人工微结构光声调控物理与应用学术研讨会

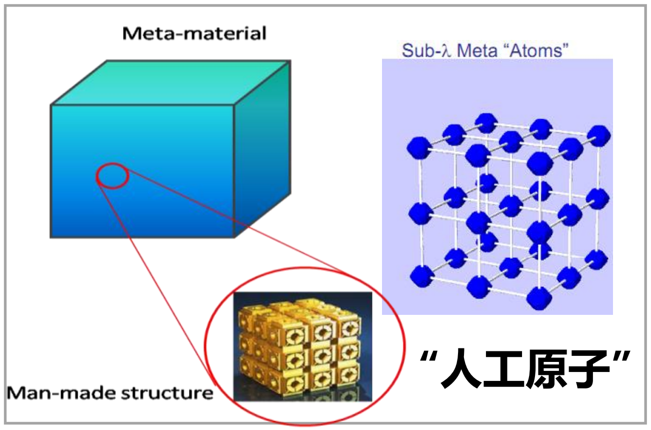
相位超构表面：异常衍射特性及物理

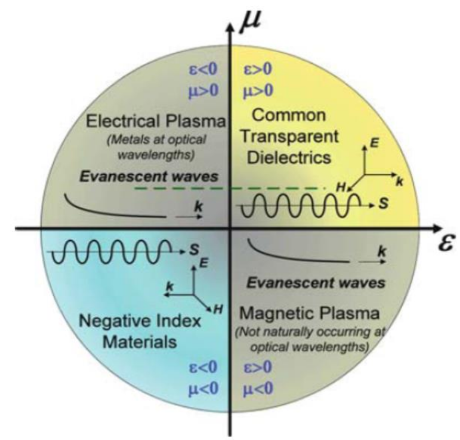
徐亚东　苏州大学

2023. 11. 26 @安徽理工大学

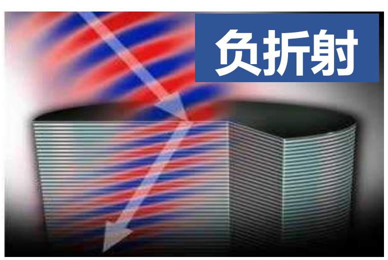
研究背景：超构材料

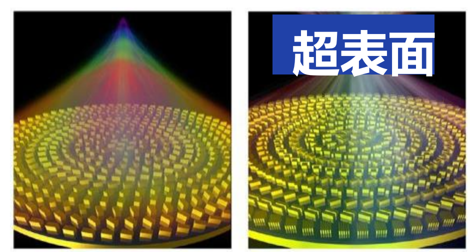
超构材料：“功能基元”+序构，调控光场新方式、新思路





- 突破自然限制
- 超常物理性质
- 任意参数





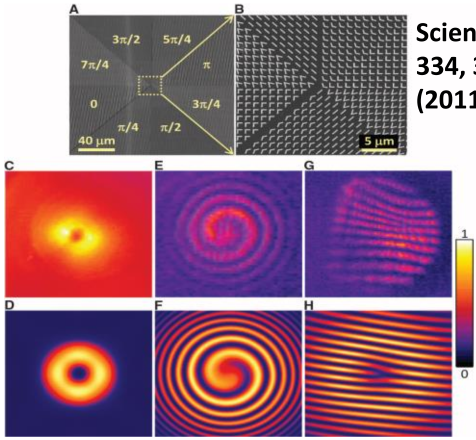
发展历史

2000 → 2006 → 2018

1998-2012：三维超构材料

2011-至今: 二维超构表面

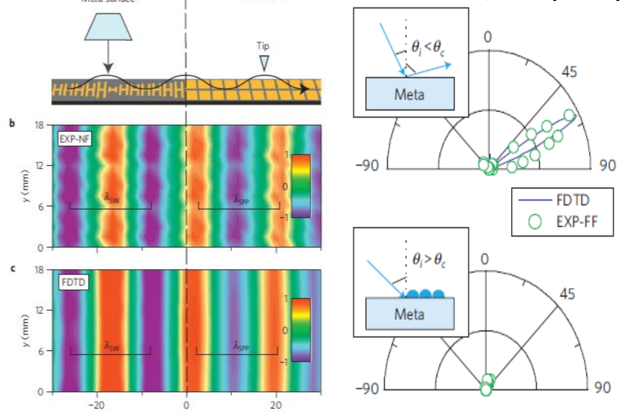
研究背景：超构表面



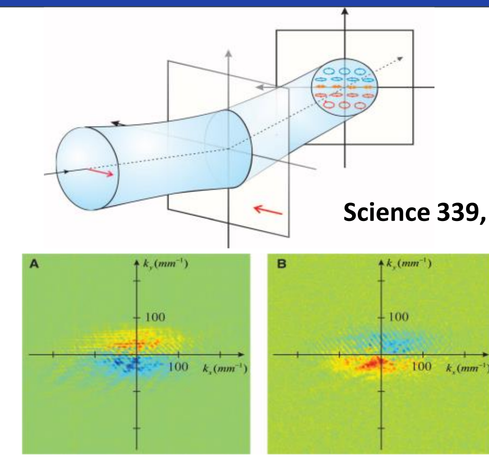
Science 334, 333 (2011)

涡旋光产生

Nat. Mater. 11, 426 (2012)

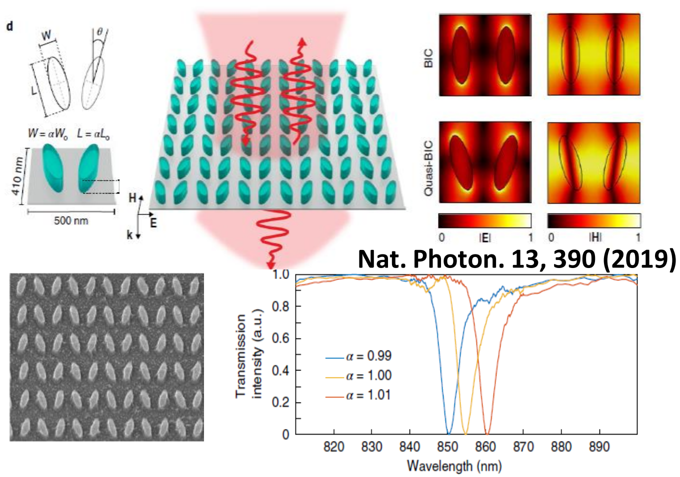


平面波到表面波转化



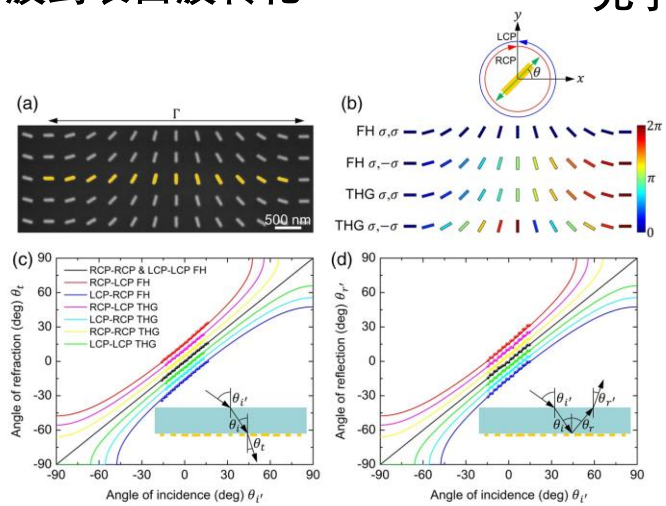
Science 339, 1405 (2013)

光子自旋Hall效应



Nat. Photon. 13, 390 (2019)

全介质：光谱成像



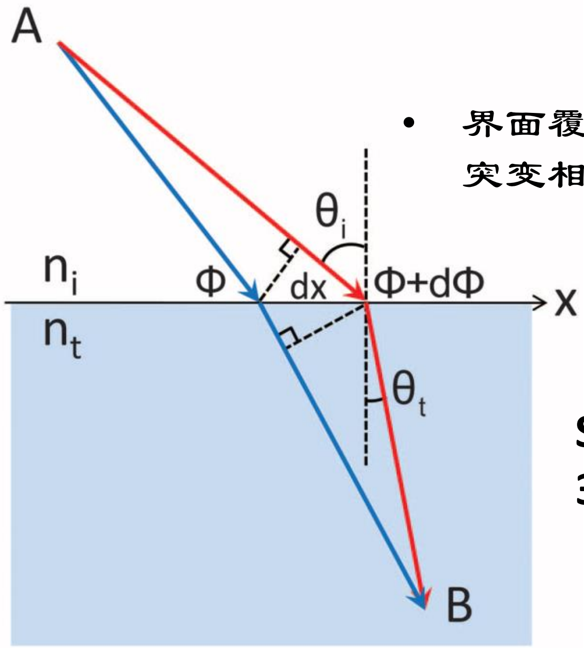
PRL 121, 046101 (2018)

非线性超构表面;

1. 新效应、器件
2. 单一功能-可调控/重构
3. 线性光学-非线性光学
4. 声学、力学交叉等

强大的波场调控能力：相位、幅度、偏振、OAM等

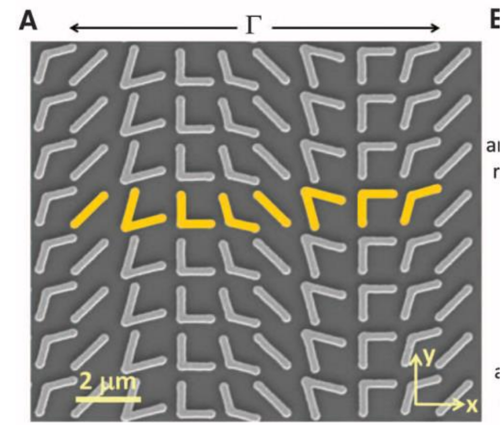
核心物理：广义折射/反射定律



- 界面覆盖0到2Pi突变相位

Science 334, 333 (2011)

微结构单元：调控相位和幅度

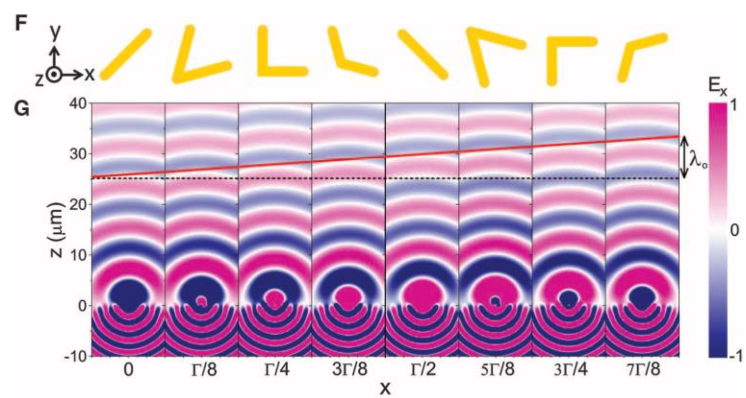


Generalized Snell laws

$$\sin(\theta_t)\, n_t - \sin(\theta_i)\, n_i = \frac{1}{k_0}\frac{d\Phi}{dx}$$

$$\sin(\theta_r)\, n_i - \sin(\theta_i)\, n_i = \frac{1}{k_0}\frac{d\Phi}{dx}$$

相位梯度

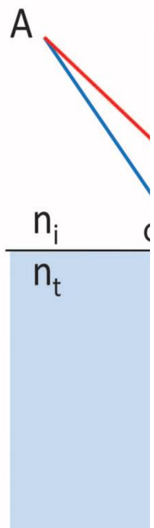


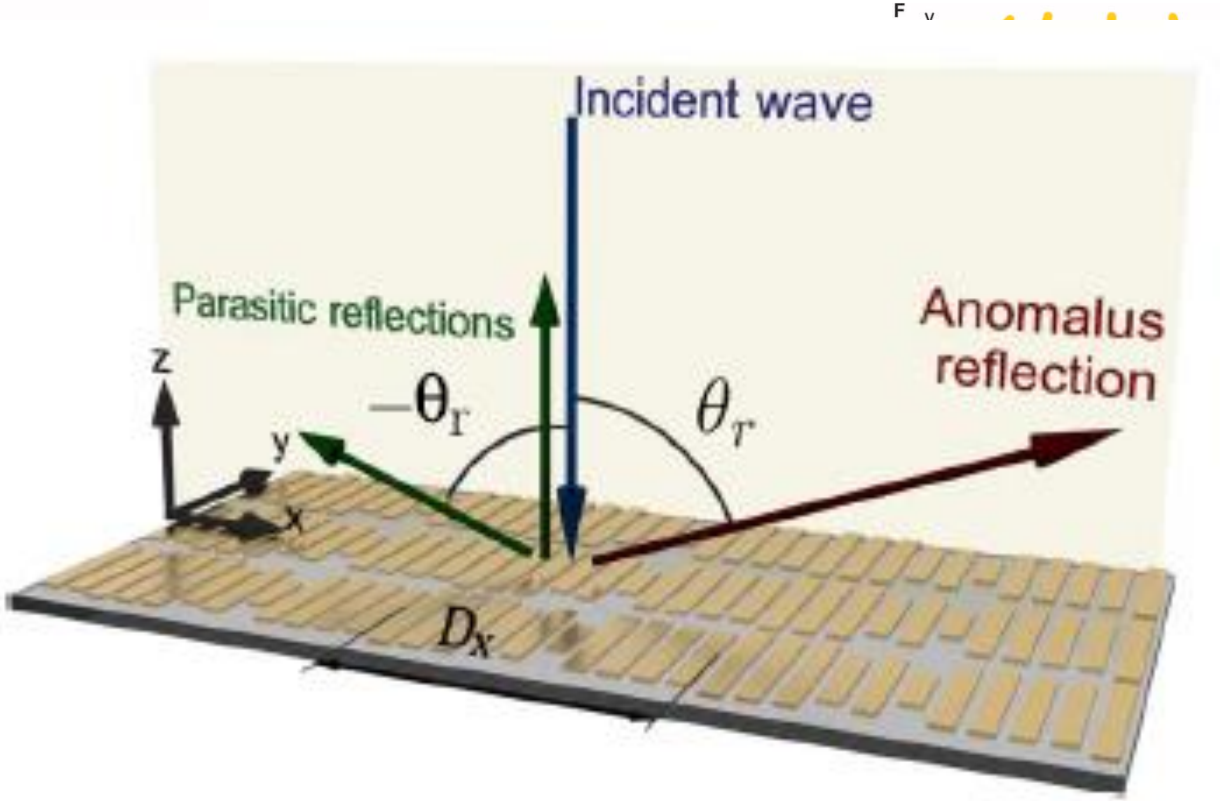
相位梯度：操控光的传播提供新的自由度

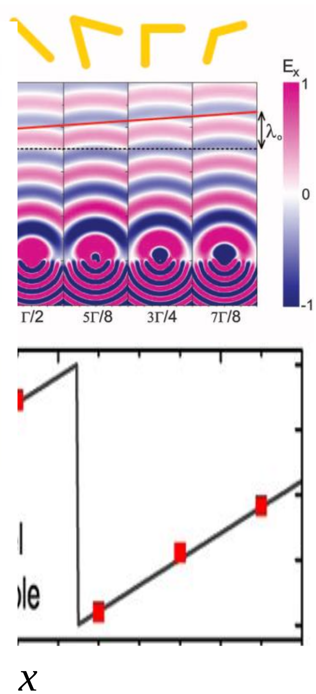
挑战：复杂衍射特性、规律和机制不清

实际：离散突变相位

理想：连续变化突变相位







rlattice（G=2pi/p)
n

$$n_{t/r}\sin\theta_{t/r} - n_i\sin\theta_i = \frac{1}{k_0}\frac{d\Phi}{dx} + n\frac{G}{k_0}$$

(原则上m越多，越好)

相位梯度：操控光的传播提供新的自由度

挑战：复杂衍射特性、规律和机制不清

PHYSICAL REVIEW X 6, 041008 (2016)

Wave-front Transformation with Gradient Metasurfaces

Nasim Mohammadi Estakhri and Andrea Alù*
Department of Electrical and Computer Engineering,
The University of Texas at Austin, Austin, Texas 78712, USA
(Received 9 July 2015; revised manuscript received 16 August 2016; published 14 October 2016)

Relying on abrupt phase discontinuities, metasurfaces characterized by a transversely inhomogeneous surface impedance profile have been recently explored as an ultrathin platform to generate arbitrary wave fronts over subwavelength thicknesses. Here, we outline fundamental limitations of passive gradient metasurfaces in molding the impinging wave and show that local phase compensation is essentially insufficient to realize arbitrary wave manipulation, but full-wave designs should be considered. These findings represent a critical step towards realistic and highly efficient conformal wave manipulation beyond the scope of ray optics, enabling unprecedented nanoscale light molding.

DOI: 10.1103/PhysRevX.6.041008 Subject Areas: Metamaterials, Nanophysics, Optics

Metasurface 效率低得必然性

1. 超薄-非Maxwell Equations的解！
2. 光栅衍射-其它衍射order

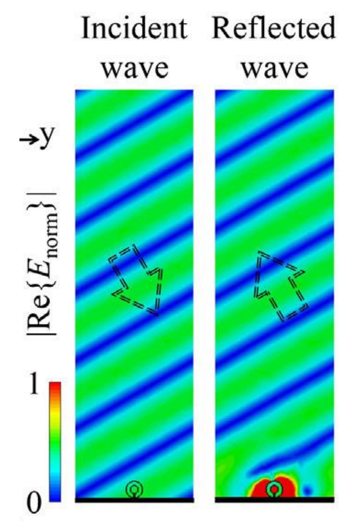
PRL 119, 067404 (2017) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2017

Metagratings: Beyond the Limits of Graded Metasurfaces for Wave Front Control

Younes Ra'di, Dimitrios L. Sounas, and Andrea Alù*
Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712, USA
(Received 8 May 2017; published 10 August 2017)

Graded metasurfaces exploit the local momentum imparted by an impedance gradient to mold the impinging wave front. This approach suffers from fundamental limits on the overall conversion efficiency, and it is challenged by fabrication limitations on the spatial resolution. Here, we introduce the concept of metagratings, formed by periodic arrays of carefully tailored bianisotropic inclusions and show that they enable wave front engineering with unitary efficiency and significantly lower fabrication demands. We employ this concept to design reflective metasurfaces for wave front steering without limitations on efficiency. A similar approach can be extended to transmitted beams and arbitrary wave front transformation, opening opportunities for highly efficient metasurfaces for extreme wave manipulation.

超构光栅



ARTICLE

DOI: 10.1038/s41467-018-03831-7 OPEN

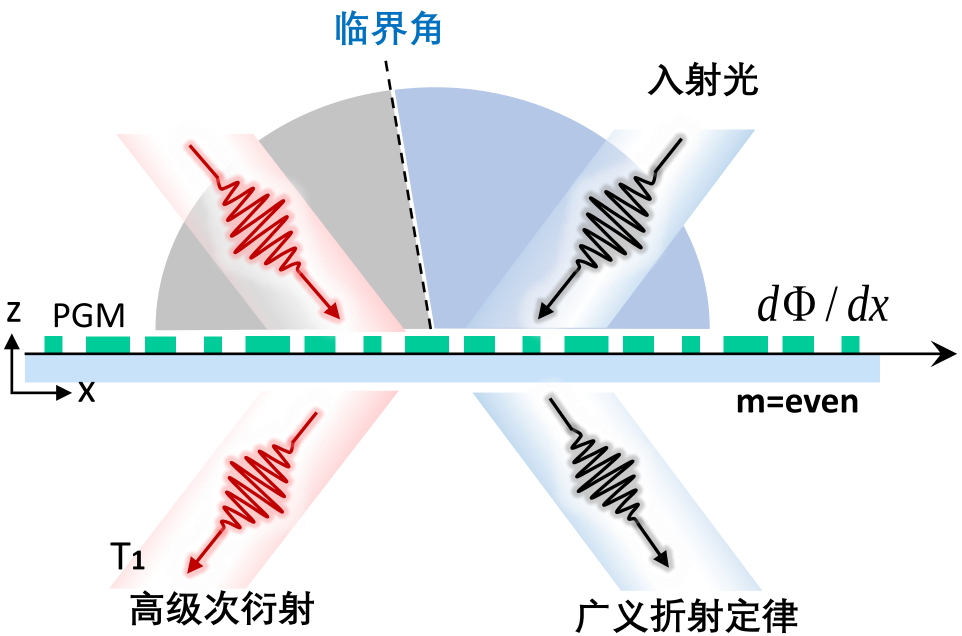
Ultra-thin high-efficiency mid-infrared transmissive Huygens meta-optics

Li Zhang[1,2], Jun Ding[3,4], Hanyu Zheng[1,2], Sensong An[4], Hongtao Lin[2], Bowen Zheng[4], Qingyang Du[2], Gufan Yin[2], Jerome Michon[2], Yifei Zhang[2], Zhuoran Fang[2], Mikhail Y. Shalaginov[2], Longjiang Deng[1], Tian Gu[2], Hualiang Zhang[4] & Juejun Hu[2]

Nature Communications 9, 1481 (2018).

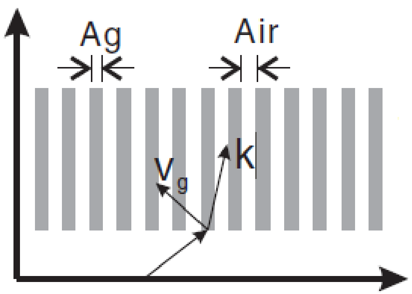
关键科学问题

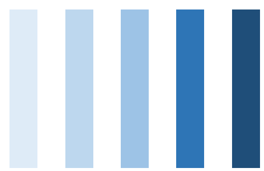
相位梯度超构表面：

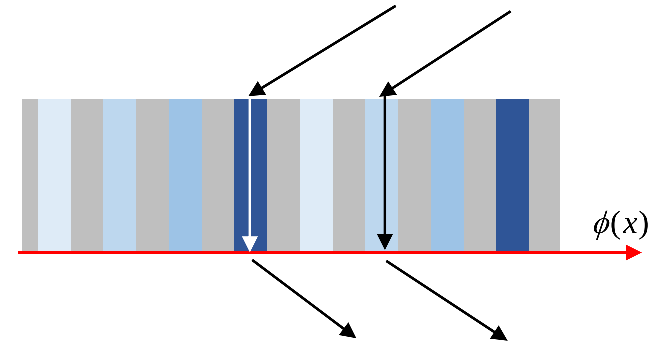


衍射特性、规律和物理机制？

思路：超构光栅-亚波长渐变光栅结构







亚波长金属光栅

- Extraordinary Optical Transmission
- Optical Negative refraction
- Metals Transparent

不同折射率材料

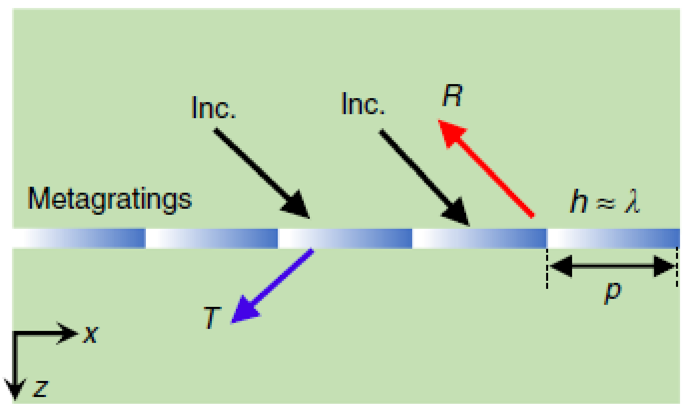
- Effective medium Theory
- High refractive index
- Negative/zero index

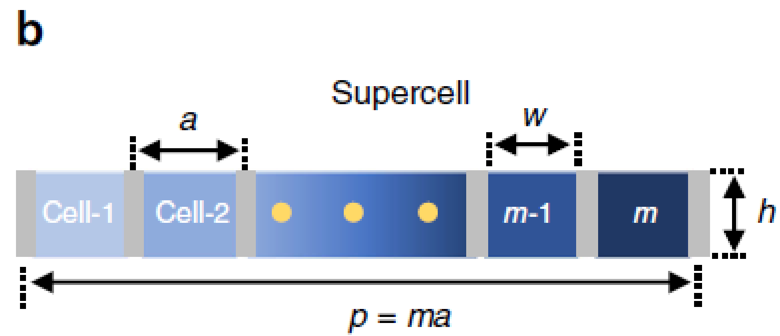
亚波长渐变金属光栅结构

- 在出射界面上引入一个覆盖0到2Pi的突变相位
- 实现广义的Snell law
- 提高效率
- 结构相对简单，便于理论解析

研究模型：超构光栅

相位梯度大小: $\frac{d\Phi}{dx} = k_0$





Generalized Snell laws

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$$\sin(\theta_r)\, n_i - \sin(\theta_i)\, n_i = \frac{1}{k_0}\frac{d\Phi}{dx}$$

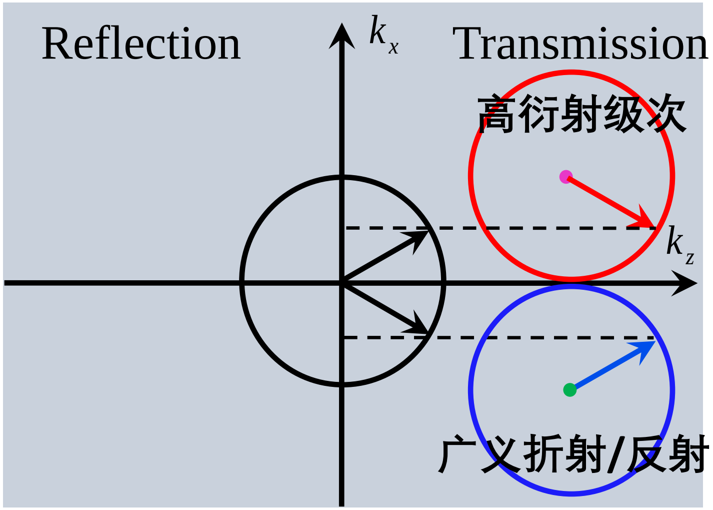
相位梯度

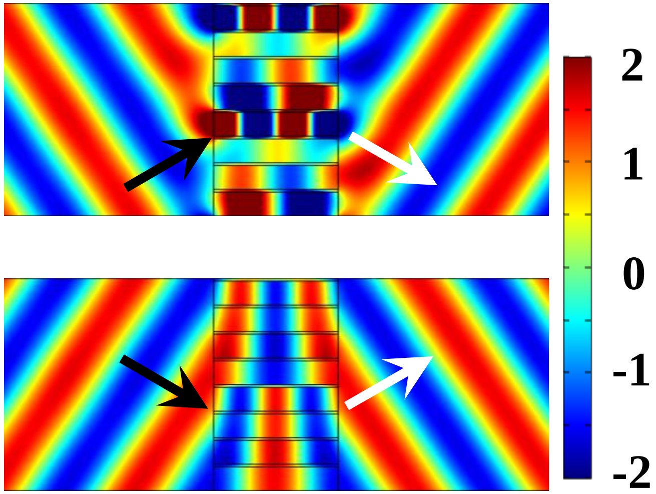
Only for 入射角度<0:

入射角度>0:

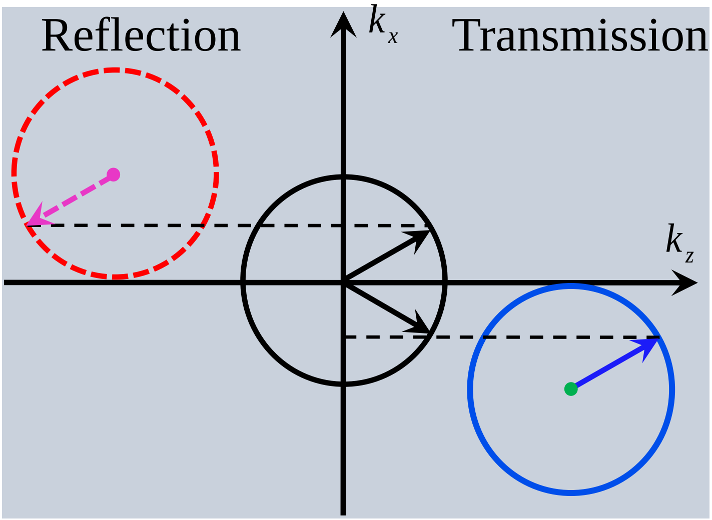
发现：奇偶反转衍射规律

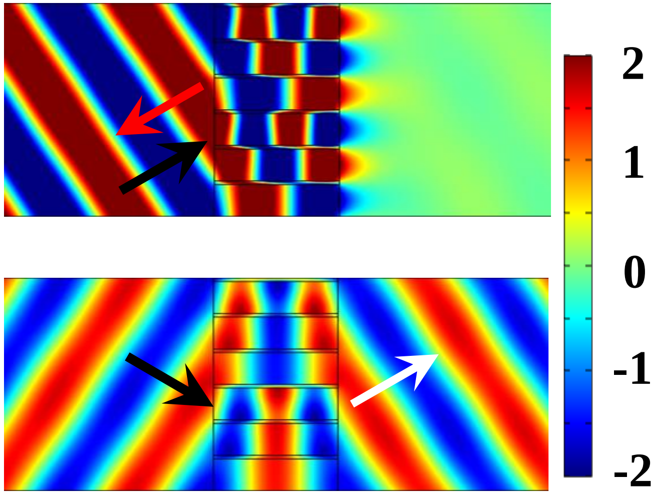
m=4 (Even)





m=3 (Odd)



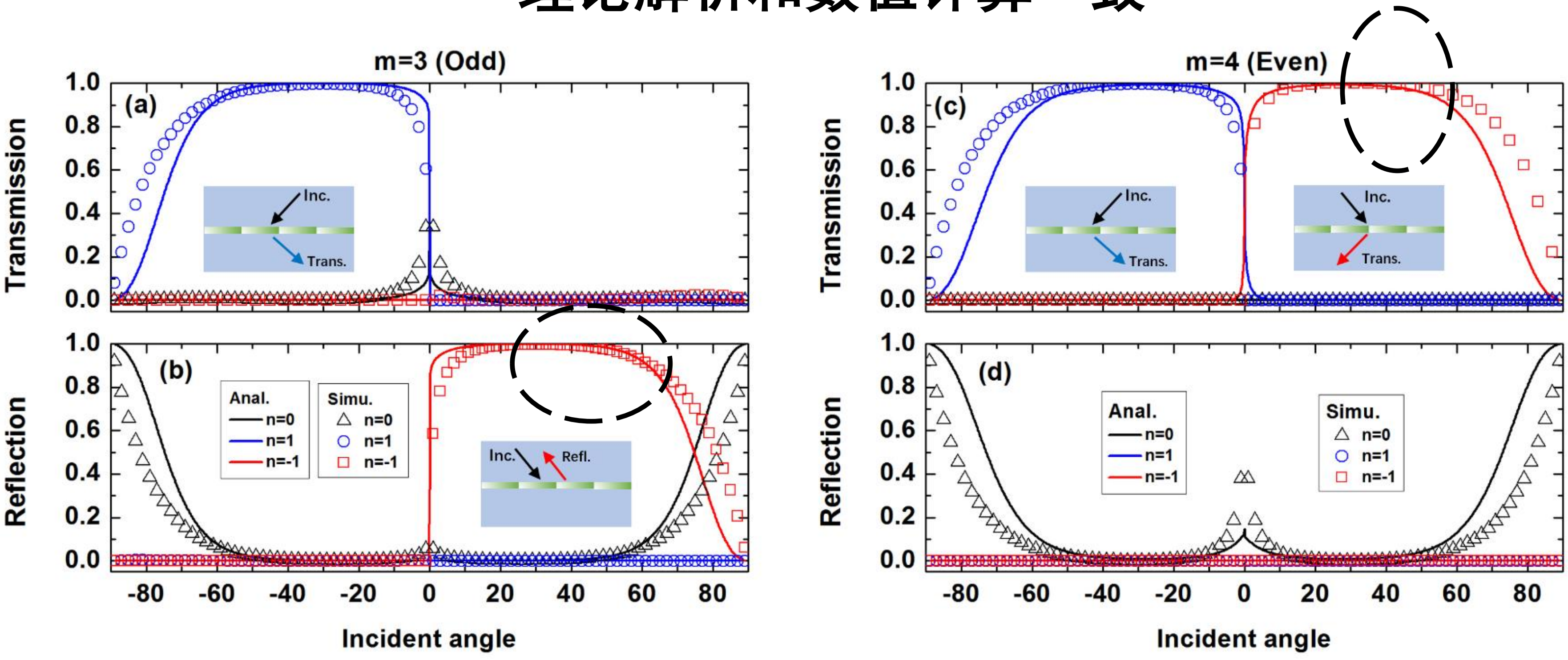


Yadong Xu et. al, Nature Communications* 10, 2326 (2019)

发现：奇偶反转衍射规律

Coupled mode theory （CMT）理论解析

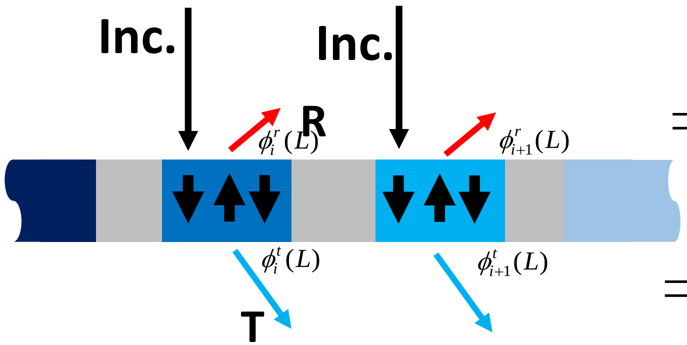
理论解析和数值计算一致

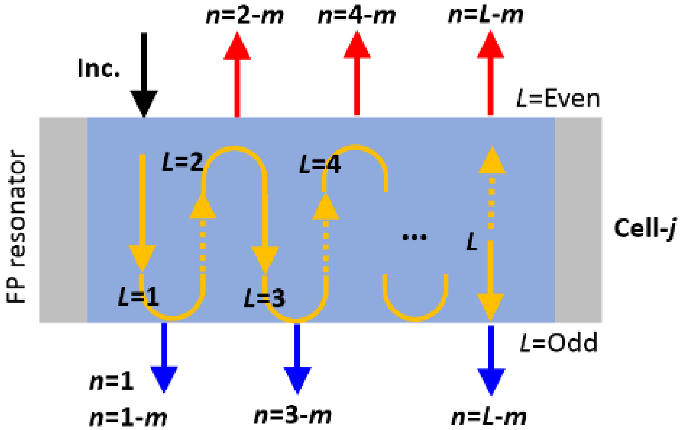


- 奇偶数相关的T/R for n=-1
- 普遍现象：m=5/6; 20/21

发现：奇偶反转衍射规律

■ 物理解释及衍射机制





金属槽中多次全反射效应

- 相邻槽间相位差
- 某个衍射级次所需相位差

$$\Rightarrow \Delta\phi_r = \varphi_0 l,\ \ l = 2, 4, 6\ldots \qquad \phi_n = \frac{2\pi}{m} n$$

$$(\varphi_0 = 2\pi / m)$$

$$\Rightarrow \Delta\phi_t = \varphi_0 l,\ \ l = 1, 3, 5\ldots \qquad \phi_n = \frac{2\pi}{m} n$$

$$R : \Delta\phi_r - 2\pi j = \varphi_n \qquad T : \Delta\phi_t - 2\pi j = \varphi_n$$

$$\Rightarrow l - mj = n \qquad \Rightarrow l - mj = n$$

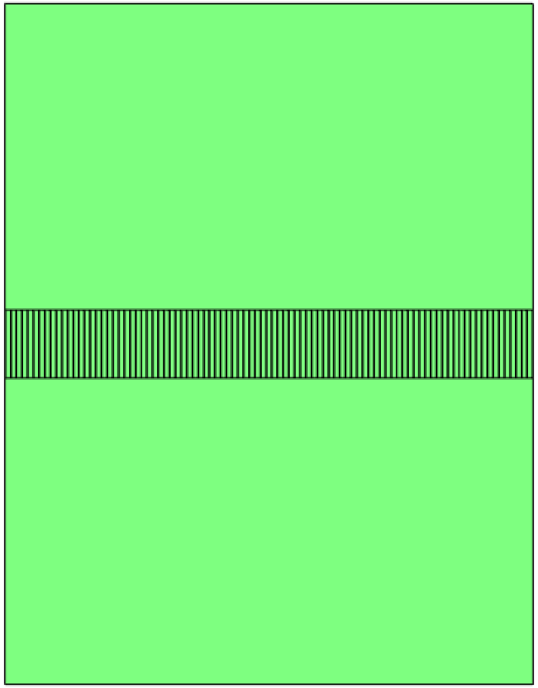
$$n_r \sin\theta_r - n_i \sin\theta_i = \frac{1}{k_0}\frac{d\Phi}{dx} + n\frac{G}{k_0};\ m = odd$$

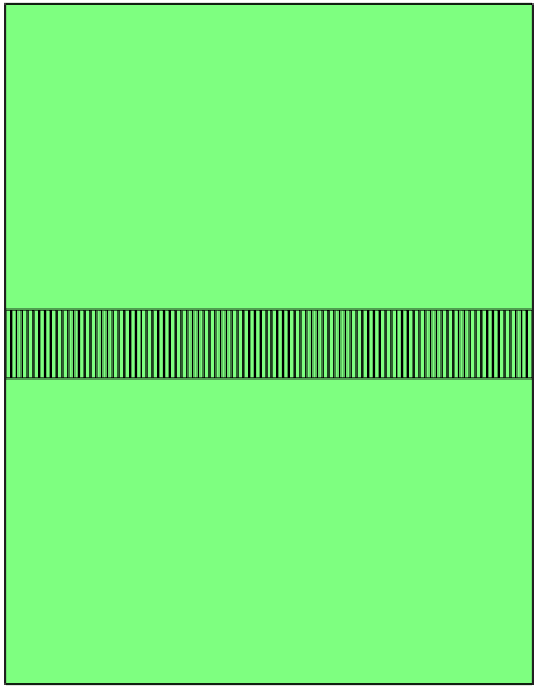
$$n_t \sin\theta_t - n_i \sin\theta_i = \frac{1}{k_0}\frac{d\Phi}{dx} + n\frac{G}{k_0};\ m = even$$

重要意义

(1) 发现新衍射方程
(2) 单元个数m，新自由

脉冲瞬态模拟计算和分析

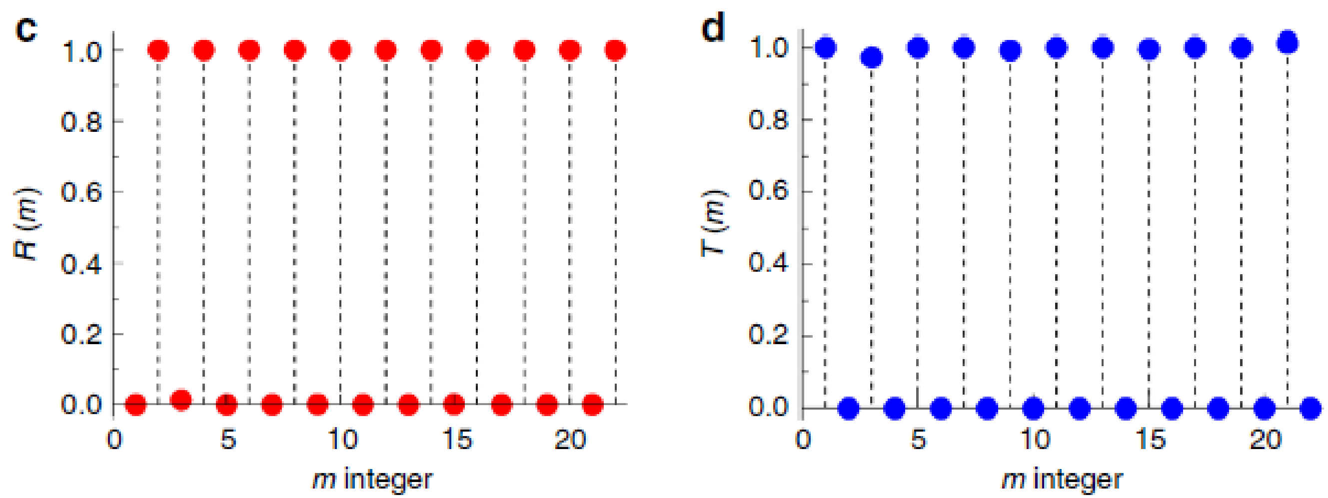




鲁棒性：奇偶反转

相位梯度大小: $\frac{d\Phi}{dx}=1.5k_0$ → **GSL: 100%反射**

偶数：全透射， 奇数：全透射



理论解析结果:

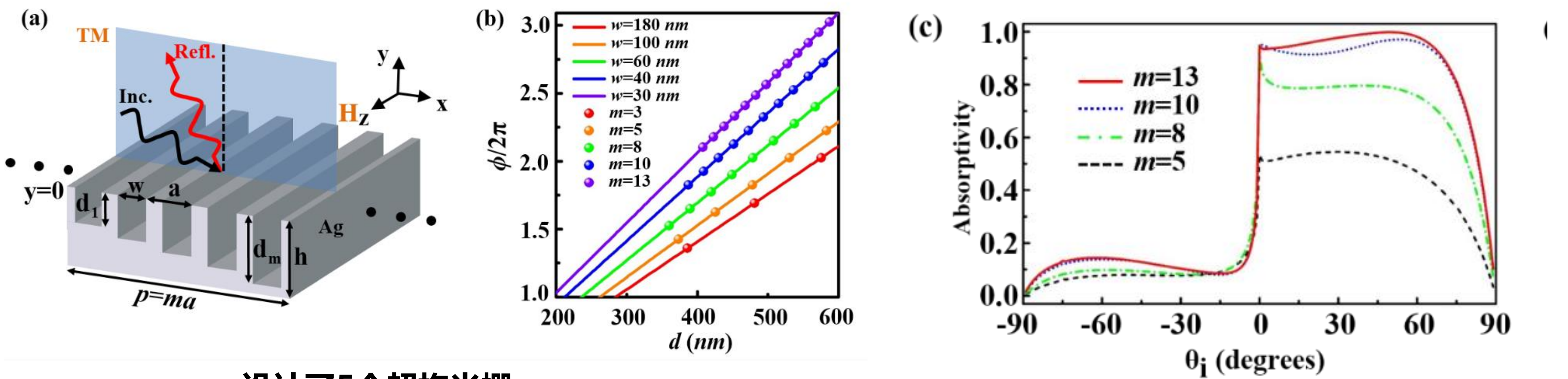
$$r_0 = 0, \quad t_0 = \exp(-i\varphi_T), \; m \text{ is odd;}$$

$$r_0 = \exp(-i\varphi_R), \quad t_0 = 0, \quad m \text{ is even;}$$

拓展：新光栅衍射方程、衍射规律

➢m相关的不对称吸收新效应-多重内全反射物理机制

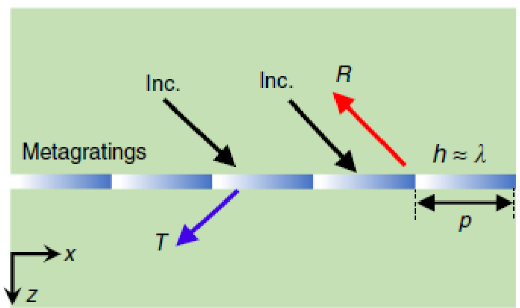
λ=650nm
$\varepsilon_{\mathrm{Ag}}=-17.36+0.715i$

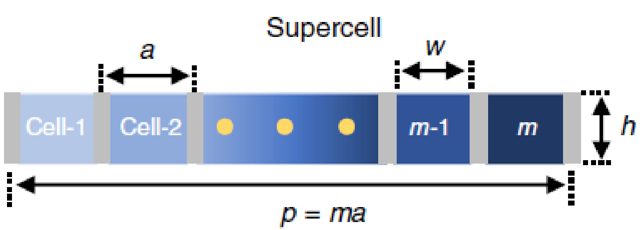


- 设计了5个超构光栅
- 保持相位梯度不变（650nm）
- m改变

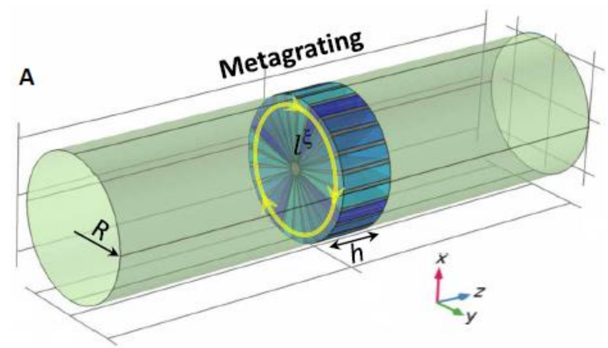
Yadong Xu* et al, *Phy. Rev. Appl.* 12, 024006 (2019).

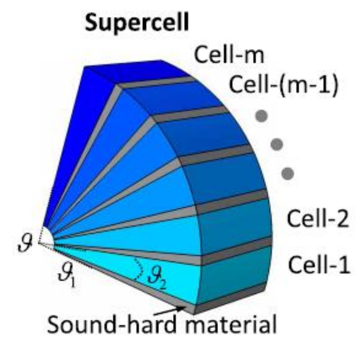
从平面波到涡旋波场调控





平面波





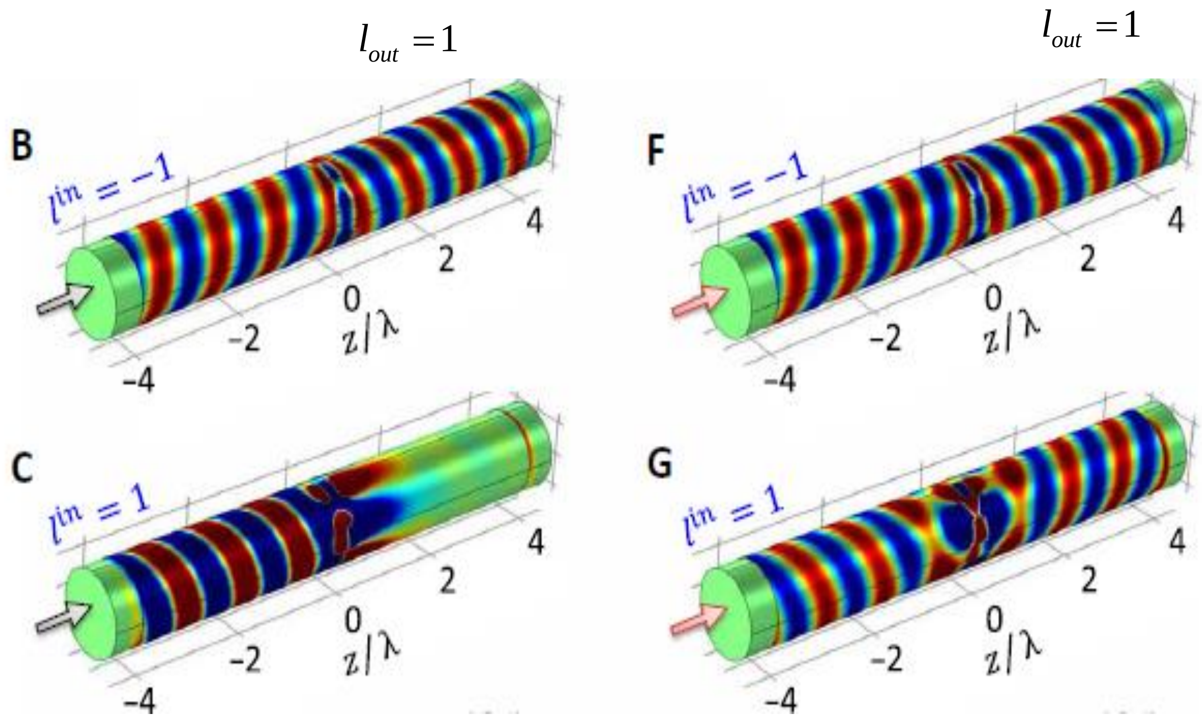
相位梯度：拓扑荷q

涡旋波

Y. Xu* et al, *Science Advances 6,* eaba9876 (2020)

OAM-不对称、高效率波涡旋衍射操控

m=5　　　　m=6

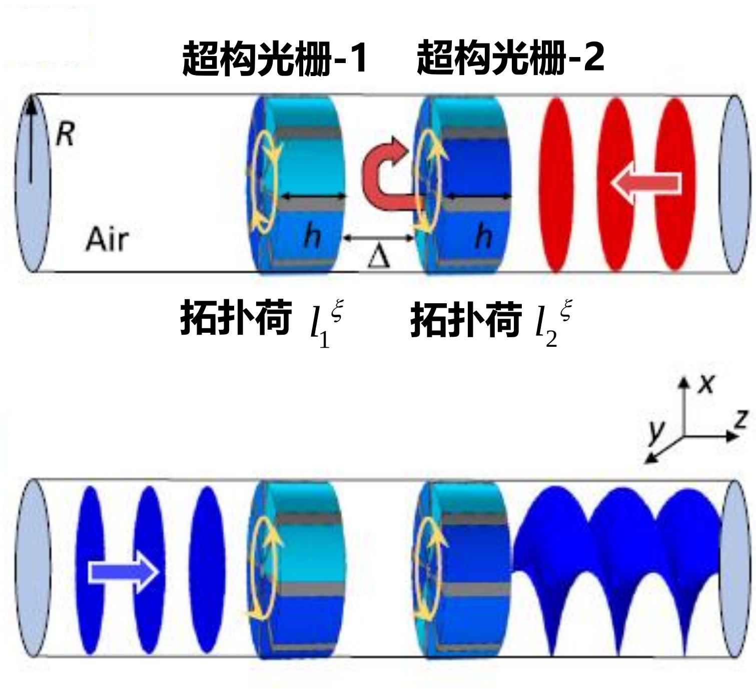


新OAM守恒公式

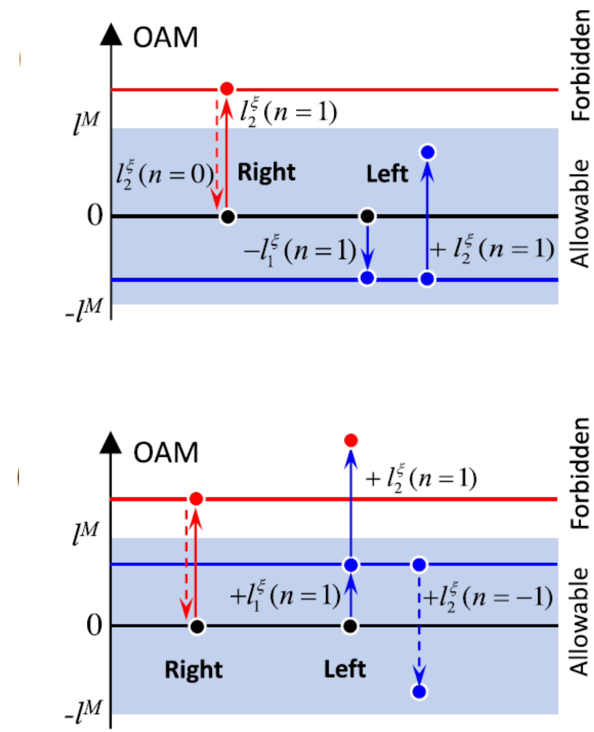
$$\begin{cases} l^{t} = l^{in} + nl^{\xi}, L = \text{odd} \\ -l^{r} = l^{in} + nl^{\xi}, L = \text{even} \end{cases}$$

Y. Xu* et al, *Science Advances 6,* eaba9876 (2020)

双层体系： OAM单向转化，涡旋波不对称传输



双层体系

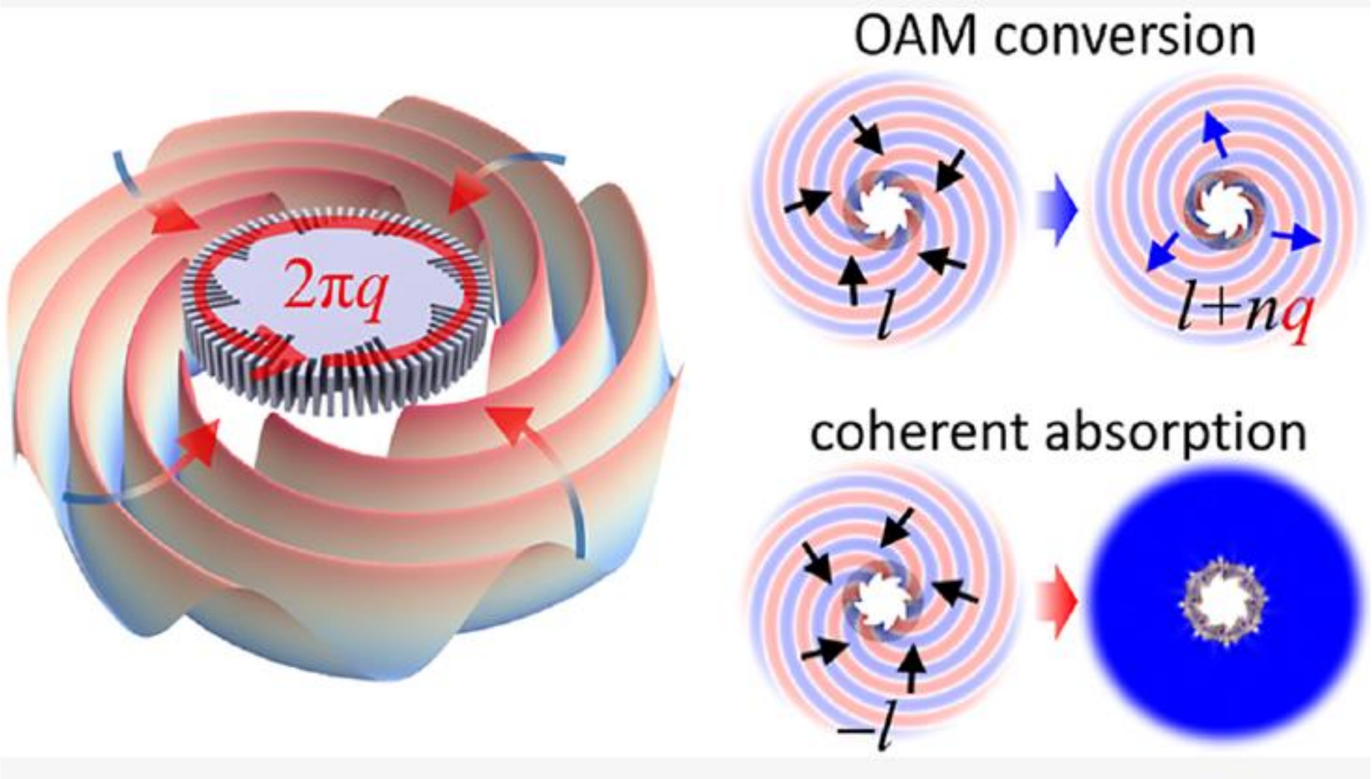


单向转化过程

✓ **物理机制：空间对称性破缺和外拓扑荷联合作用**

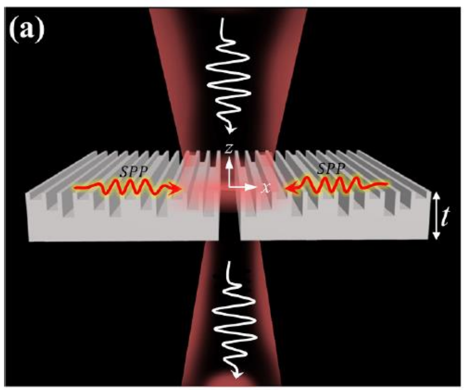
Y. Xu et al, Phys. Rev. Lett.* 128, 104501 (2022)

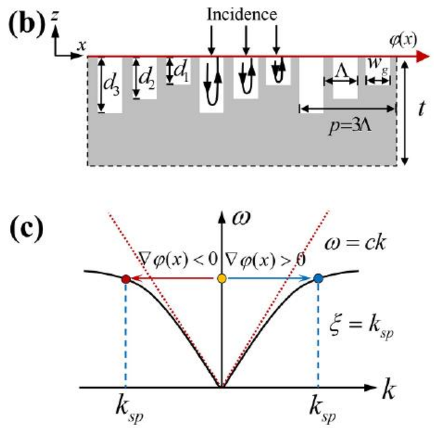
散射问题：单个柱体电磁波/声波散射特性

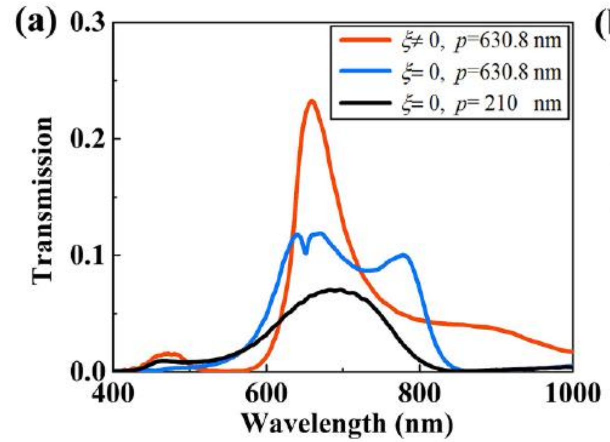


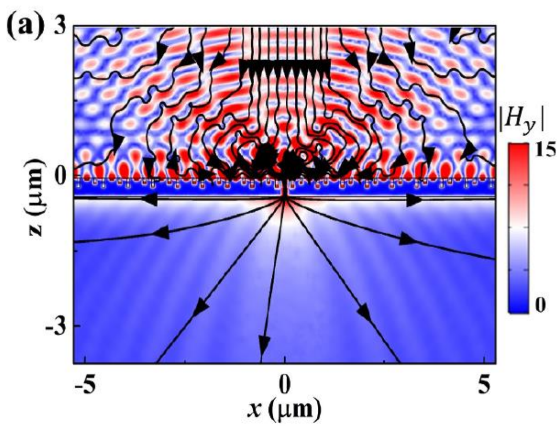
Yadong Xu* et al, ACS Photonics 8, 2027−2032 (2021).

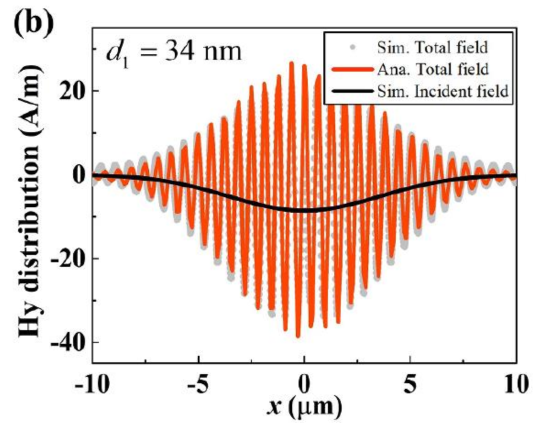
亚波长孔/缝衍射问题：





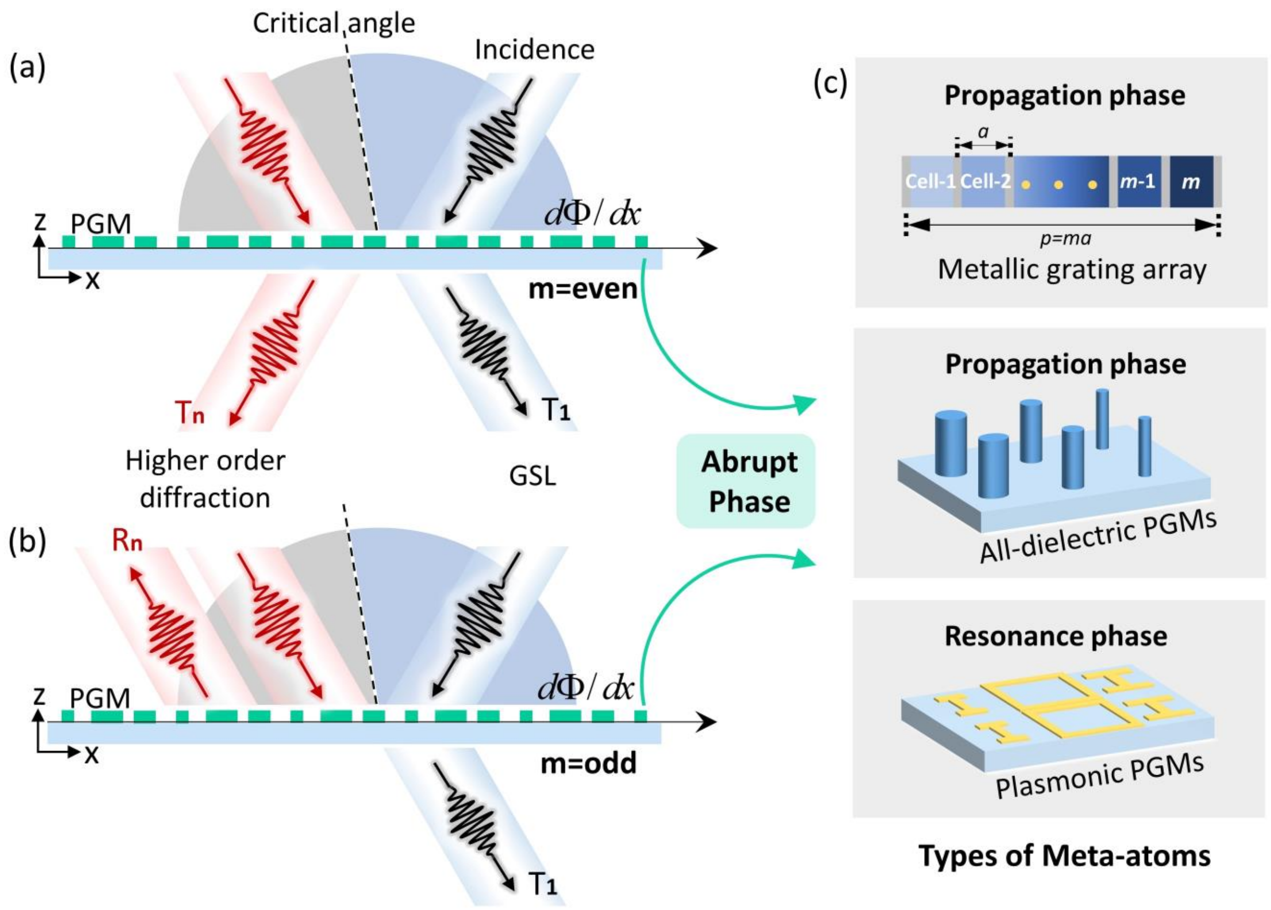






Yadong Xu* et al, New J. Phys. 25, 053004 (2023)

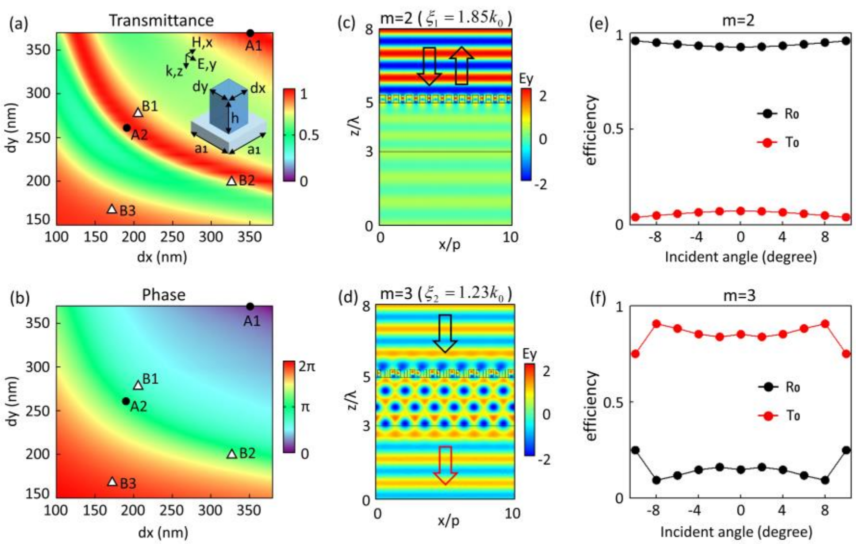
？适用：超薄梯度超构表面



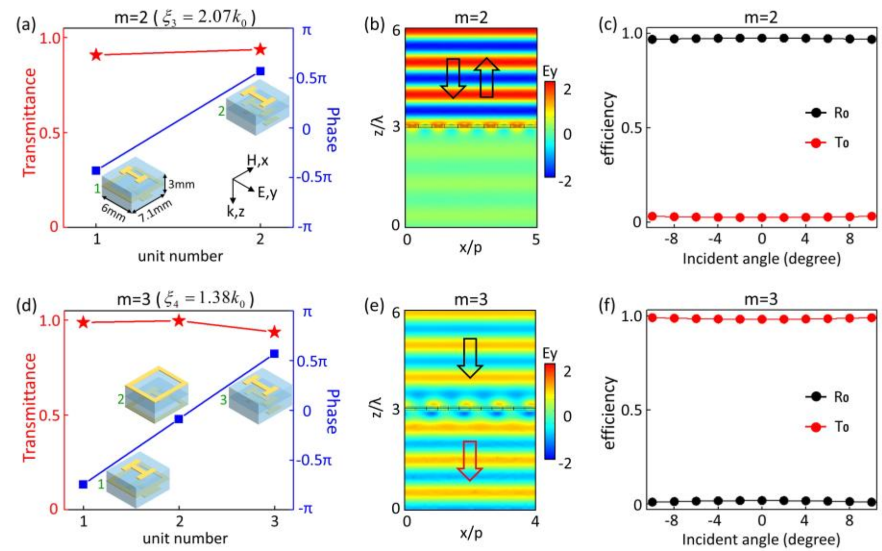
超薄梯度超构表面：奇偶规律？？

适用：超薄梯度超构表面

全介质梯度超表面:



金属梯度超表面:



Yadong Xu* et al, Physical Review A, 2023

总结

- ◆围绕相位超构表面，做了一些研究工作
- ◆相位梯度：光、声等波场调控新的**自由度**
- ◆超晶格单元个数及其奇偶性：**又一参量**

人工微结构光声调控物理与应用学术研讨会

感谢聆听！

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