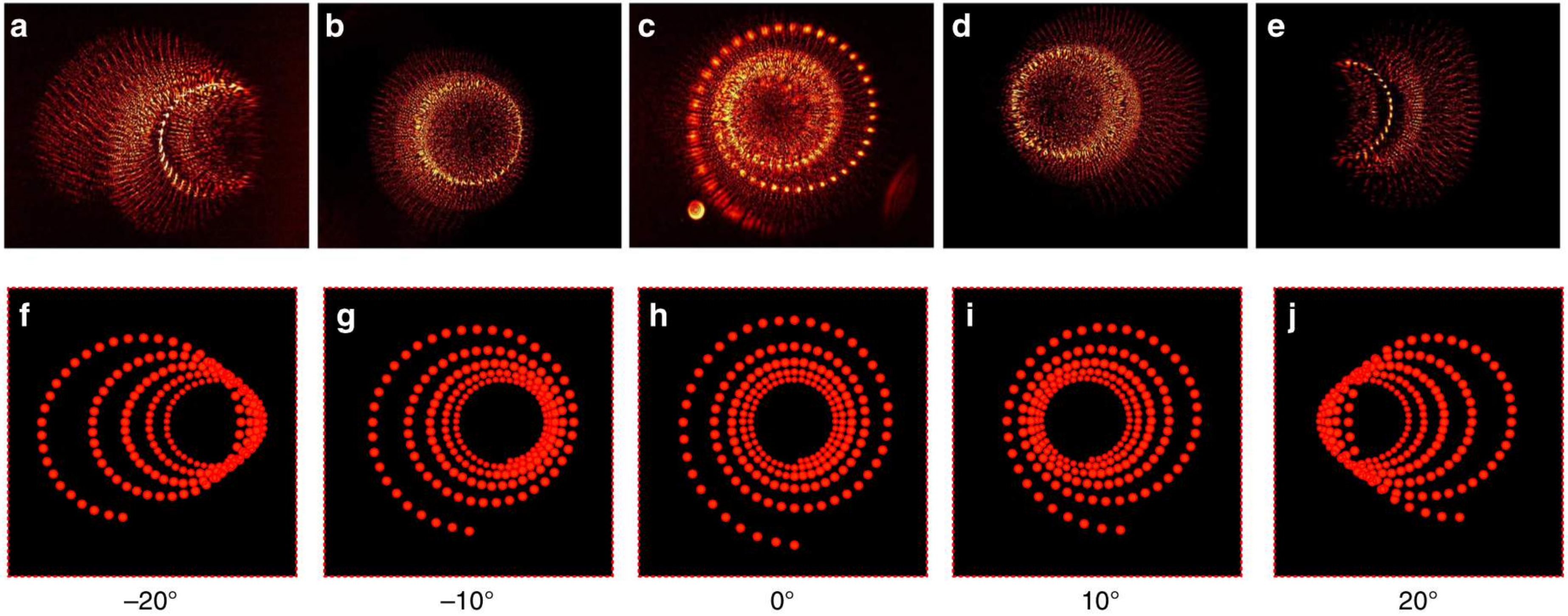
等离激元表面实现全息



Huang L et al. Three-dimensional optical holography using a plasmonic metasurface[J]. Nature communications, 2013, 4.

RL 等离激元表面实现全息

- 优势：像素尺寸更小，视场角度更宽 $\sin\theta = \frac{1}{2s}\lambda$



Huang L et al. Three-dimensional optical holography using a plasmonic metasurface[J]. Nature communications, 2013, 4.

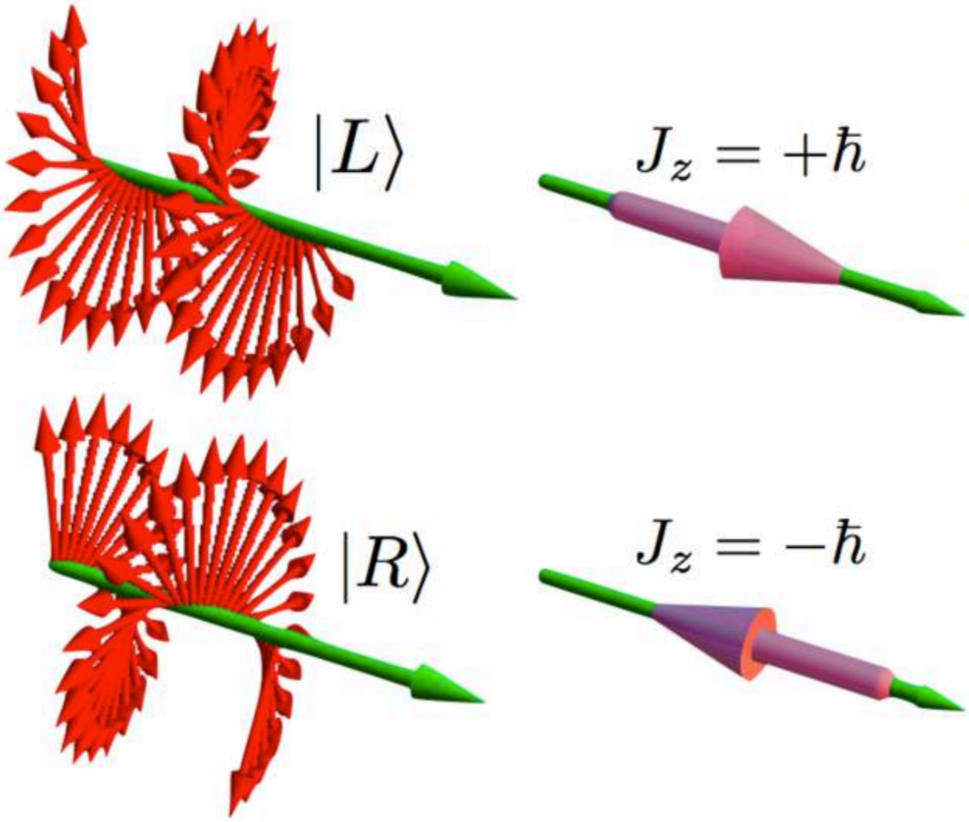
自旋-轨道相互作用

L-S Interaction

- 光的轨道角动量
- “几何相”与“动力学相”
- 自旋-轨道转化的规律

光的自旋、轨道角动量

光子自旋角动量>>光束的旋光性



$$|L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ i\\ 0\end{pmatrix}e^{i(kz-\omega t)}$$

$$|R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ -i\\ 0\end{pmatrix}e^{i(kz-\omega t)}$$

LS

光的自旋、轨道角动量

光子轨道角动量

>>光束的螺旋特性

对于近轴的圆光束：

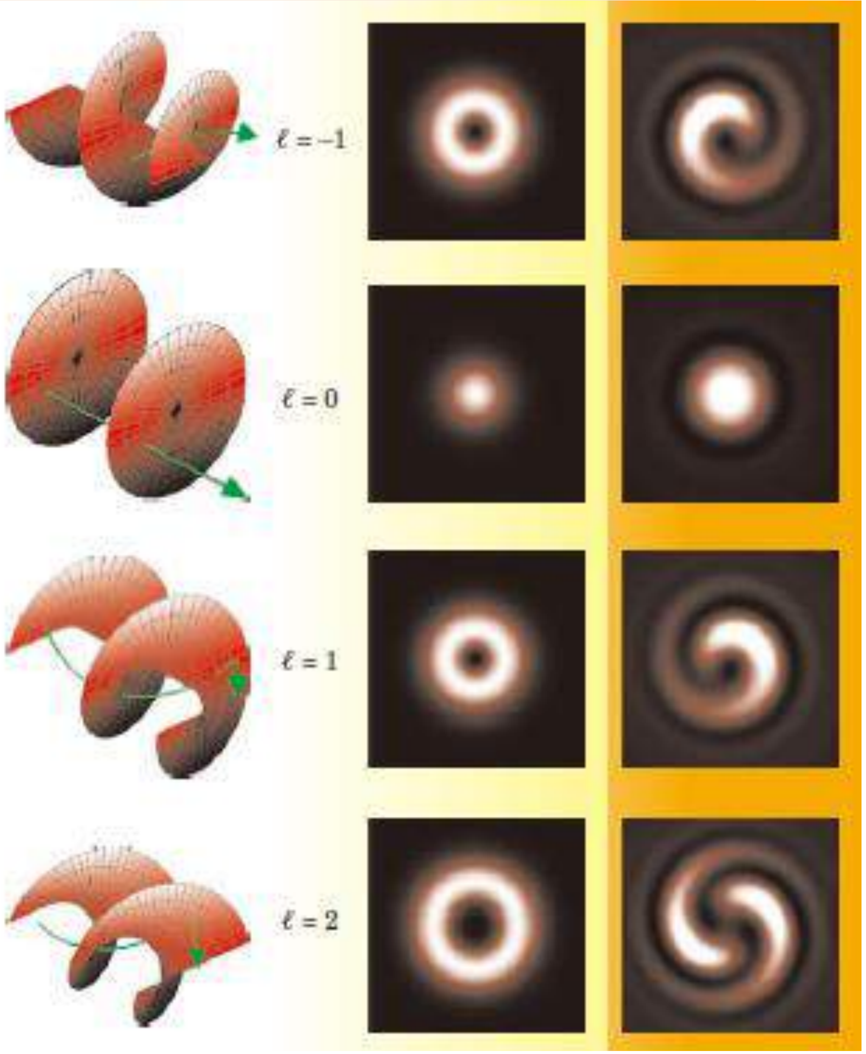
$J=L+S$

S: $\sigma{\downarrow}+$ $\sigma{\downarrow}-$

（各点偏振性质决定）

L: $e{\uparrow}il\phi$

（空间相因子决定）



Allen L et al. Physical Review A, 1992, 45(11): 8185.

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光的自旋、轨道角动量(补充)

- 电磁波的角动量密度 $\boxed{j=\epsilon_0\, r\times(E\times B)}$
- 做体积分，得： $J=\epsilon_0\int r\times(E\times B)\,d^3r$
- 对于近轴的圆光束，作分解：

$$J=\epsilon_0\int(E\times A)\,d^3r\ +\epsilon_0\sum_{i=x,y,z}\int E^i\,(r\times\nabla)\,A^i\,d^3r$$

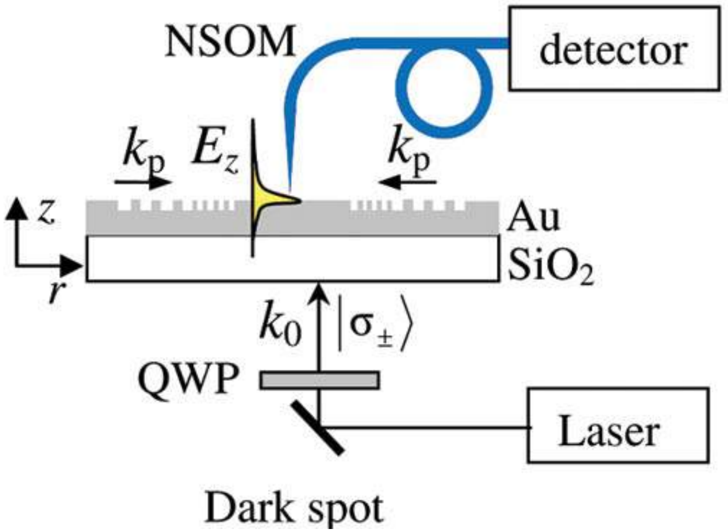
S: 表达式第一项

L: 表达式第二项

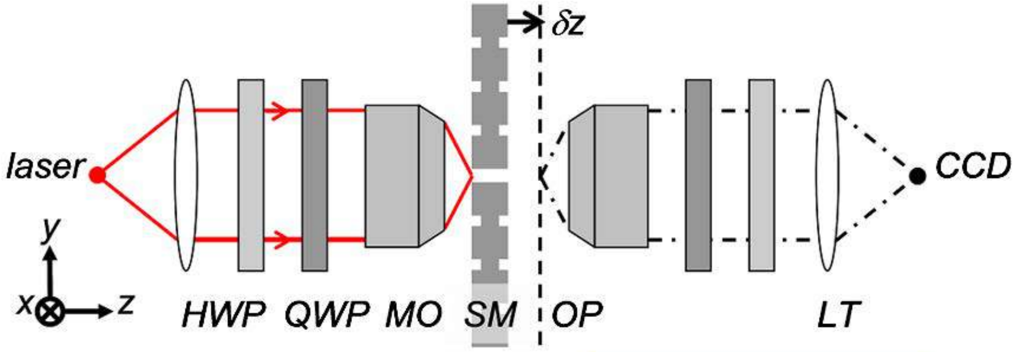
$$J=L+S$$

LS 圆环光栅SPP:耦合，传播与解耦合

- 单面刻光栅：
  - 近场信号探测



- 双面刻光栅：
  - 远场信号
  - SPP→LSP→SPP



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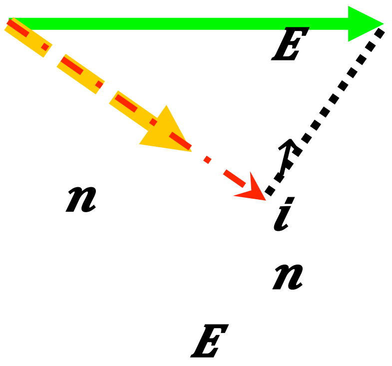
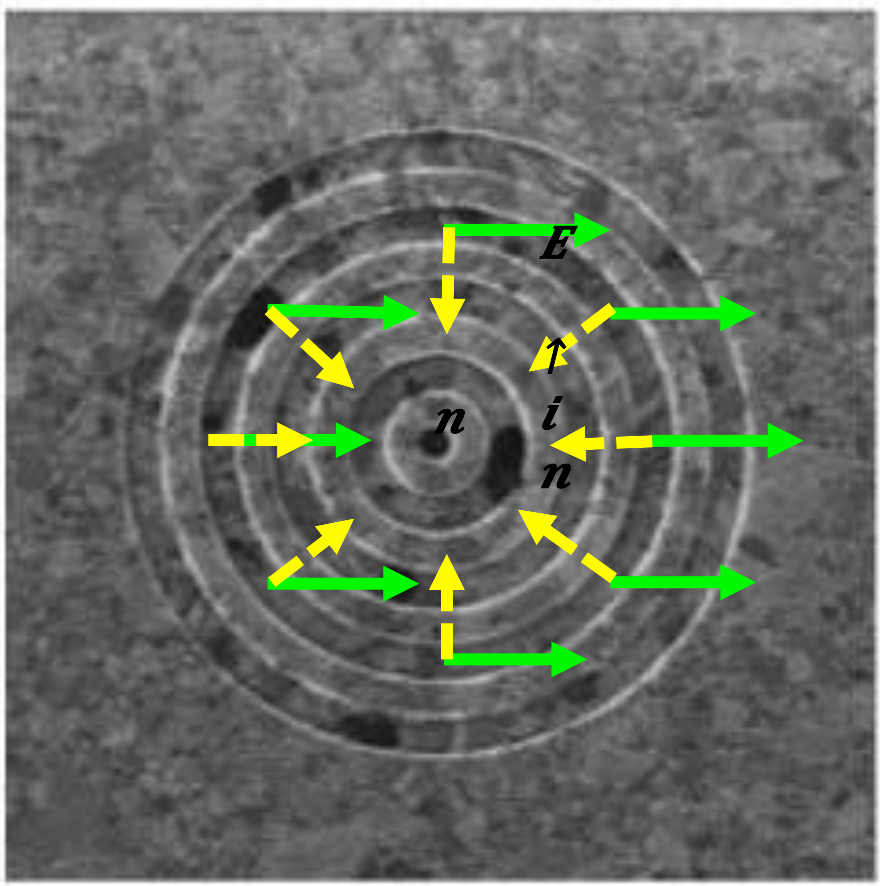
SPP光栅耦合：投影特性

SPP的激发：

场强E^{in} 沿光栅法向投影



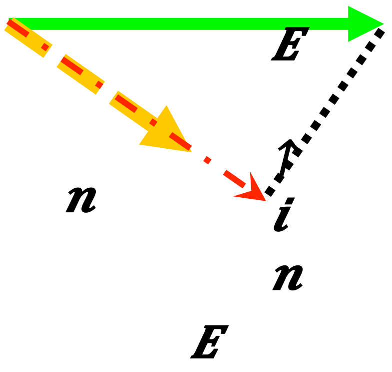
$\vec{E}^{SP} \sim (\vec{E}^{in} \cdot \vec{n})\vec{n}$



SPP光栅耦合：投影特性

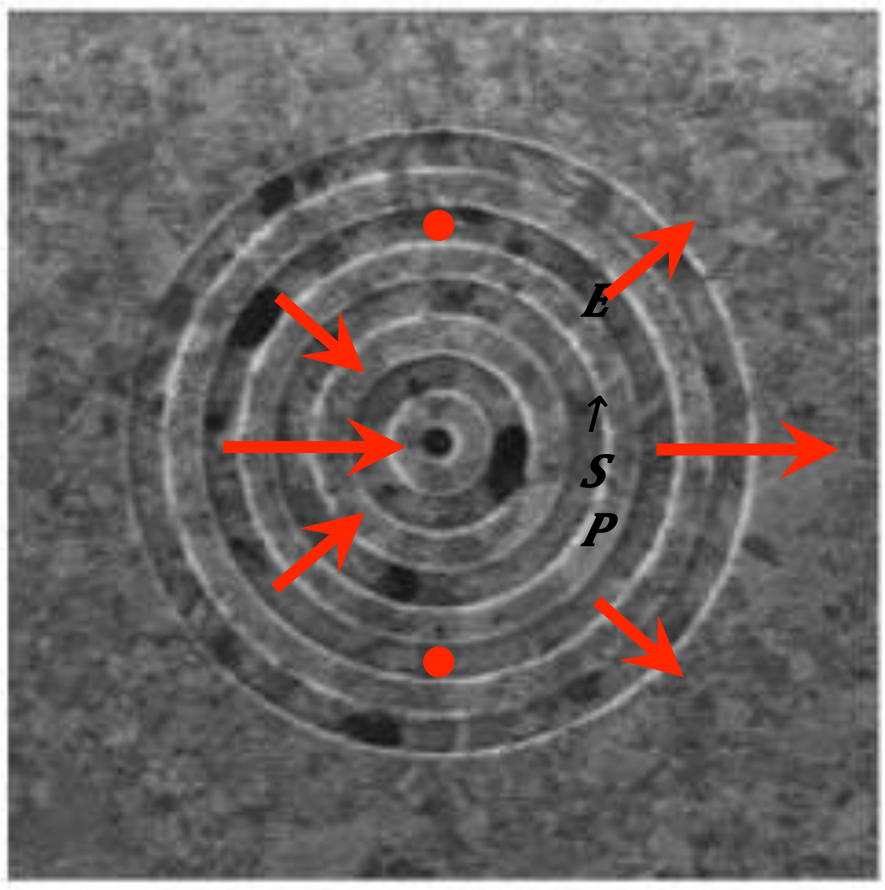
SPP的激发：

场强E^{in} 沿光栅法向投影



E ↑SP ~ (E ↑in ·n)n

↑
S
P



SPP光栅耦合：投影特性

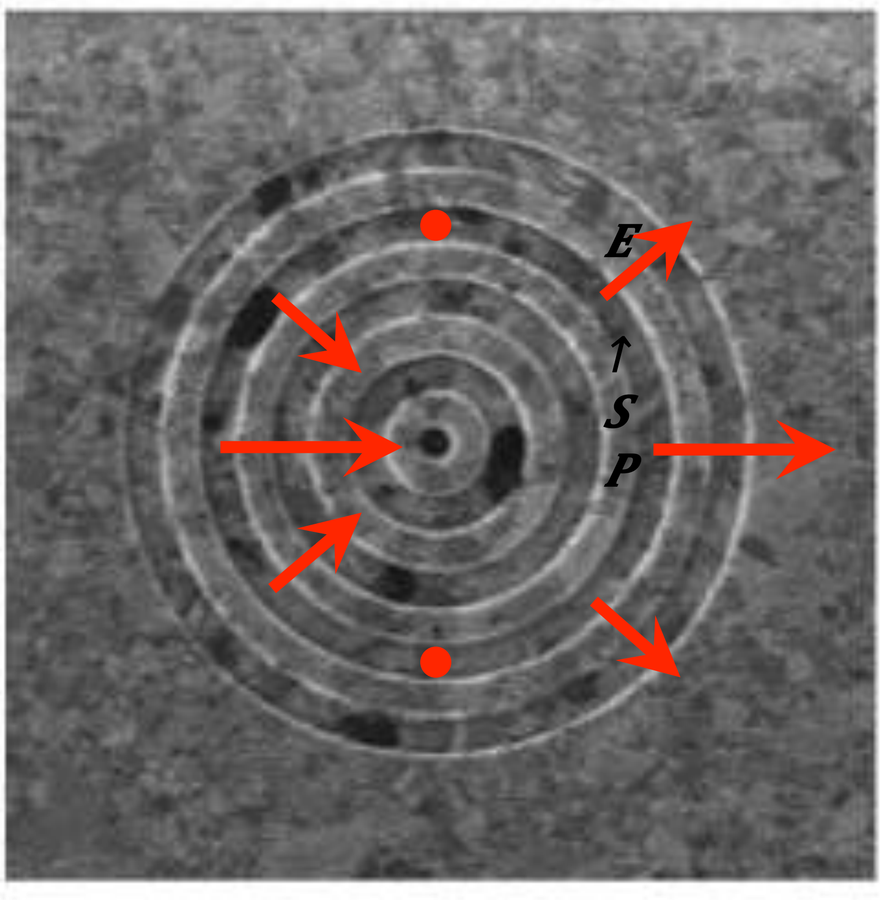
左/右旋光：

E^{in}的方向周期性变化

→E^{SP}的方向随之变化

$E^{SP}(t) \sim (E^{in}(t)\cdot n)n$

→向内传播的E^{SP}方向时刻改变



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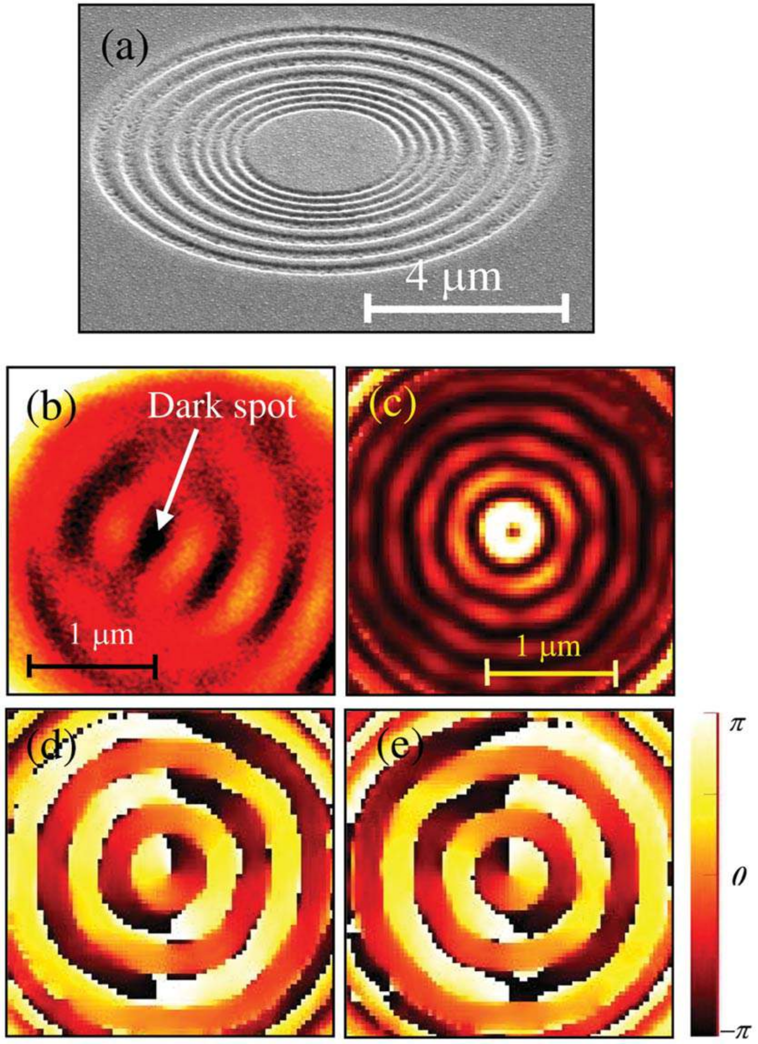
“几何相”的产生

SPP耦合场E^{SP}的旋转>>相位的积累效应



左/右旋光射入>>激发轨道角动量光

$\sigma=\pm1 \rightarrow\perp l=\pm1$

自旋到轨道的转化

Hasman et al. PRL., 2008, 101(4): 043903.

LS

非圆环光栅：旋转对称破缺

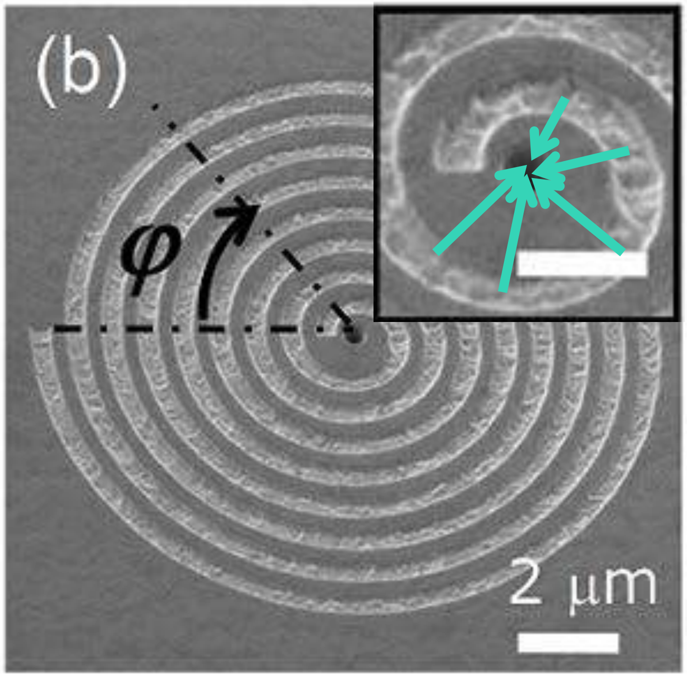
需要更高的轨道角动量 l？

改变光栅的形状！

“阿基米德螺线”光栅

$\rho = a + b\phi$

- 不同角度：到达圆孔传输距离不同>>不同相位差
- 相同角度：λ整数倍距离差，到达圆孔时积累相同相位差



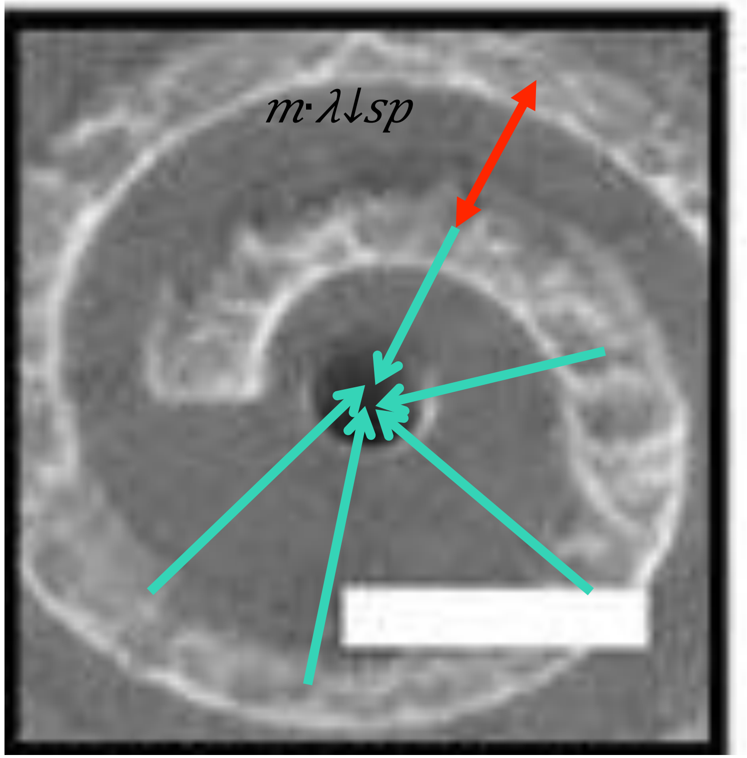
“动力学相”的产生

- 不同角度>>不同相位差
- 相同角度>>相同相位差

E^{SP}的路径差
>>产生径向偏差

$$\rho = m\ \phi\lambda{\downarrow}sp\ /2\pi\ \rho$$

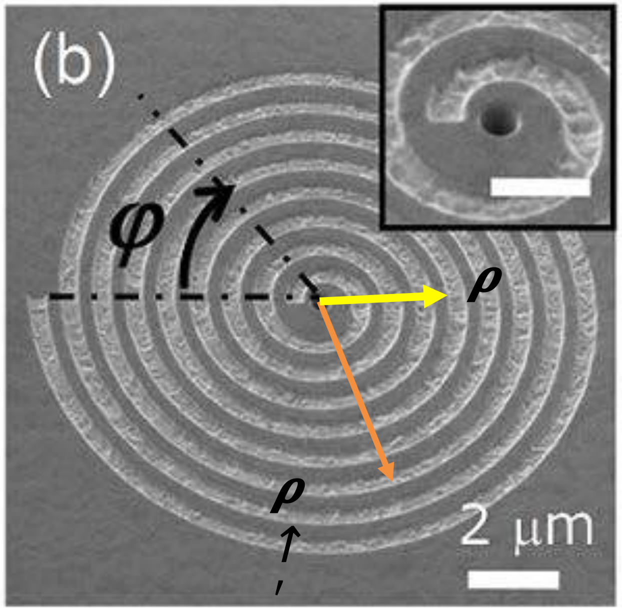
整数m:光栅倾斜程度
绕一圈相位变化2π*m



SPP传播的“传播子”理论

- 光栅耦合->表面点光源发光
- 惠更斯-菲涅尔原理：

  点源影响叠加
- 远场近似：
  - 考虑到点源离中心较远，逐圈考虑光栅的激发
  - 法向近似沿半径ρ方向



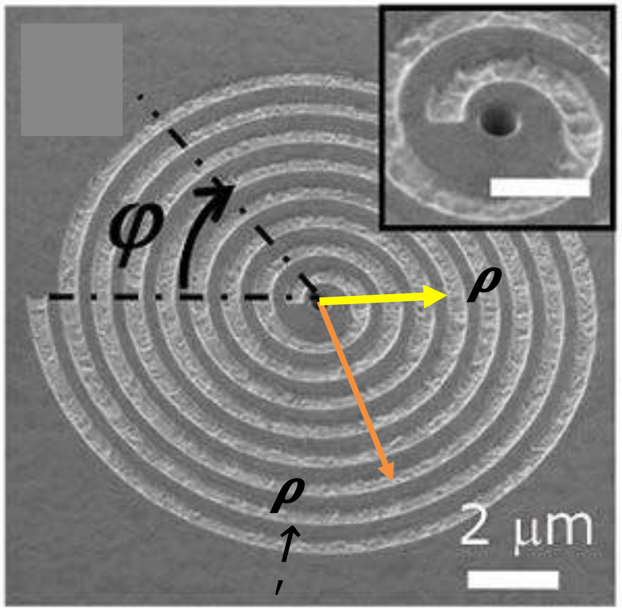
Ebbesen et al. PRL, 2013, 110(20): 203906.

SPP传播的“传播子”理论

光栅耦合：点源影响函数

$E^{sp}(\rho)\sim\delta(\rho-\rho')*\{G(\rho,\rho')\,[n\otimes n]\cdot E^{in}(\rho')\}$

- 格林函数 $G(\rho,\rho')=e^{ik_{sp}(\rho-\rho')}/|\rho-$
（柱面波形式）
- 光栅法向 $n=\kappa^{-1}\,d^2\rho/ds^2$

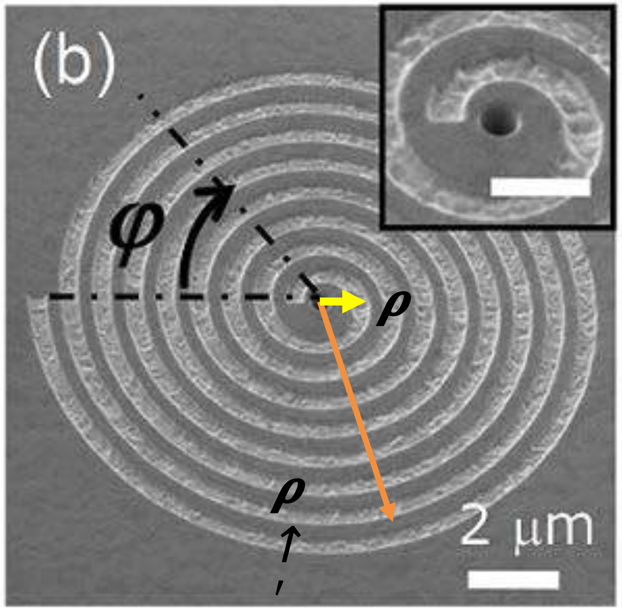


Ebbesen et al. PRL, 2013, 110(20): 203906.

SPP传播的“传播子”理论

远场近似 ($\rho \ll \rho'$ 时)

- 光栅法向 $n \approx -\rho$
- 分圈考虑光栅（共n圈）
    - $\rho' = \rho'(n,\phi)$
    - $\delta(\rho-\rho') = \delta(\rho-\rho'_n)$
    - n:离散求和　ϕ:环路积分



$$E^{sp}(\rho) \sim \delta(\rho-\rho') * \{G(\rho,\rho')\,[n \otimes n] \cdot E^{in}(\rho')\}$$

⬇

$$E^{sp}(\rho_0,\phi_0) \simeq \sum_n \sqrt{n\lambda_{sp}}\; f(n\lambda_{sp}) \int_0^{2\pi} d\phi\; e^{im\phi}\, e^{-ik_{sp}\rho_0 \cos(\phi-\phi_0)}$$

SPP传播的“传播子”理论

$$E^{sp}(\rho_0,\phi_0)\simeq \sum_n \sqrt{n\lambda_{sp}}\; f(n\lambda_{sp})\int_0^{2\pi} d\phi\, e^{im\phi}\, e^{-ik_{sp}\rho_0\cos(\phi-\phi_0)}$$

- 耦合矩阵:
  - $E^{SP}=C(m_{in})\cdot E^{in}$
  - $C(m_{in})=e^{im_{in}\phi_0}\int_0^{2\pi} d\phi\, e^{im_{in}\phi}\, e^{-ik_{sp}\rho_0\cos\phi}\quad \rho\,\rho$
- 解耦合:逆过程

  \>>解耦合矩阵：$C(m_{in})$求厄米共轭$C^{+}(m_{out})$
- 转换矩阵：
  - $T=C^{+}(m_{out})C(m_{in})$

LS

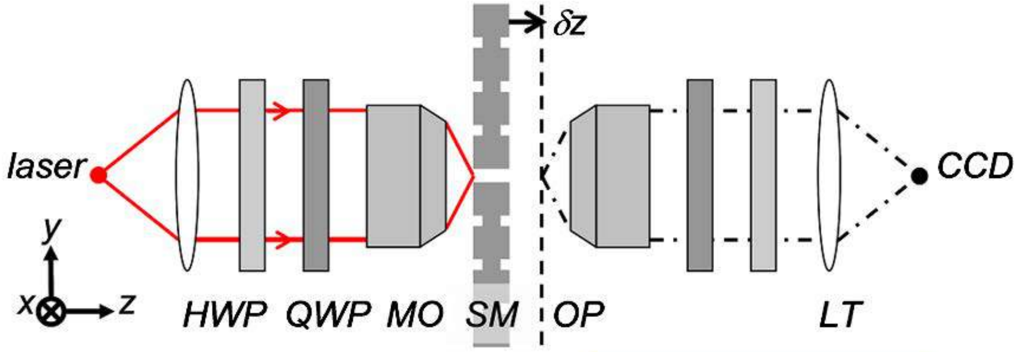
SPP传播的“传播子”理论

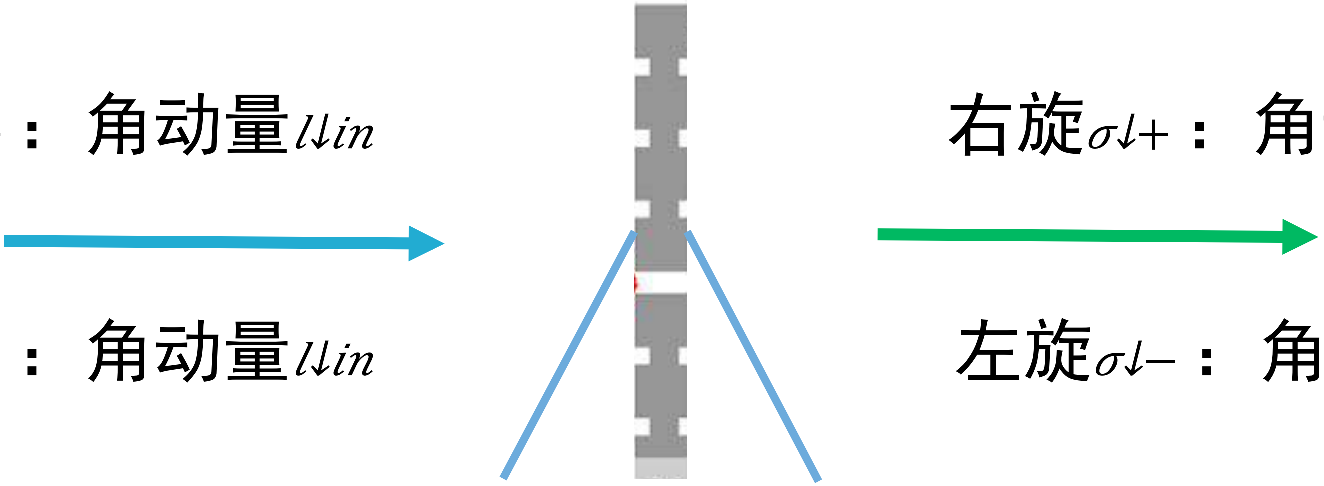
- 转换矩阵：
    - $T = C^{+}(m_{out})C(m_{in})$

- 计算结果：
    - $T \propto e^{i(m_{in}-m_{out})\phi}\begin{pmatrix} t_{++} & t_{\pm} e^{-2i\phi} \\ t_{\mp} e^{2i\phi} & t_{--} \end{pmatrix}$

    - $t_{++}(r) = J_{m_{out}-1}(k_{sp}\rho)\, J_{m_{in}-1}(k_{sp}\rho_h)$
    - $t_{\pm}(r) = -J_{m_{out}-1}(k_{sp}\rho)\, J_{m_{in}+1}(k_{sp}\rho_h)$
    - $t_{\mp}(r) = -J_{m_{out}+1}(k_{sp}\rho)\, J_{m_{in}-1}(k_{sp}\rho_h)$
    - $t_{--}(r) = J_{m_{out}+1}(k_{sp}\rho)\, J_{m_{in}+1}(k_{sp}\rho_h)$

远场光的现象总结





右旋$\sigma\downarrow+$： 角动量$l\downarrow in$

或

左旋$\sigma\downarrow-$： 角动量$l\downarrow in$

右旋$\sigma\downarrow+$： 角动量$l\downarrow+$

左旋$\sigma\downarrow-$： 角动量$l\downarrow-$

螺旋数$m\downarrow in$　螺旋数$m\downarrow out$

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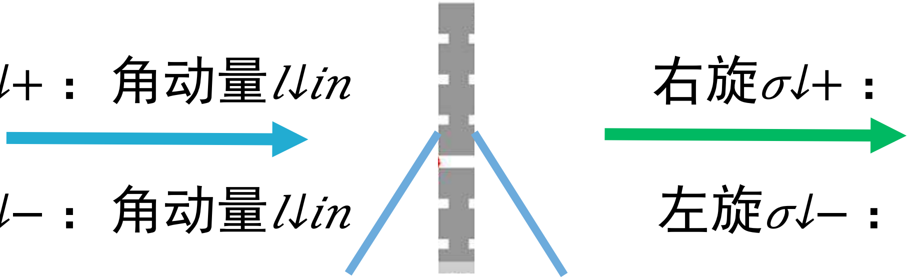
远场光的现象总结



右旋σ_+：角动量l_{in}

或

左旋σ_-：角动量l_{in}

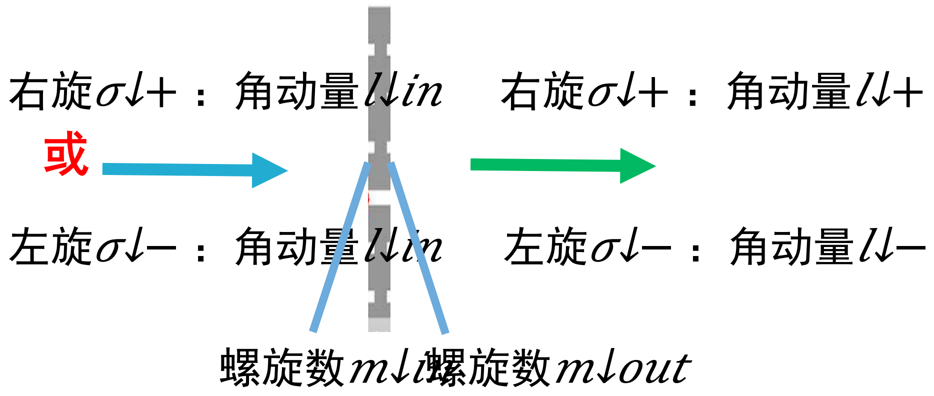
螺旋数m_{in}　螺旋数m_{out}

右旋σ_+：角动量l_+

左旋σ_-：角动量l_-

	出射右旋分量**角动量**l_+	出射左旋分量**角动量**l_-
入射l_{in}：右旋σ_+	$l_{in}+m_{in}-m_{out}$	$l_{in}+m_{in}-m_{out}-2$
入射l_{in}：左旋σ_-	$l_{in}+m_{in}-m_{out}+2$	$l_{in}+m_{in}-m_{out}$

LS 远场光的现象总结



右旋$\sigma\downarrow+$ ： 角动量$l\downarrow in$

或

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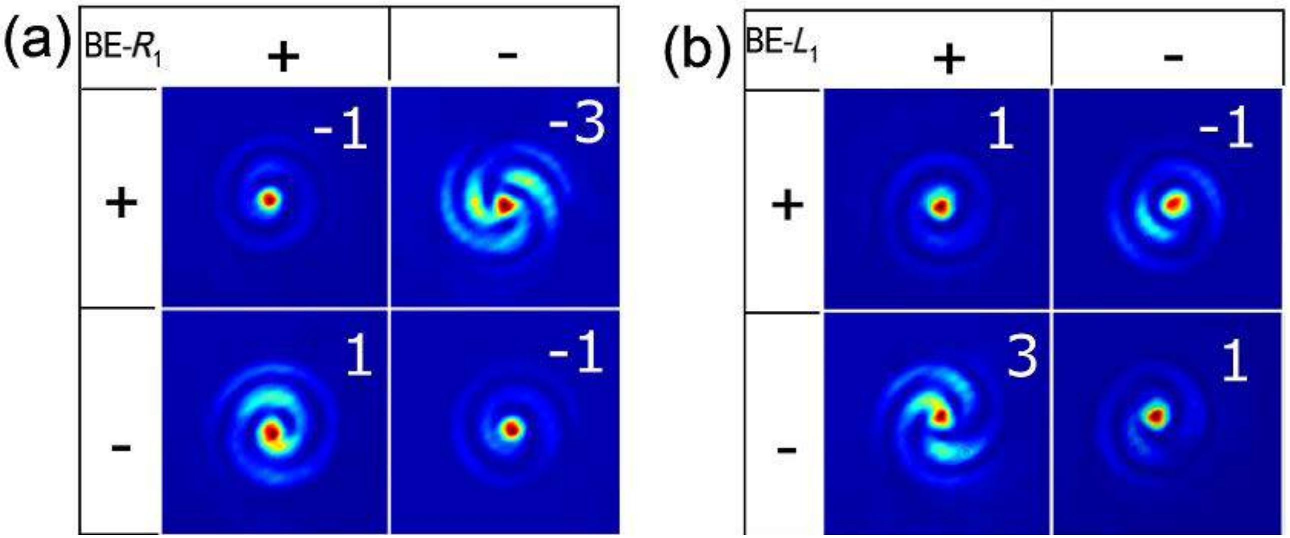
右旋$\sigma\downarrow+$ ： 角动量$l\downarrow+$

左旋$\sigma\downarrow-$ ： 角动量$l\downarrow-$

螺旋数$m\downarrow in$

螺旋数$m\downarrow out$

	出射右旋分量角动量$l\downarrow+$	出射左旋分量角动量$l\downarrow-$
入射$l\downarrow in$：右旋$\sigma\downarrow+$	$l\downarrow in+m\downarrow in-m\downarrow out$	$l\downarrow in+m\downarrow in-m\downarrow out-2$
入射$l\downarrow in$：左旋$\sigma\downarrow-$	$l\downarrow in+m\downarrow in-m\downarrow out+2$	$l\downarrow in+m\downarrow in-m\downarrow out$



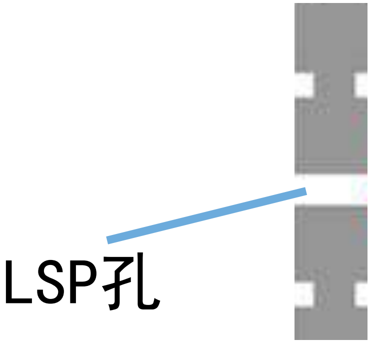
BE: m=0

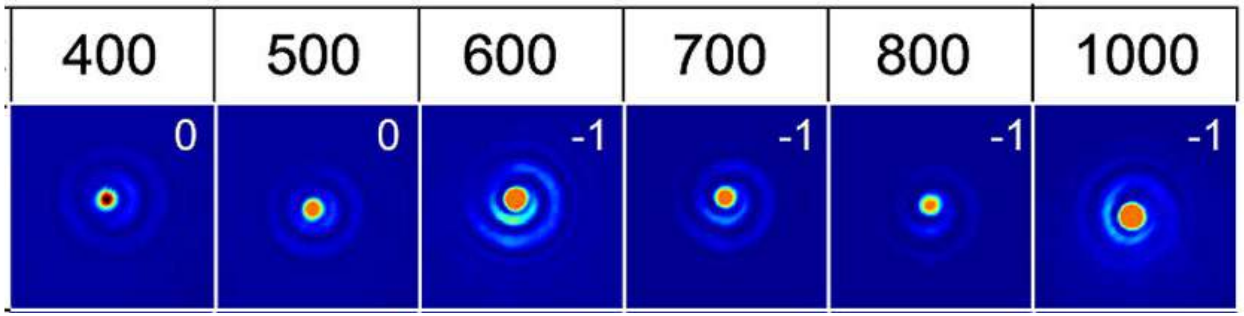
R_1: m=1

L_1: m=-1

一个细节：LSP的截止模式

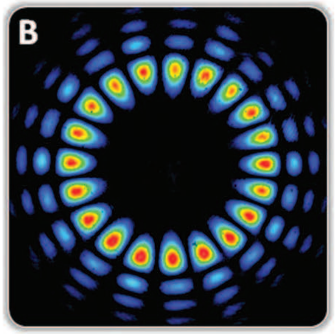
- 螺旋光（$l\neq0$）：
  - 环绕经过LSP孔
- LSP宽度限制:
  - 螺旋光存在截止孔径

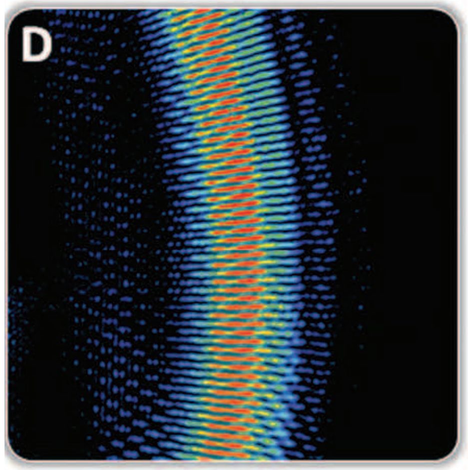


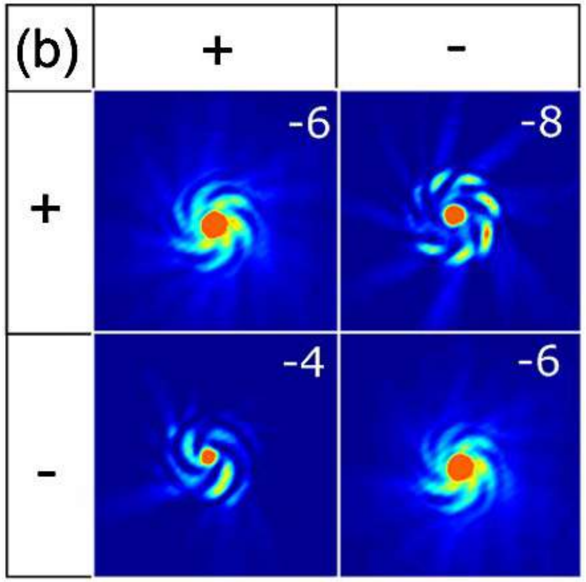


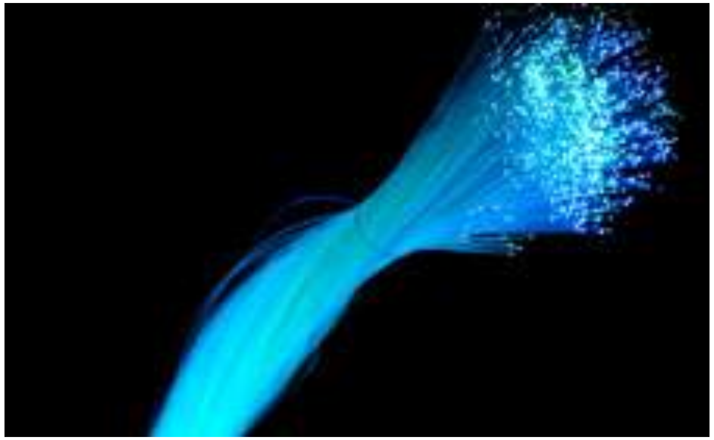
角动量光学：应用

- 轨道角动量光:
  - 高维（l=300）；
  - 稳定;信道间独立性好;
  - 信息编码，传输，计算
- SPP自旋轨道转化:
  - 角动量光之间的相互转化
  - 量子计算逻辑元件：CNOT门









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总结：SP及其旋光特性应用

内容	SP特性/应用
• 表面等离激元简介 • SPP/LSP 原理与特性； • 增强透射效应中SPP/LSP特性的具体体现	• SPP特性： • 表面局域性 • LSP特性： • 场增强特性
• LSP中的旋光特性应用 • LSP调控左右旋光相位； • 排列结构进行聚焦、成像； • 排列结构实现全息	• LSP旋光特性： • 出射光强一致 • 像素尺寸小
• SPP实现自旋轨道转化 • 光束的轨道角动量； • ‘几何相’与‘动力学相’； • 自旋-轨道转化的规律；	• SPP旋光特性： • 自旋控制轨道的转换 • 信道的编码与转换

THX！

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感谢王漱明老师在研习讨论中给予的指导！

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