

超构表面中多维光场调控 及其智能优化设计

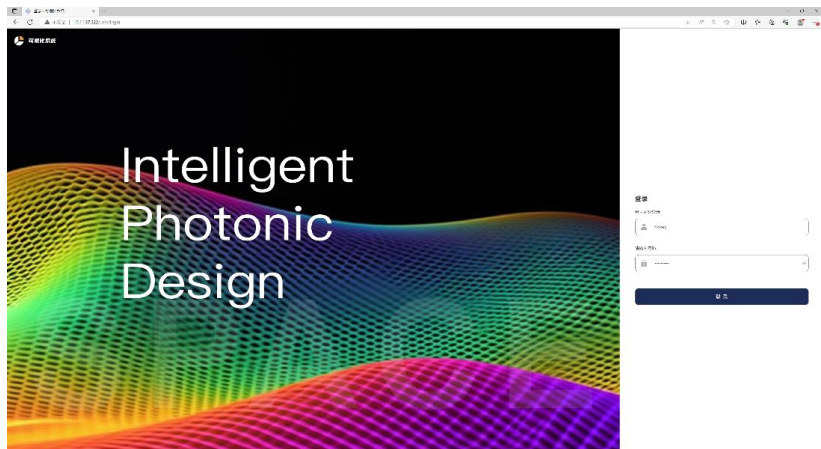
熊波

信息与电子工程学院

2023.11.26

团队介绍:

1. 团队教师: 储涛 (国家千人), 马蔚 (国家优青), **熊波 (国家青拔)**
2. 隶属于浙江大学微电子集成系统研究所 (校级所)
3. 研究方向: 光通信/互连/计算/感知, **超表面器件, 微纳成像、智能设计**、MEMS器件, 800G收发、Lidar、光开关、硅基激光器、Si/LN调制器、微型光谱仪、光电封装
4. 主要合作: 华为、中国电科



智能光电子设计平台

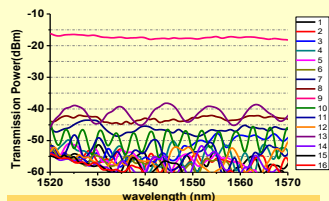
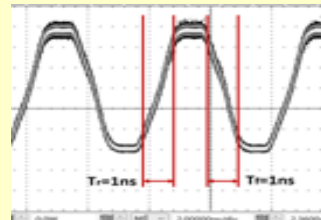
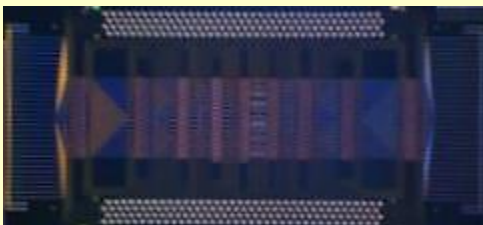


超构表面多维度光场调控

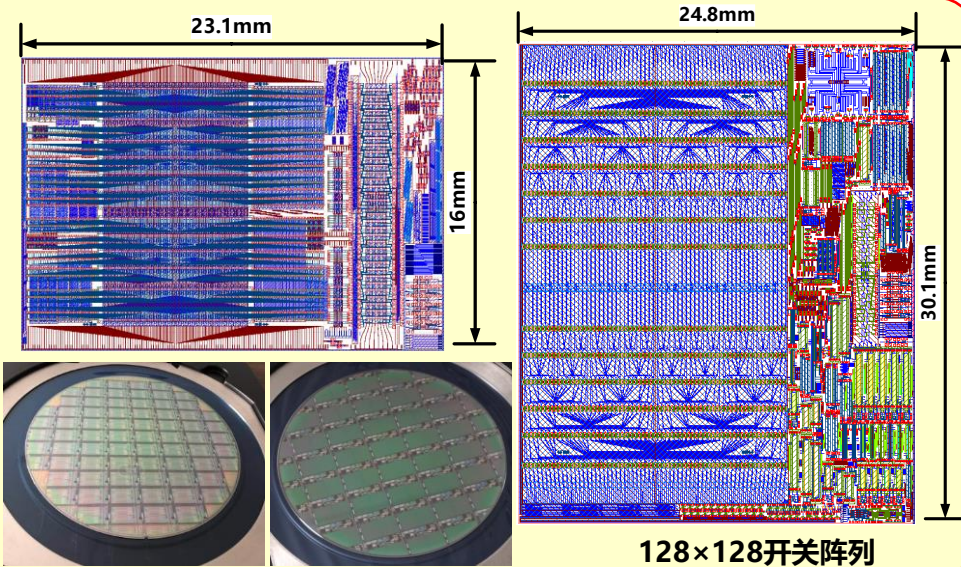
硅光方向代表性成果

● Largest Optical Switch

32x32 Chip: **12.1 x 5.2 mm**, **144 MZI**



Tao CHU Gr. ZJU
OFC2018

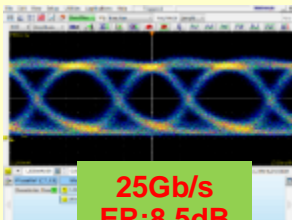
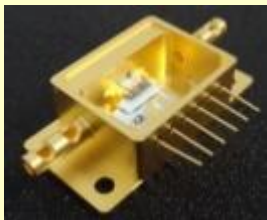


128x128开关阵列

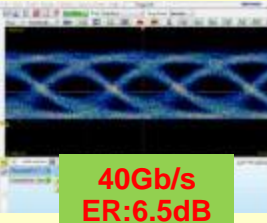
- 32x32 Benes network
- IL: **-12.8dB**; XT: **-19.2dB**
- Switch speed: **1ns**

Packaged module

EPIC 2016



25Gb/s
ER:8.5dB

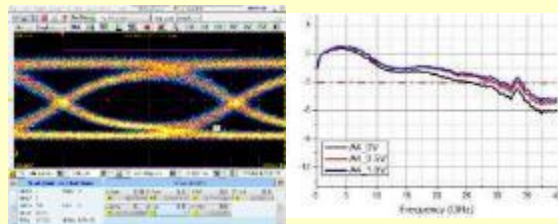


40Gb/s
ER:6.5dB



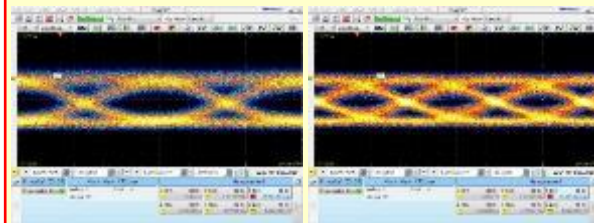
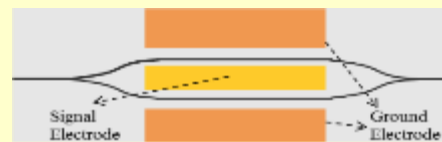
30Gb/s
ER:7.1dB

Low driving Voltage



25Gb/s, ER:6.13dB, $V_{pp} < 2V$

LNOI Modulator



1st sample, 64Gb/s

目录

一、研究背景介绍

二、超构表面中多自由度调控

三、微纳器件智能逆向设计

四、总结与展望

研究背景

后摩尔时代对信息感知与传输能力爆炸性增长的需求；
“建设**高速泛在、集成互联**的信息基础设施……增强**数据感知、传输能力**”。
——《“十四五”规划与2035年远景目标》



光通信技术

传输速率提升**受限**于复用通道**数目**



光感知技术

感知能力提升**受限**于信息探测**维度**

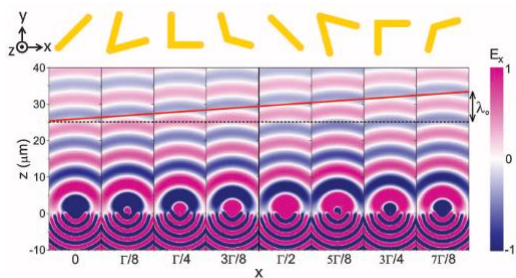
共性需求：**多维度的光场调控**

超构表面

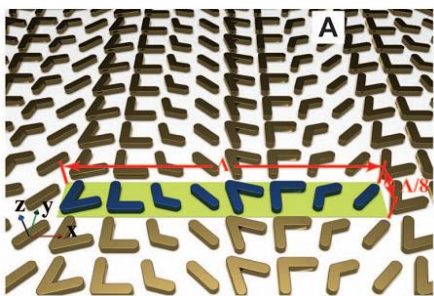
- **Metasurface**: **flat, ultrathin** optical components that produce abrupt changes over the **scale of the free-space wavelength** in the **phase, amplitude and/or polarization** of a light beam.

N. F. Yu, *et al.*, *Nat. Mater.* **13**, 139 (2014).

Metallic structures

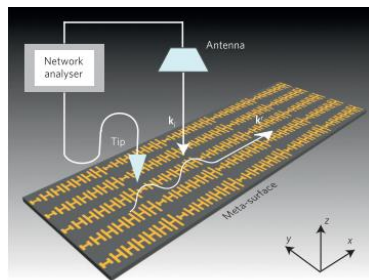


N. F. Yu, *et al.* *Science* **334**, 6054 (2011).

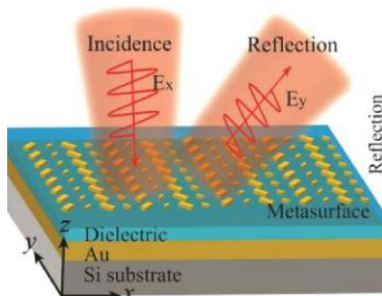


X. J. Ni, *et al.* *Science* **335**, 6067 (2012).

MIM structures

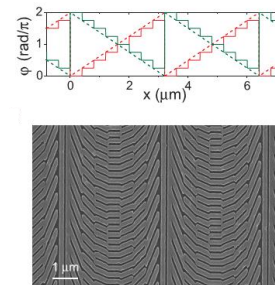


S. L. Sun, *et al.* *Nature Materials* **11**, 5 (2012).

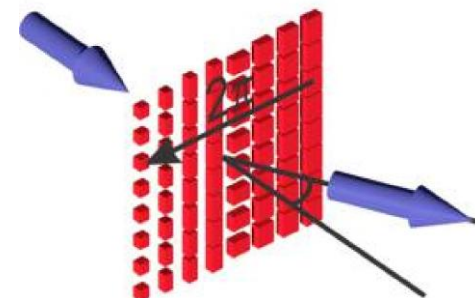


F. Ding, *et al.* *ACS Nano* **4**, 4111 (2015).

Dielectric structures

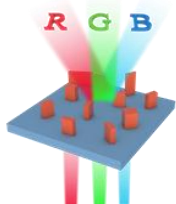


D. M. Lin, *et al.* *Science* **345**, 298 (2014).

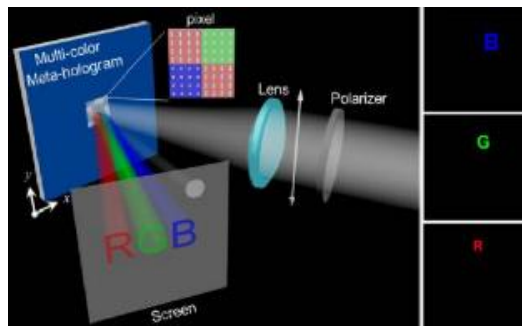


M. I. Shalaev, *et al.* *Nano letter* **15**, 6261 (2015).

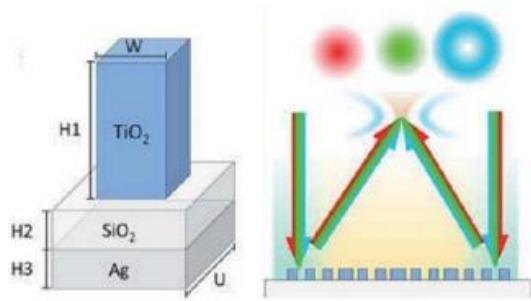
多功能集成超构表面



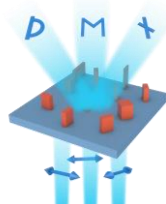
波分复用



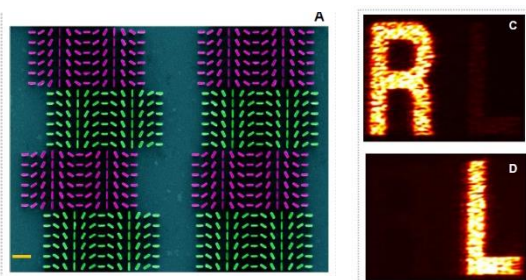
Y. W. Huang, *et al.* *Nano Letter* **15**, 3122 (2015).



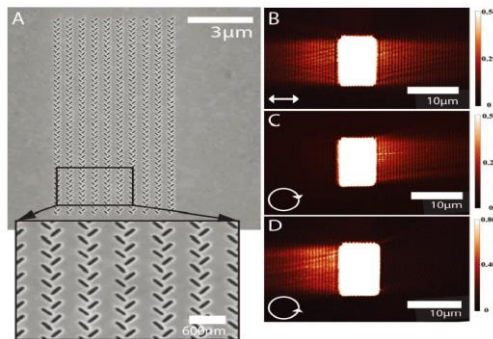
Z. J. Shi, *et al.* *Nano Letter* **18**, 2420 (2018).



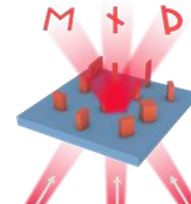
偏振复用



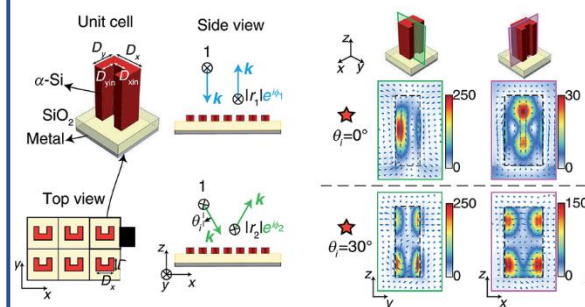
M. Khorasaninejad, *et al.* *Sci. Adv.* **2**, e1501258 (2016).



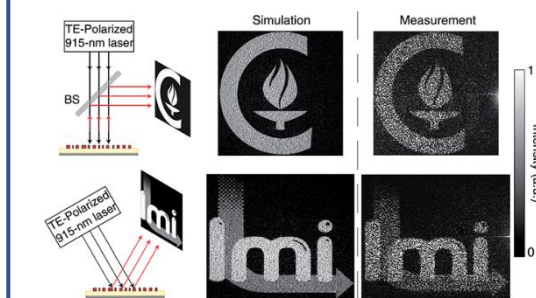
J. Lin, *et al.* *Science* **340**, 331-334 (2013).



角度复用

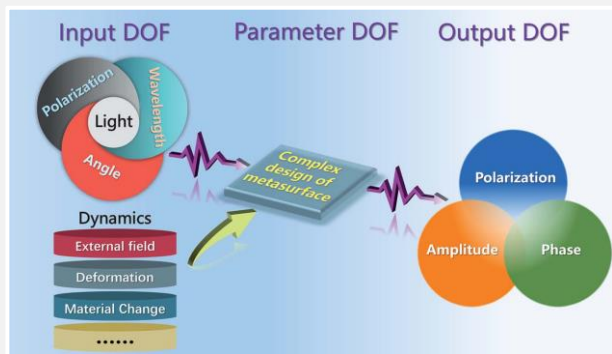


S. M. Kamali, *et al.* *Phys. Rev. X* **7**, 041056 (2017).



如何实现普适的多功能集成设计？

Multifunctional metasurfaces



B. Xiong *et al.*
Nanoscale Adv. **1**, 3786 (2019)

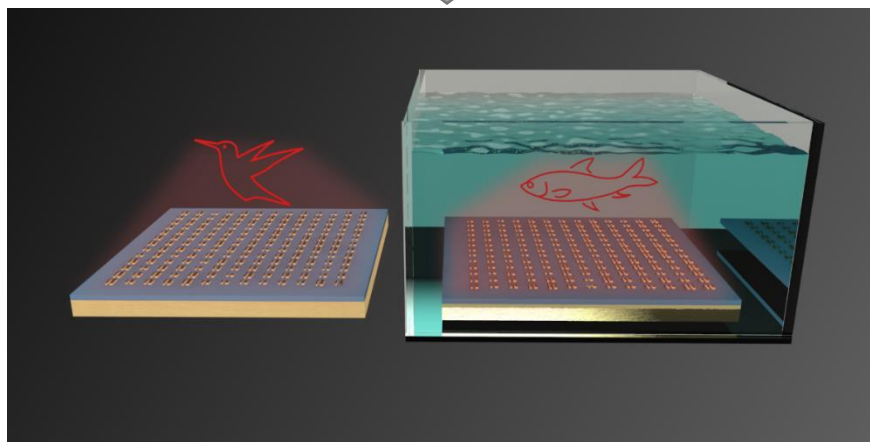
Holographic display



<https://news.mit.edu/2021/3d-holograms-vr-0310>



Dynamic devices supported by liquid immersion



Challenges:

1. Environment sensitive response
2. In the visible regime

目录

一、背景介绍



二、超构表面中多自由度调控

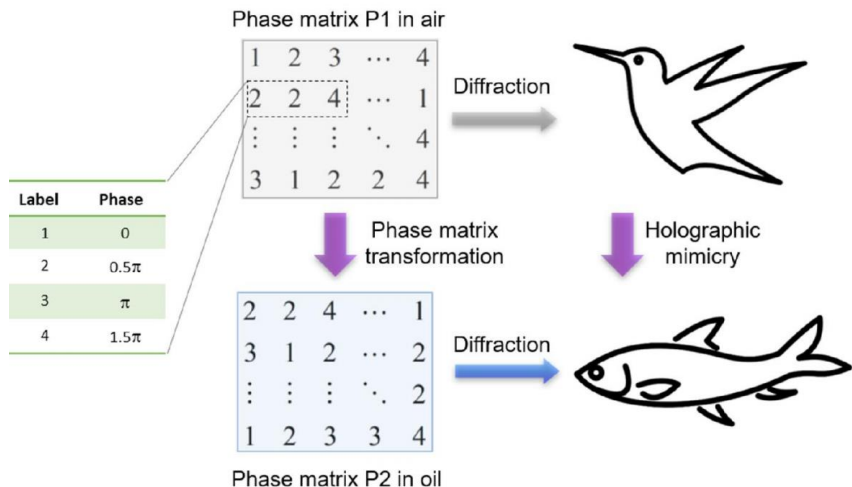
三、微纳器件智能逆向设计

四、总结与展望

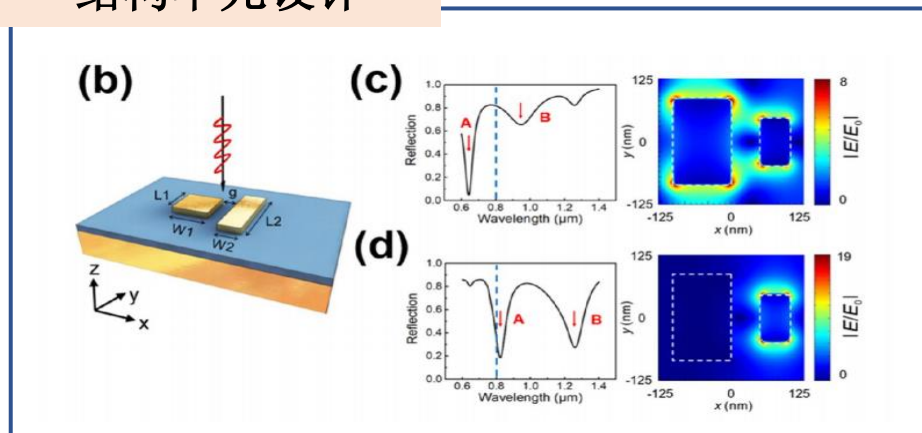
新型动态超构表面全息设计

设计原理

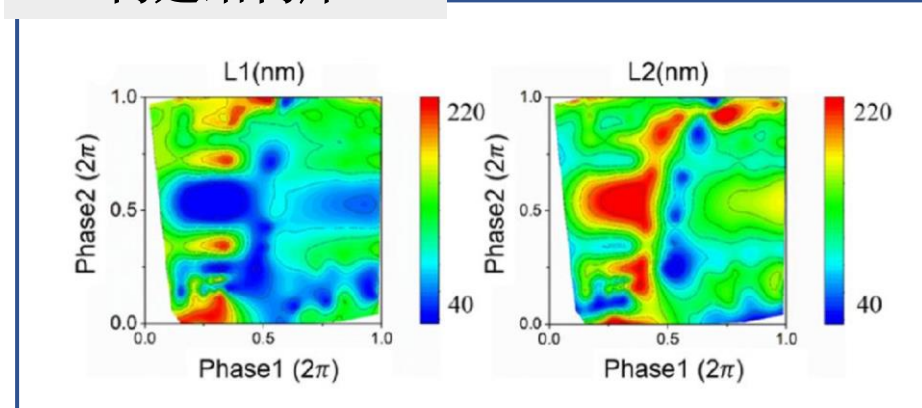
相位矩阵变换（完备性）



结构单元设计



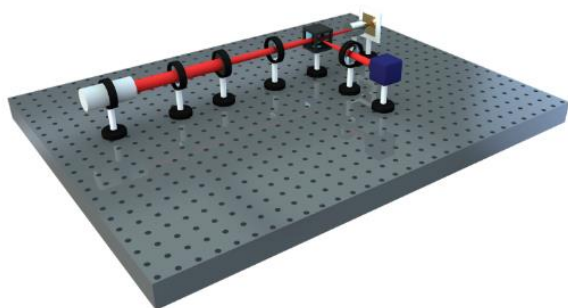
构建结构库



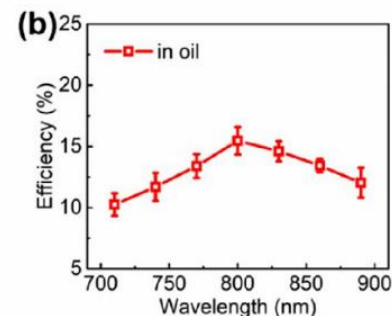
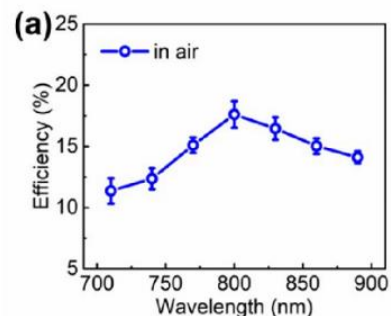
Advanced Materials **33(21)**, 2005864 (2021)

动态全息实验验证

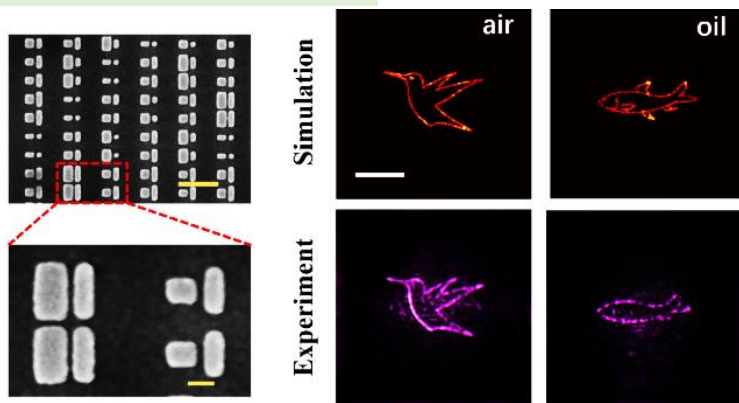
实验测量光路



工作效率 ~15%



全息拟态伪装测量

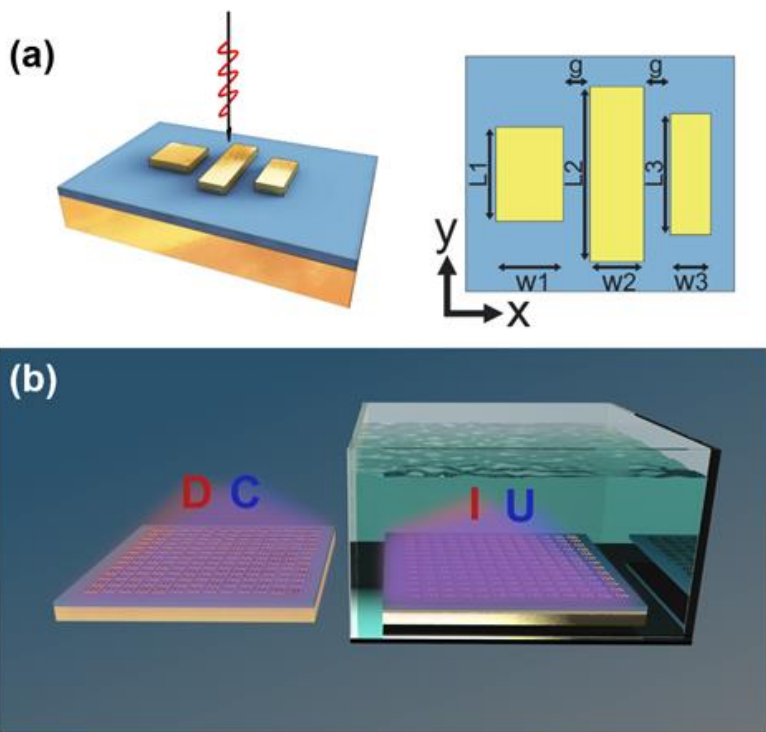


- 样品SEM照片，大小为 $200\ \mu\text{m}$ ，标尺依次为 $500\ \text{nm}$ 和 $100\ \text{nm}$ ；
- 在空气和液体环境下的样品测量结果：两张独立的全息图像，标尺为 $50\ \mu\text{m}$ ；

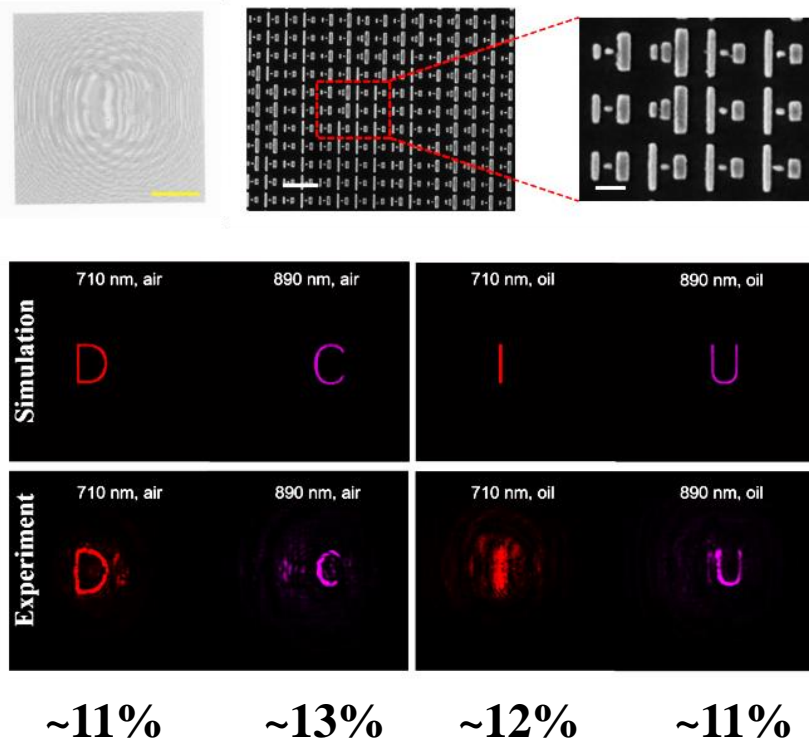
Advanced Materials **33(21)**, 2005864 (2021)

多维度混合调控实验验证

功能示意图

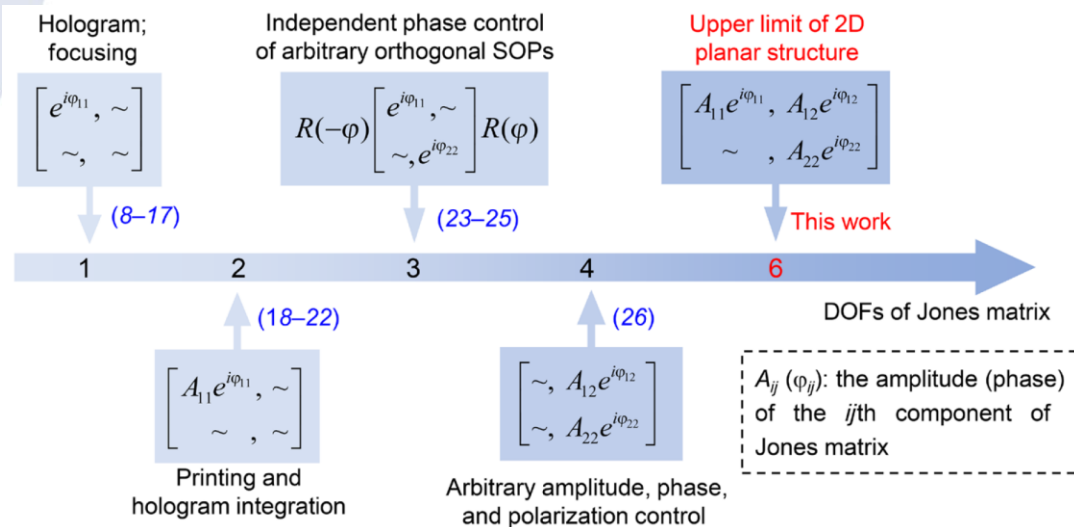


彩色动态全息实验

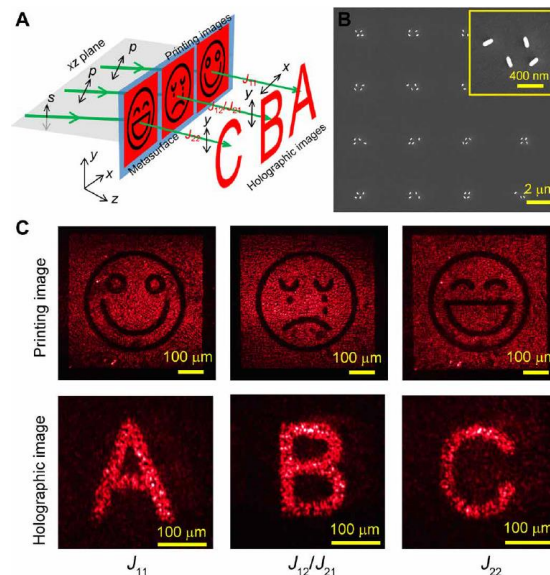
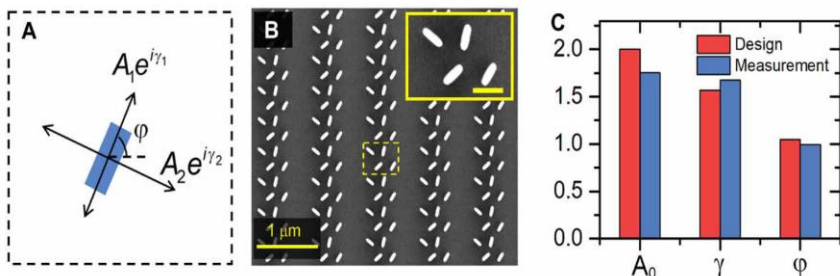


Advanced Materials **33**(21), 2005864 (2021)

超构表面中多通道偏振复用



$$J = R(-\varphi) \begin{bmatrix} A_1 e^{i\gamma_1}, 0 \\ 0, A_2 e^{i\gamma_2} \end{bmatrix} R(\varphi) = \begin{bmatrix} E_x & E_{xy} \\ E_{xy} & E_y \end{bmatrix}$$

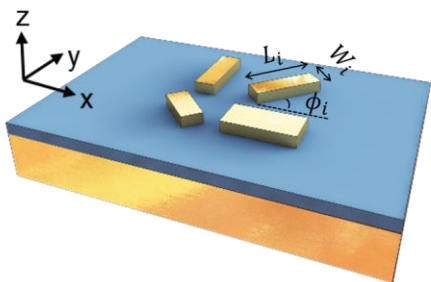


- 琼斯矩阵元带有特定的偏振方向；
- 3个矩阵元的复振幅独立可调；
- 对应3个偏振通道，可实现全息和印刷图像显示；

Y. J. Bao, et al. Sci. Adv. 7, eabh0365 (2021).

超定方程的求解

复合结构单元



$$\begin{bmatrix} E_x & E_{xy} \\ E_{xy} & E_y \end{bmatrix}$$

$$\begin{aligned} O_\theta &= [\cos \theta \quad \sin \theta] \begin{bmatrix} E_x & E_{xy} \\ E_{xy} & E_y \end{bmatrix} \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} \\ &= [\cos^2 \theta \quad \sin 2\theta \quad \sin^2 \theta] \cdot \begin{bmatrix} E_x \\ E_{xy} \\ E_y \end{bmatrix} \end{aligned}$$

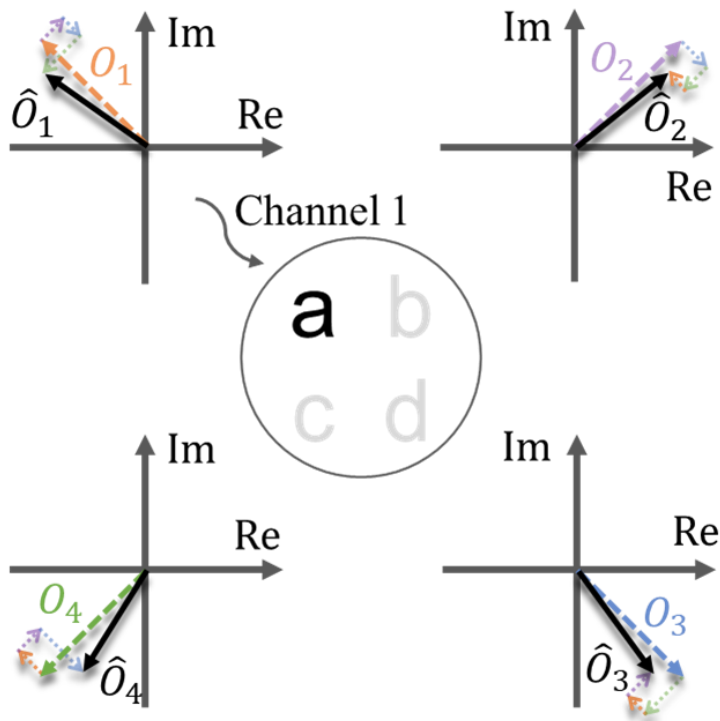
$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ \dots \\ O_M \end{bmatrix} = \begin{bmatrix} \cos^2 \theta_1 & \sin 2\theta_1 & \sin^2 \theta_1 \\ \cos^2 \theta_2 & \sin 2\theta_2 & \sin^2 \theta_2 \\ \cos^2 \theta_3 & \sin 2\theta_3 & \sin^2 \theta_3 \\ \dots & \dots & \dots \\ \cos^2 \theta_M & \sin 2\theta_M & \sin^2 \theta_M \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_{xy} \\ E_y \end{bmatrix}$$

- 兼容任意的线偏振方向;
- 将物理上的偏振通道数目问题转化成数学上线性方程组的求解性问题;

Science 379(6629), 294-299 (2023)

引入关联噪声：最小二乘解

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ \dots \\ O_M \end{bmatrix} = \begin{bmatrix} \cos^2 \theta_1 & \sin 2\theta_1 & \sin^2 \theta_1 \\ \cos^2 \theta_2 & \sin 2\theta_2 & \sin^2 \theta_2 \\ \cos^2 \theta_3 & \sin 2\theta_3 & \sin^2 \theta_3 \\ \dots & \dots & \dots \\ \cos^2 \theta_M & \sin 2\theta_M & \sin^2 \theta_M \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_{xy} \\ E_y \end{bmatrix}$$



1. 最小二乘解，产生新通道

$$O = A \cdot E \quad \hat{E} = (A^T A)^{-1} A^T O$$

2. 关联噪声的定义

$$\hat{O} = A \cdot \hat{E} = [A(A^T A)^{-1} A^T] O \equiv H \cdot O$$

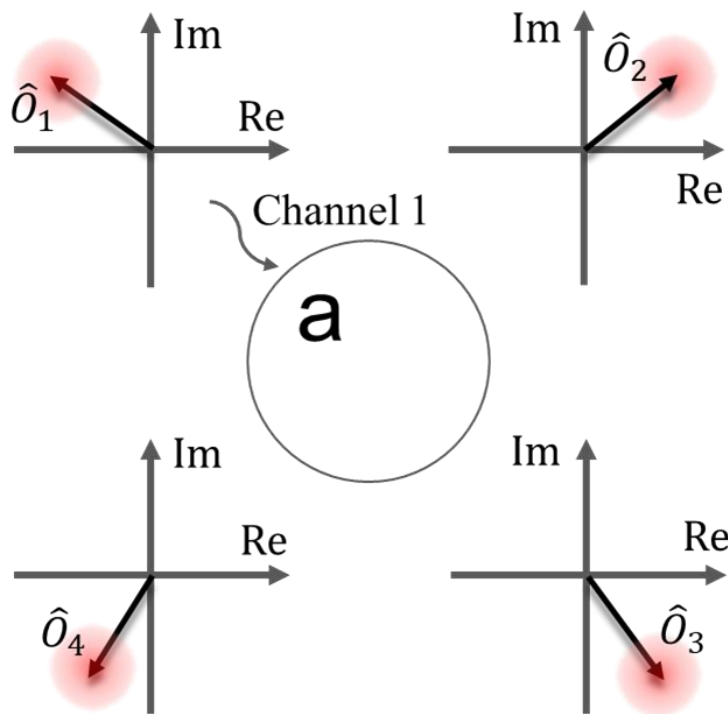
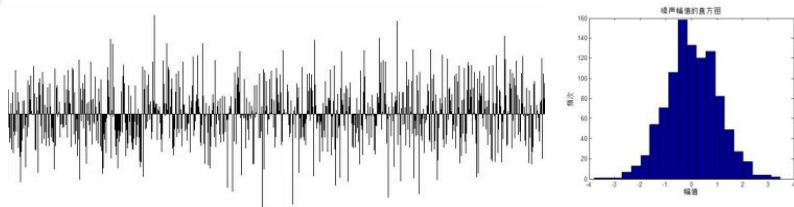
$$\Delta O_c \equiv |\hat{O} - O| = |A \cdot \hat{E} - O|$$

3. 新通道的串扰问题

$$\hat{O}_i = \sum_{j=1}^M H_{ij} \cdot O_j$$

Science 379(6629), 294-299 (2023)

引入非关联噪声：高斯白噪声



1. 加性高斯白噪声的定义

- 高斯白噪声(White Gaussian Noise)的概率分布是正态函数;
- 其在两个随机变量之间, 不仅是互不相关的, 而且还是统计独立的;
- 其是分析信道加性噪声的理想模型, 诸如热噪声等;

2. 引入过程

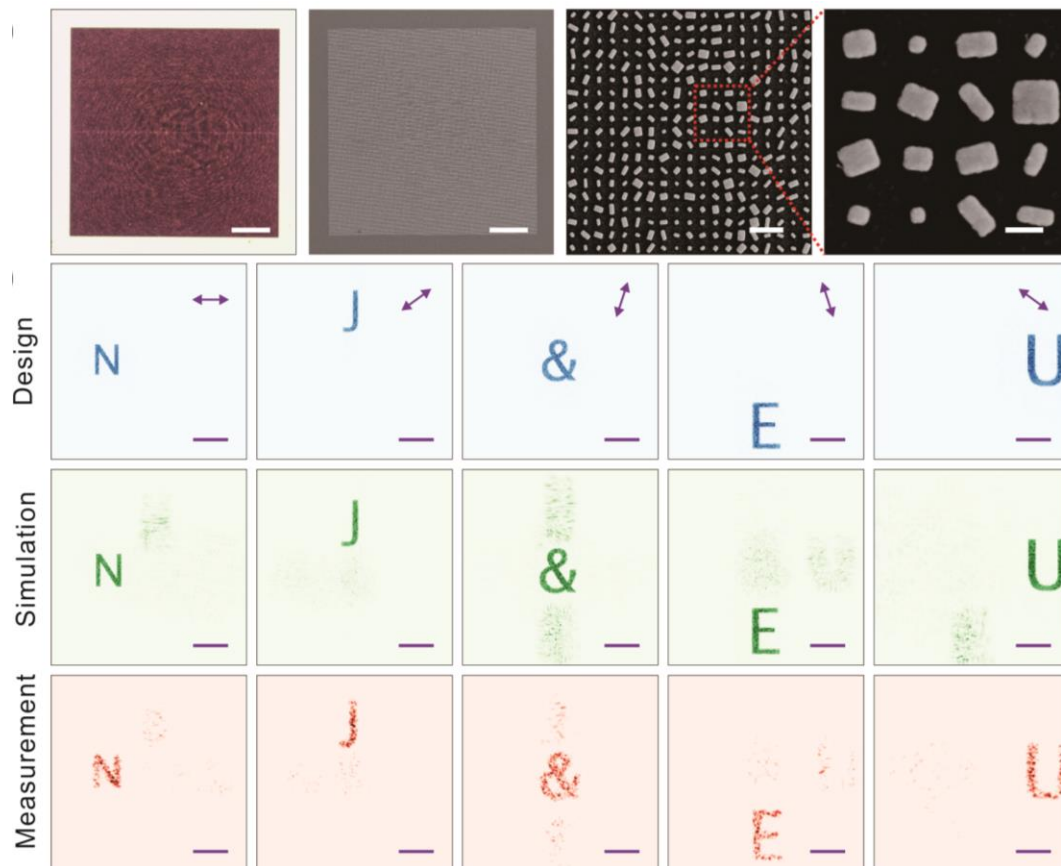
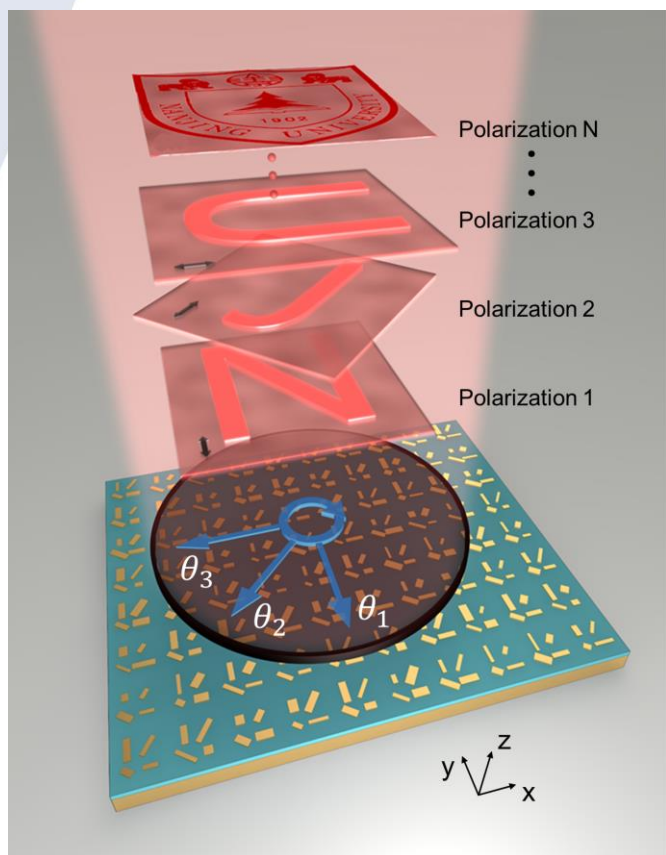
$$\hat{E}_n = (A^T A)^{-1} A^T \cdot O + \delta E$$



$$\begin{aligned} \hat{O}_n &= A \cdot \hat{E}_n = [A(A^T A)^{-1} A^T] \cdot O + A \cdot \delta E \\ &\equiv H \cdot O + A \cdot \delta E = \hat{O} + A \cdot \delta E \end{aligned}$$

Science 379(6629), 294-299 (2023)

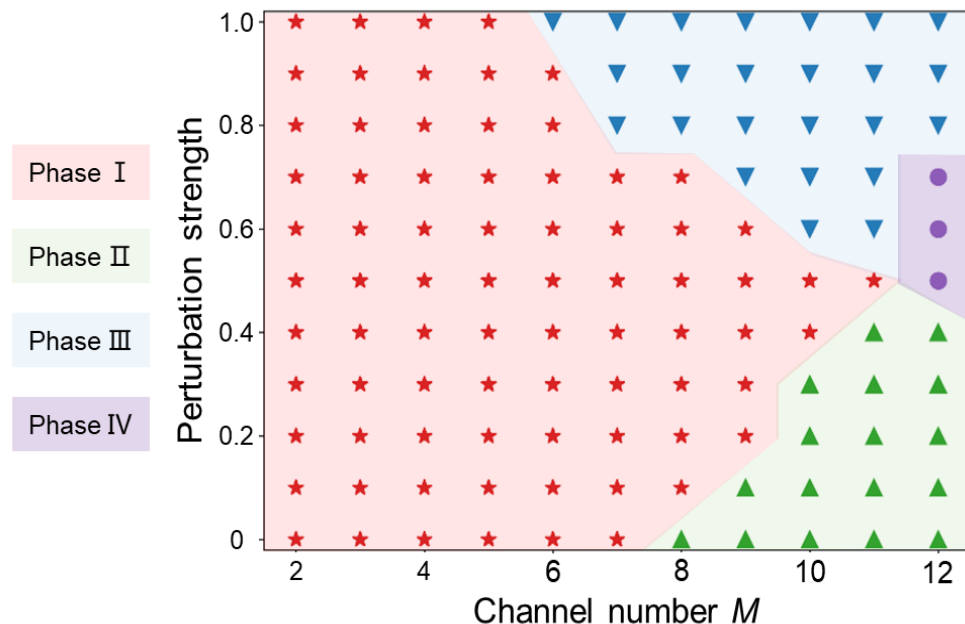
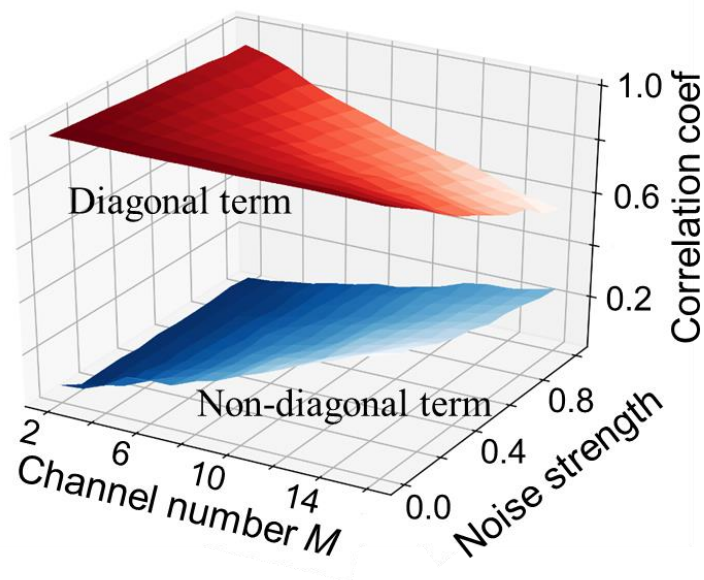
5通道实验验证



Science **379(6629)**, 294-299 (2023)

偏振复用相图

- 相图显示：符合阈值条件的最多偏振通道数目为11；
- 系数 r 过大会导致目标信号被破坏，过小则导致串扰太大；

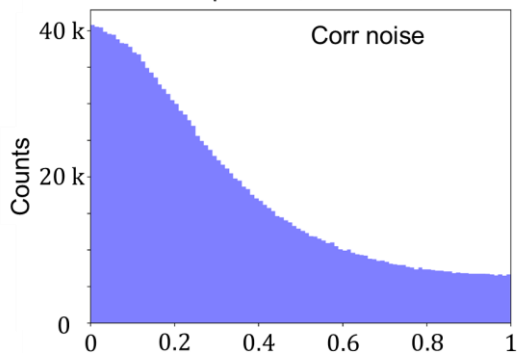


Science **379(6629)**, 294-299 (2023)

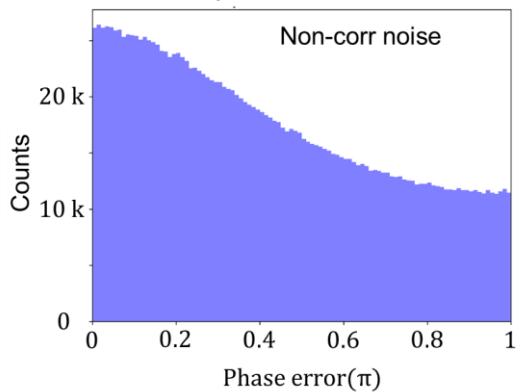
新上限的实验验证

噪声分布

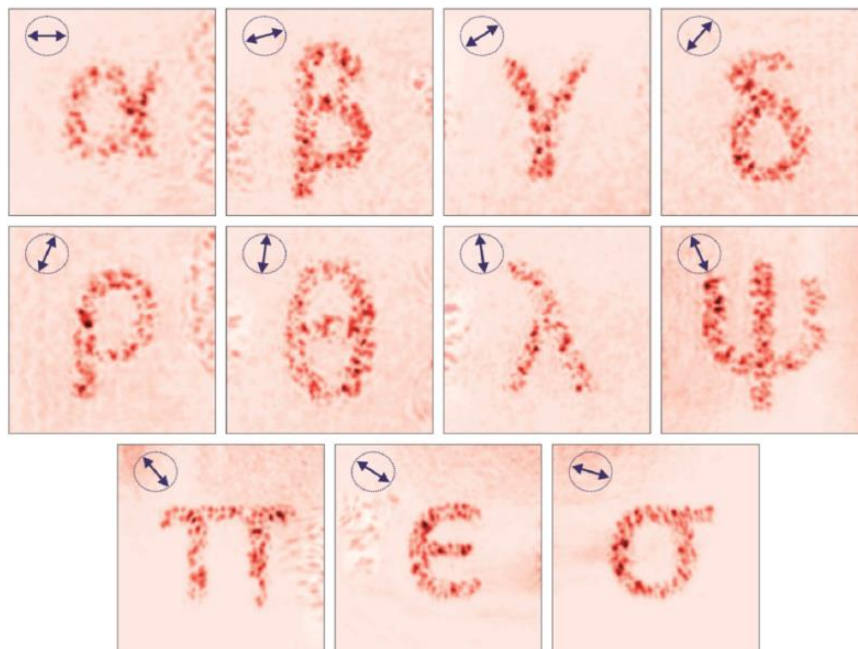
$\mu: 0.33, \sigma: 0.26$



$\mu: 0.42, \sigma: 0.28$

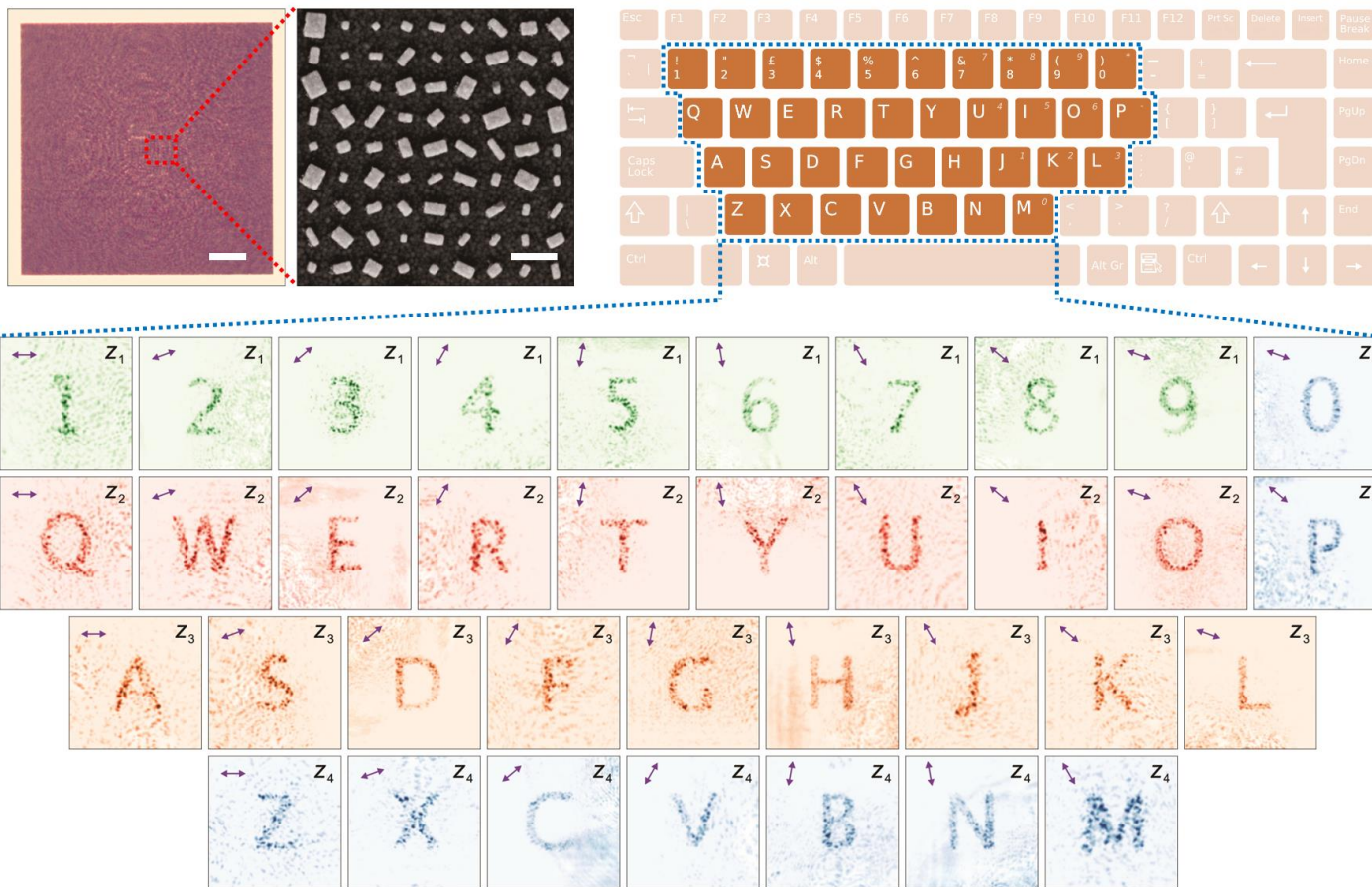


实验测量



Science **379(6629)**, 294-299 (2023)

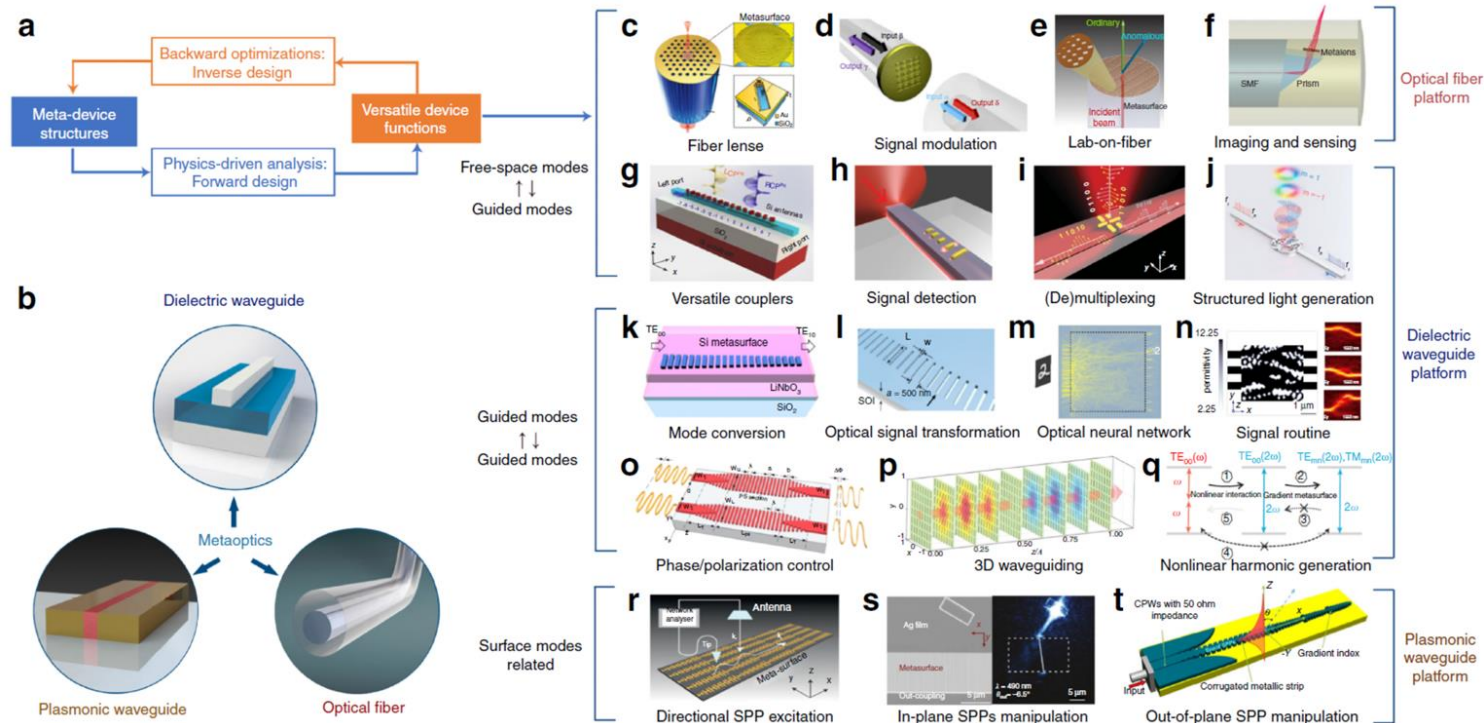
兼容性的验证：偏振+空间位置



Science 379(6629), 294-299 (2023)

基于超材料的集成光学器件

超材料+片上波导器件



- 波长复用解复用器
- 偏振控制器
- 模式控制器
- 光纤耦合器
-
- ✓ 超紧凑尺寸
- ✓ 设计灵活
- ✓ 功能多样

Yuan Meng et al, *Light: Science & Applications*, 10, 235 (2021).

目录

一、背景介绍

二、超构表面中多自由度调控

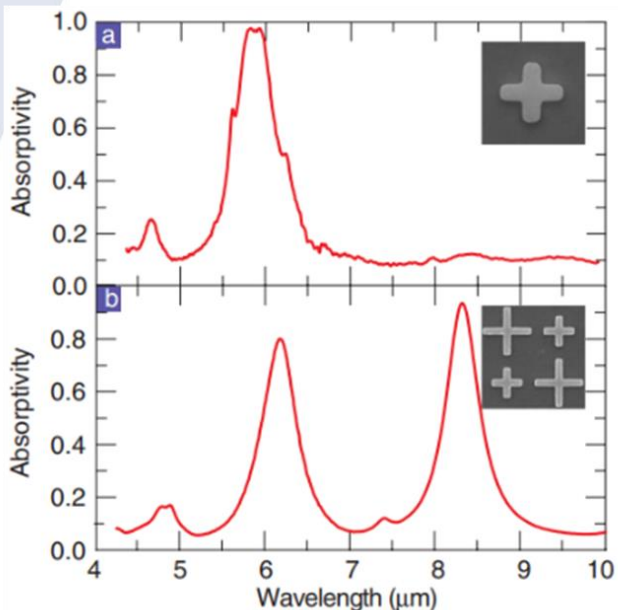


三、微纳器件智能逆向设计

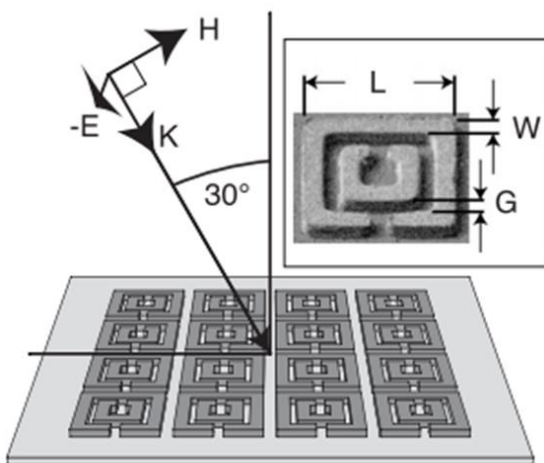
四、总结与展望

超表面人工微结构的设计

常规设计方法：物理直觉+简化模型+数值仿真

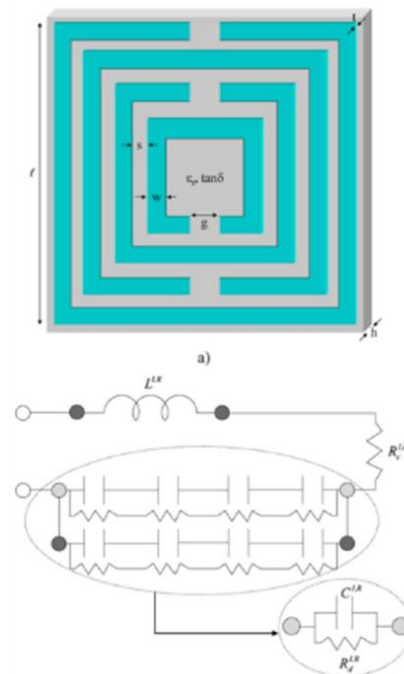


- 偶极电谐振子天线
- 尺寸决定谐振波长
- 不同尺寸复用



- 劈裂环 (split ring)
- 垂直方向磁场产生谐振
- 电谐振+磁谐振

T. J. Yen et al, *Science* **303**, 5663 (2004)



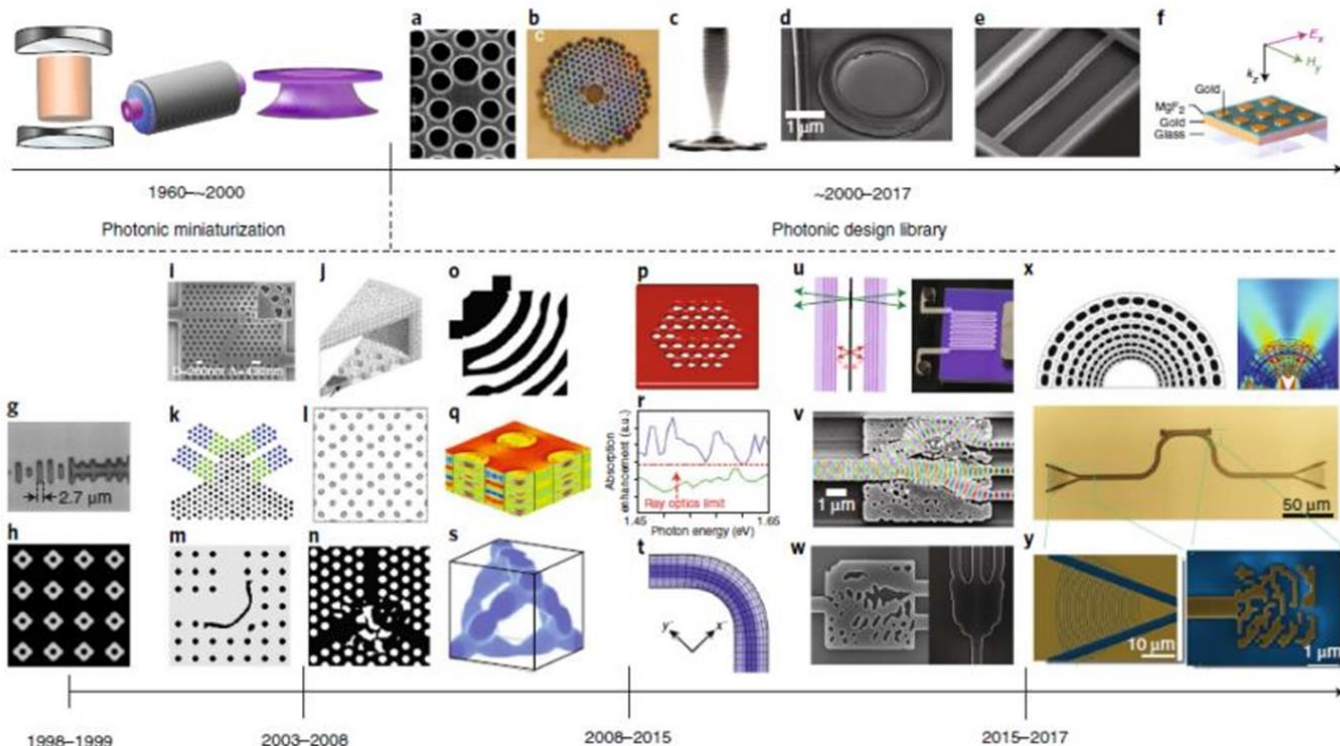
- 等效电路模型
- 电学参数拟合超表面响应

Filiberto Bilotti et al, *IEEE Transactions on Microwave Theory and Technique*, **55**, 12, 2007)

Xianliang Liu et al, *Physical Review Letters*, 107, 045901 (2011)

光子结构的逆向设计

逆向问题：给定光学响应需求，如何得到满足要求的最优设计？



光子结构小型化



基于模板的设计单元库



自由形状全自由度优化

设计问题



优化问题

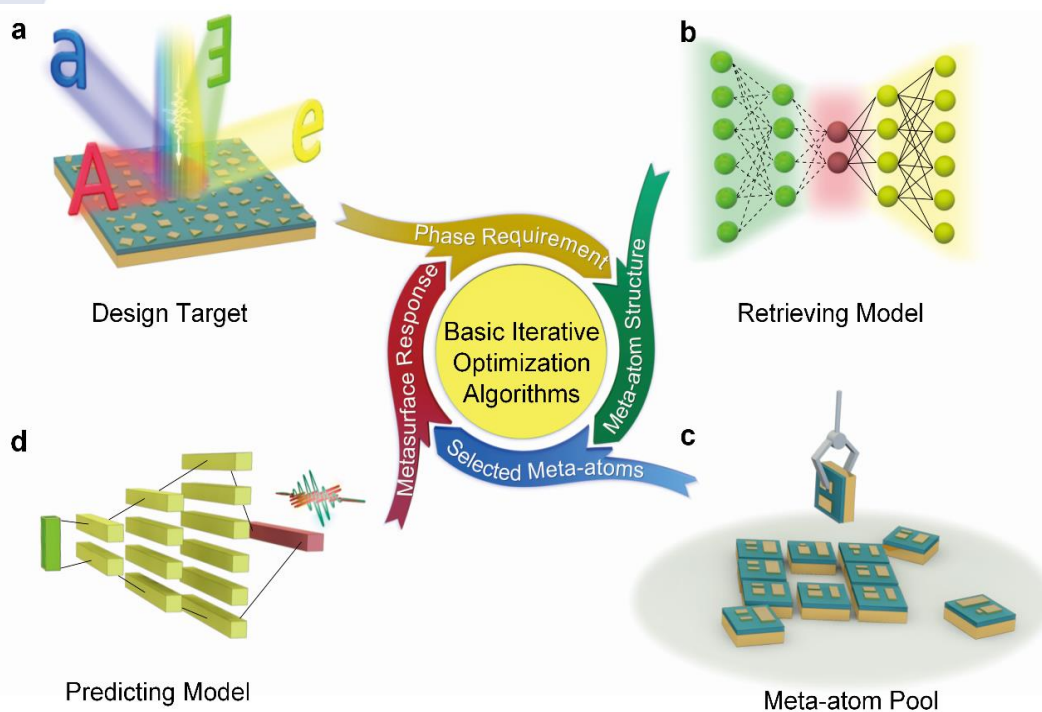
S. Molesky et al, *Nature Photonics*, 12, 11 (2018).

智能设计算法分类

	基于梯度的优化算法	基于非梯度搜索的优化算法	数据驱动算法
典型算法	伴随法、水平集法	遗传算法、粒子群算法，二元搜索，模拟退火算法	深度学习算法
算法特点	基于梯度下降，利用梯度信息指导优化过程	基于随机搜索，模拟生物进化、退火降温等过程	基于训练数据，通过神经网络学习发掘信息
优势	收敛速度快，设计自由度高	引入随机性，搜索范围广，可并行优化	模型灵活，设计速度快，设计多样性强
不足	容易陷入较差的局部最优解	大量依赖数值仿真评估优化中间结果，速度慢，同时可优化参数少	严重依赖训练数据的数量和质量

- ✓ 非常适用于大量功能、结构类似的光子器件设计
- ✓ 超材料&超表面

机器学习实现智能逆向设计框架



➤ 将机器学习模型嵌入到常规迭代优化算法中（如梯度下降算法、GS 算法）

➤ 超表面自动化设计和性能预测

✓ 正向预测模型：

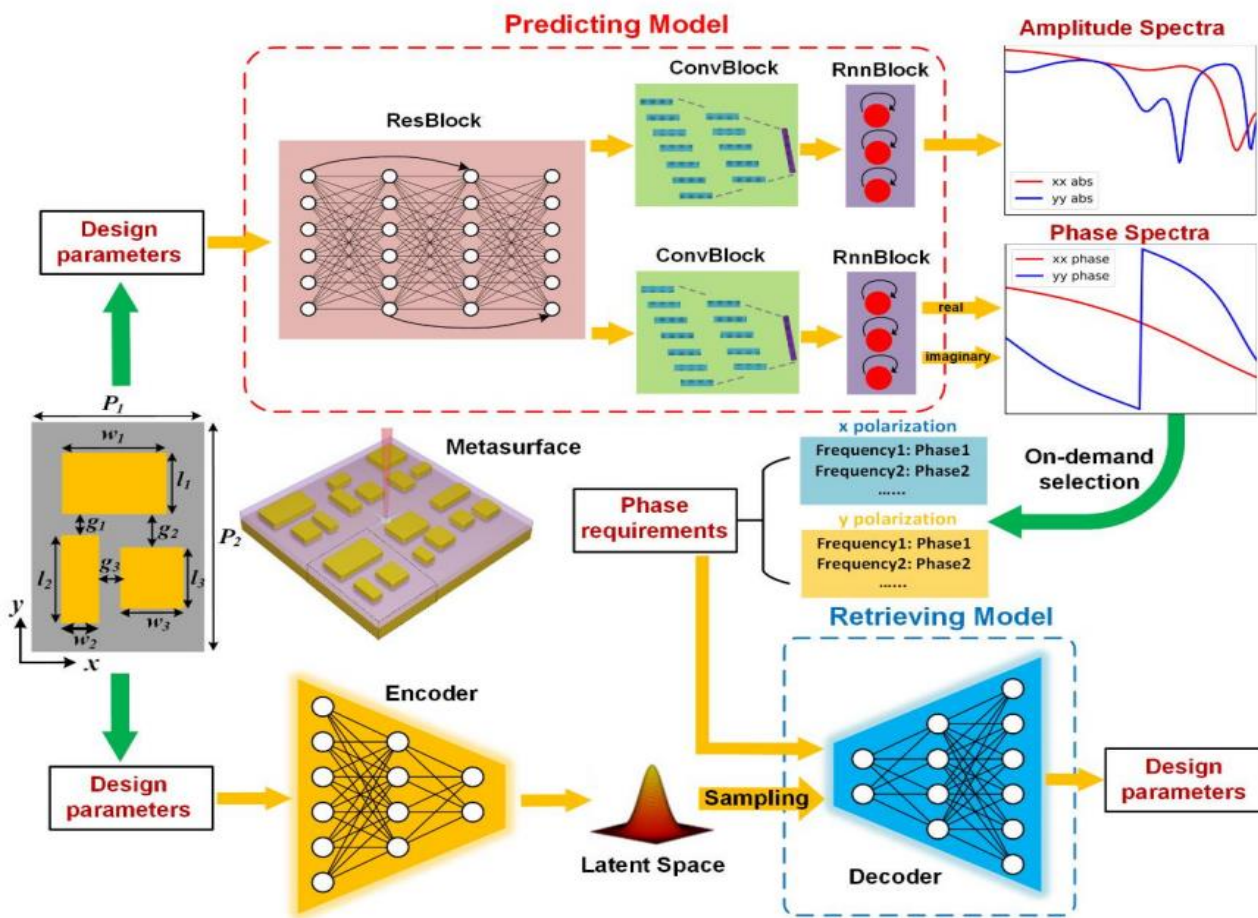
确定性建模，准确性

✓ 逆向设计模型：

生成式建模，多样性

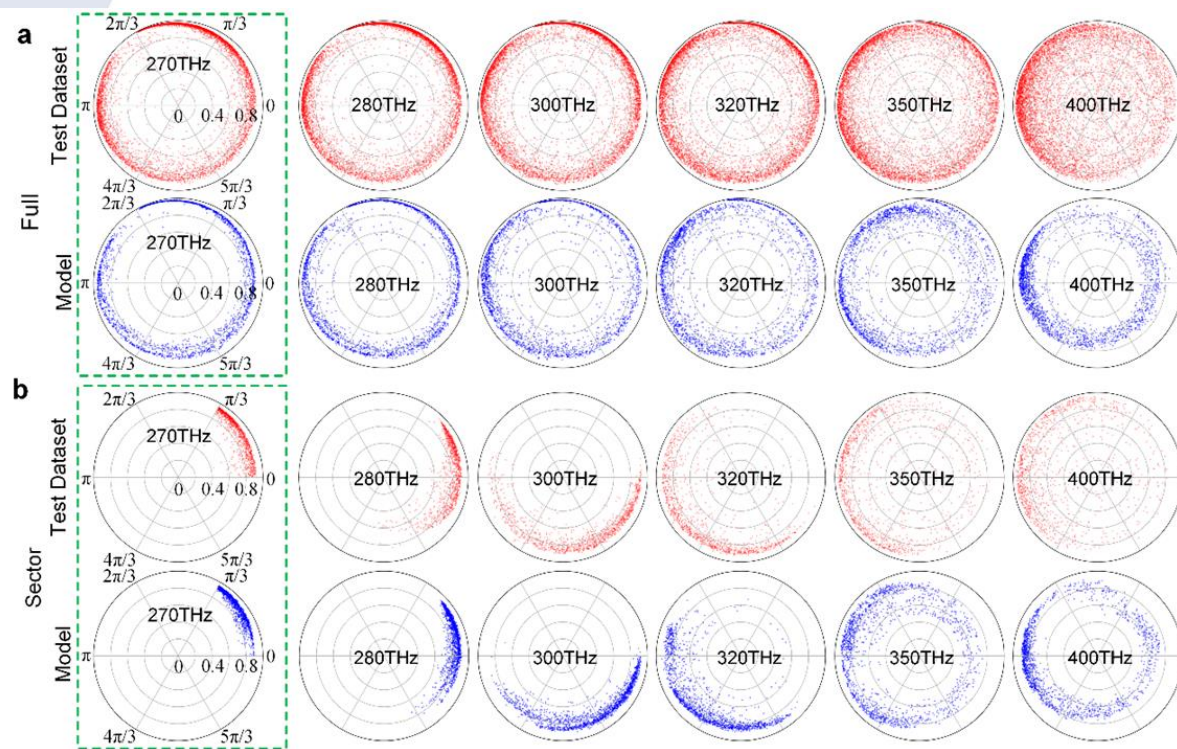
Advanced Materials, **34**(16), 2110022 (2022)

9个结构参数 VS 2条复振幅谱线



Advanced Materials, 34(16), 2110022 (2022)

生成模型：精准描述光学响应的统计分布

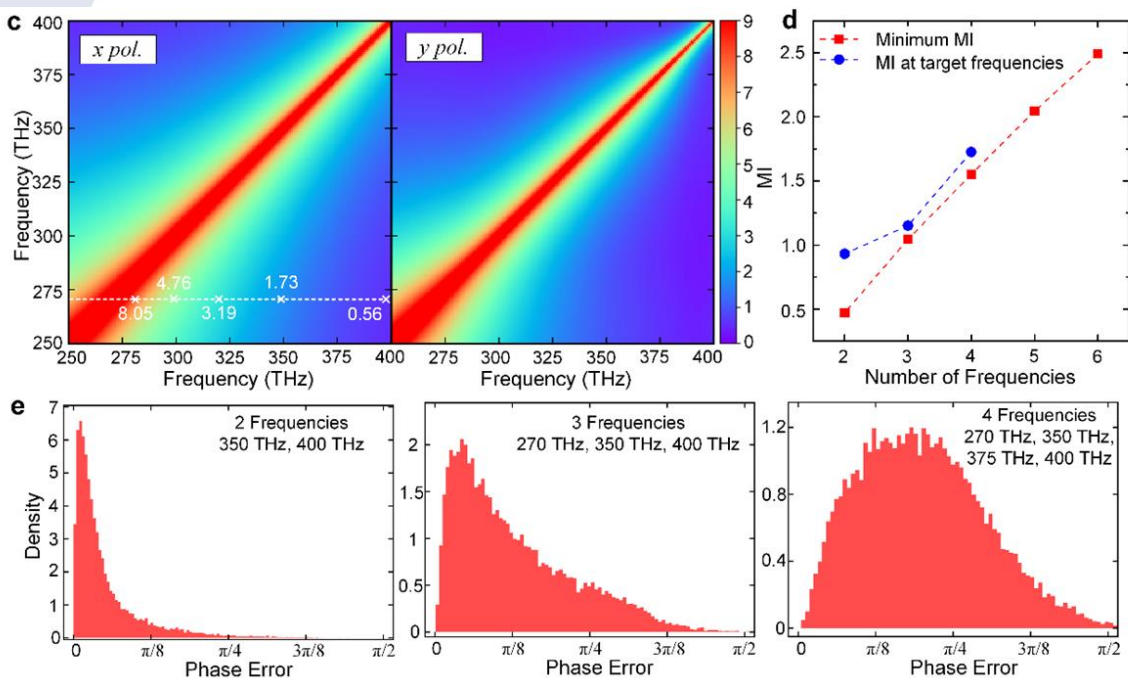


- a. 全部相位响应：(0, 2π) at 270THz
- b. 受限相位响应：(0, $\pi/3$) at 270THz

- 金属-介质-金属 (MIM) 结构
- 耦合矩形谐振单元 (Coupled Rectangular Resonator, CRR) 实现复杂的光谱响应
- 多功能超表面：多波长、多偏振设计
- 不同频率处超表面单元响应相互制约

Advanced Materials, **34**(16), 2110022 (2022)

超表面单元光学响应串扰描述与评估



- c. 计算得到的不同频点间反射系数的互信息值
- d. 最小可获得的互信息随着目标频率数的变化
- e. 随机给定相位值最佳计准的确率 v.s. 频率数目

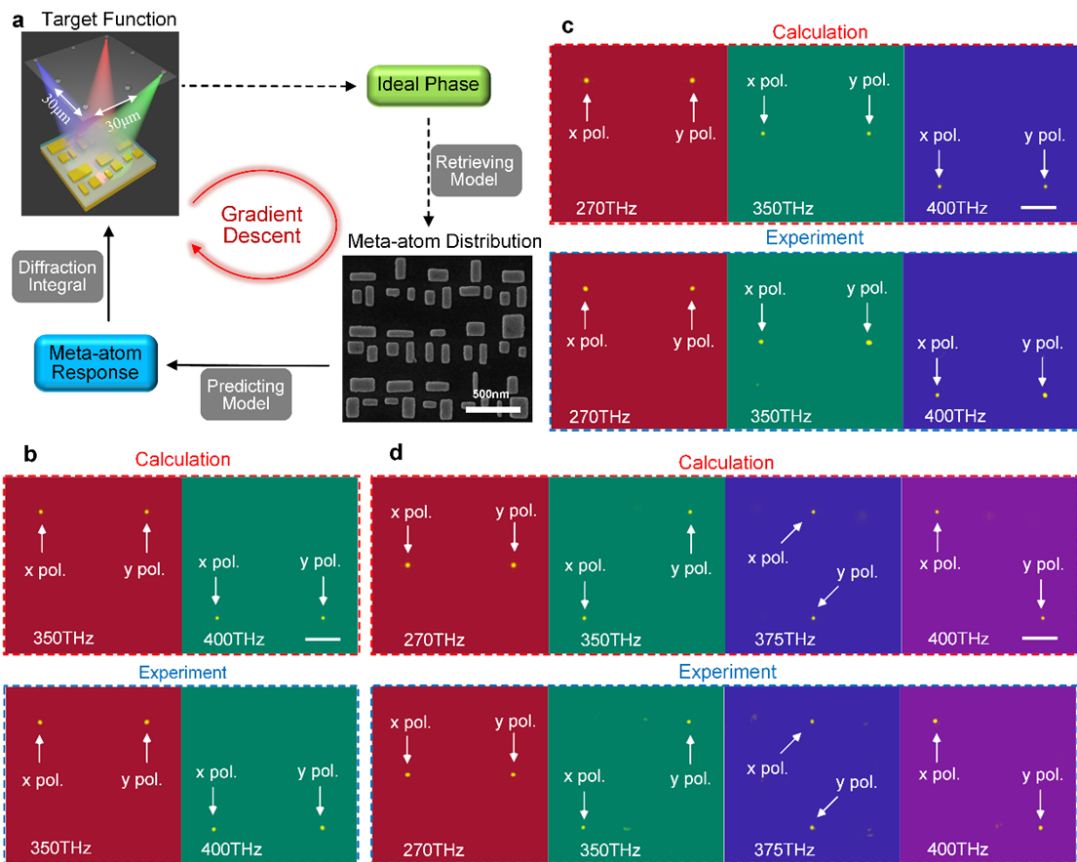
- 互信息 (mutual information, MI) 用于描述两个随机变量相互依赖的程度
- 对于两个随机变量 X, Y , X 与 Y 相互独立等价于 $I(X; Y) = 0$

$$I(X; Y) = D_{\text{KL}}(P_{(X,Y)} \| P_X \otimes P_Y)$$

- 靠近的两个频点的反射系数之间互信息较大
- 随着需要调控的频率数量增加, 平均的最小可达到互信息值增大
- 设计目标越多, 独立调控不同功能的难度越大!

Advanced Materials, **34**(16), 2110022 (2022)

多功能聚焦反射镜



- 将不同频率、不同偏振光聚焦到不同空间位置
- 最多可得到8个相对独立的功能：4个频率值和2个正交偏振态

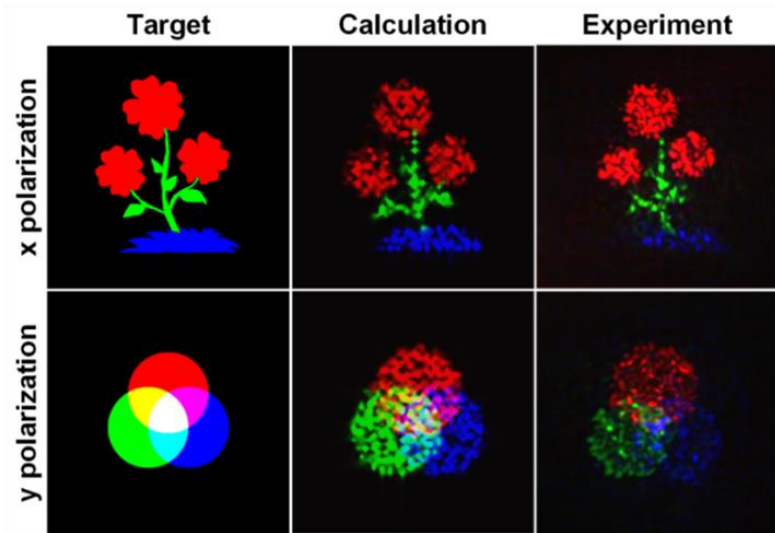
常规设计方法：

- 离散化相位（如8个相位值， $\pi/4$ 间隔）
- 根据所需相位寻找合适的meta-atom
- 根据得到的meta-atom组成超表面

对于一个4 频率、2偏振的超表面设计需要超过1600万(=8⁸)个meta-atom设计！

Advanced Materials, **34**(16), 2110022 (2022)

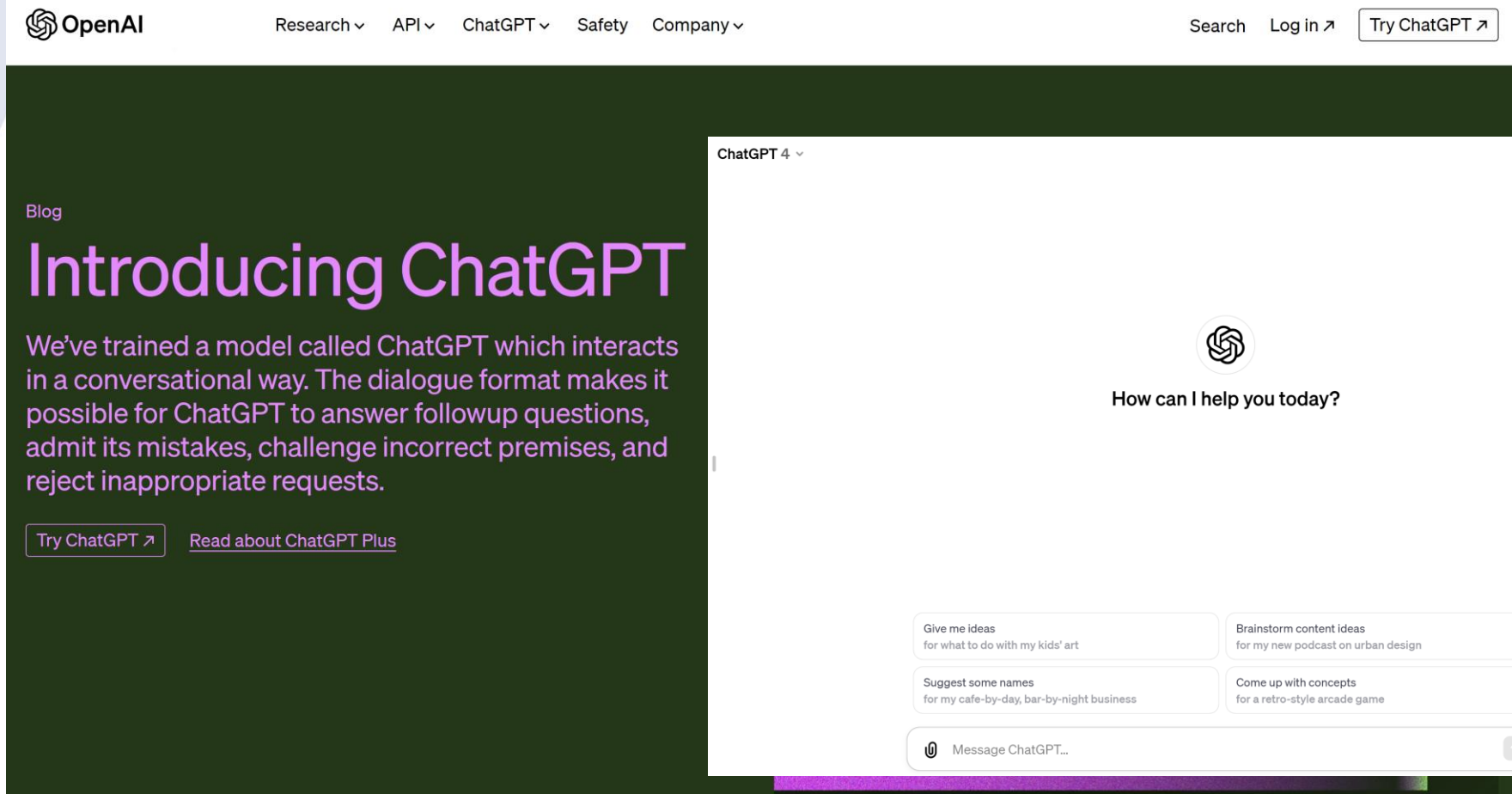
多功能全息显示



- 在不同频率、不同偏振光入射下实现不同的全息显示
- 最多可得到8个相对独立的功能：4个频率值和2个正交偏振态

Advanced Materials, **34**(16), 2110022 (2022)

Chat-GPT



The screenshot displays the OpenAI website. At the top left is the OpenAI logo. The navigation menu includes "Research", "API", "ChatGPT", "Safety", and "Company". On the right, there are links for "Search", "Log in", and a "Try ChatGPT" button. The main content area is split into two panels. The left panel features a "Blog" section with the title "Introducing ChatGPT" in large purple text. Below the title is a paragraph: "We've trained a model called ChatGPT which interacts in a conversational way. The dialogue format makes it possible for ChatGPT to answer followup questions, admit its mistakes, challenge incorrect premises, and reject inappropriate requests." At the bottom of this panel are two buttons: "Try ChatGPT" and "Read about ChatGPT Plus". The right panel shows the ChatGPT interface with the heading "ChatGPT 4". It features the OpenAI logo and the question "How can I help you today?". Below this are four example prompts in rounded rectangular boxes: "Give me ideas for what to do with my kids' art", "Brainstorm content ideas for my new podcast on urban design", "Suggest some names for my cafe-by-day, bar-by-night business", and "Come up with concepts for a retro-style arcade game". At the bottom of the interface is a text input field with the placeholder "Message ChatGPT..." and a send button.

Chat-GPT能做什么？

1. 用JPG图片格式上传八木天线的作业。

作业如下：

Consider a vertically (z) polarized Hertzian dipole near an infinitely-large perfect electric conductor (PEC) plane. Please change the distance d between the dipole and the PEC plate from half wavelength to quarter wavelength, and calculate corresponding radiation patterns at the xoz plane. You can use MATLAB to draw the patterns if necessary. Please give a physical explanation why the radiation pattern is unidirectional when the distance is equal to quarter wavelength. The case is very useful for understanding Yagi-Uda antenna (See below).

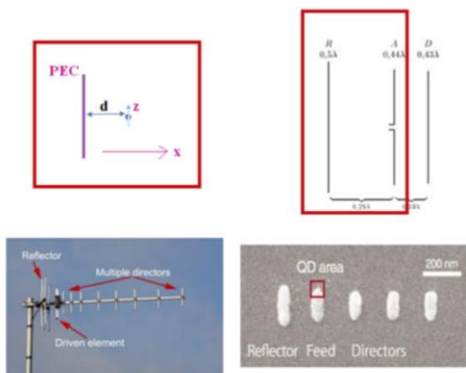


Fig. 2. The bottom two figures are the real-world Yagi-Uda antennas at microwave and optical regimes, respectively. QD area are the quantum dots as emitters. The top-right figure is a simple Yagi-Uda antenna and it composes reflector (R), driven source (feed A), and Director (D). The left-top figure takes the driven source (feed) as a Hertzian dipole and takes PEC plate as a reflector (The director is ignored). Then, you can learn how to convert a complex engineering problem to a simple mathematical model to unveil physics behind.

ChatGPT

为了完成这项作业，让我们深入了解赫兹偶极子(Hertzian dipole)在PEC (完美电导体) 平面附近的辐射模式的物理原理和计算方法。

物理解释：

当偶极子距离PEC平面四分之一波长时，偶极子辐射的电磁波在达到PEC平面时会反射。因为电磁波的相位在反射时会翻转180度，所以原始波和反射波之间在垂直于平面(即z方向)的相位差就会是半个波长。然而，在偶极子和它的镜像之间，即沿x轴方向，两者的相位会是相同的。这就导致在PEC平面一侧(z轴正方向)有相长干涉，增强了电磁波的辐射，而在另一侧(z轴负方向)有相消干涉，这意味着在那个方向上几乎没有辐射。这就形成了一个单向的辐射模式，这种效应在Yagi-Uda天线设计中得到了应用，其通过添加反射器和导向器来进一步增强这种单向性。

计算方法：

在MATLAB中，你可以用以下步骤来近似地计算辐射模式：

1. 定义常量：确定操作频率 f ，计算波长 $\lambda = \frac{c}{f}$ ，其中 c 是光速。
2. 建立坐标系：在 xoz 平面上建立坐标系，准备进行辐射强度的计算。
3. 计算电场：对于一个赫兹偶极子，垂直于PEC平面的电场分量可以用镜像法计算。在距离 d 处的电场可以表示为由偶极子和它的镜像产生的电场的叠加。
4. 计算辐射模式：利用电场的计算结果，你可以计算辐射功率密度。辐射模式可以通过画出功率密度随角度变化的极坐标图来表示。
5. 画图：使用MATLAB的极坐标或三维绘图函数来绘制辐射模式。

一边学术一边艺术

```
matlab
Copy code

f = 300e6; % 操作频率
c = 3e8; % 光速
lambda = c / f; % 波长
d = lambda / 4; % 偶极子到PEC的距离

theta = 0:0.01:2*pi; % 极坐标角度范围
E0 = 1; % 假定的电场强度

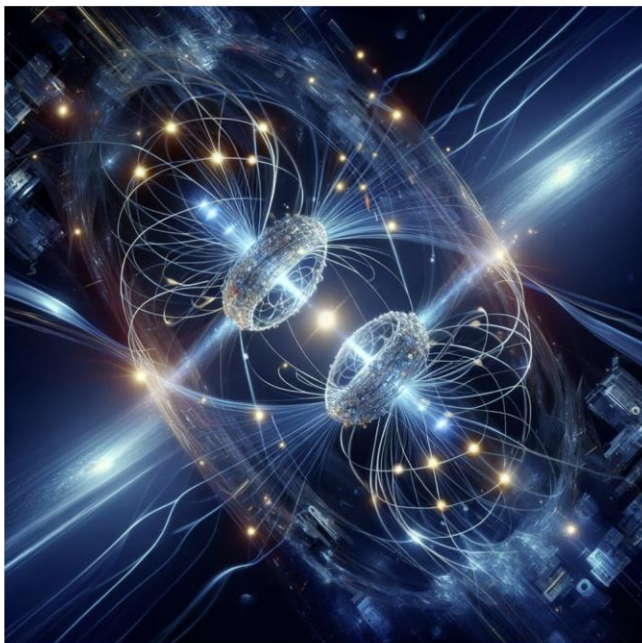
% 计算电场的干涉模式
E = E0 * (cos(2*pi*d*sin(theta)/lambda) + 1);
```

Chat-GPT能为科研做什么？

You

假设你是一名学术期出版社的编辑，请为一篇学术文章画一幅画，里面的内容是两个光子，飞向相反的方向。图片风格：科幻。

ChatGPT



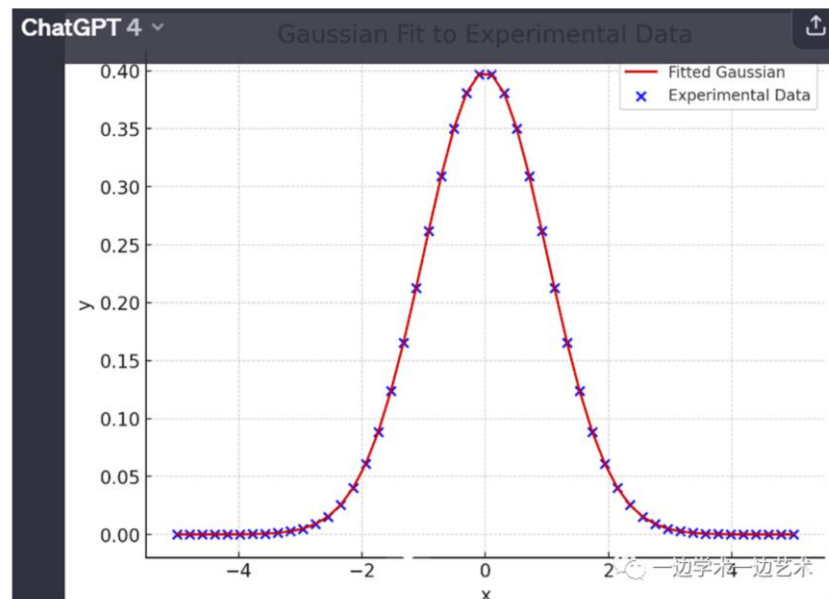
Here is the sci-fi themed illustration for your academic article, depicting two entanglement photons flying in opposite directions. Feel free to use this image for your publication.



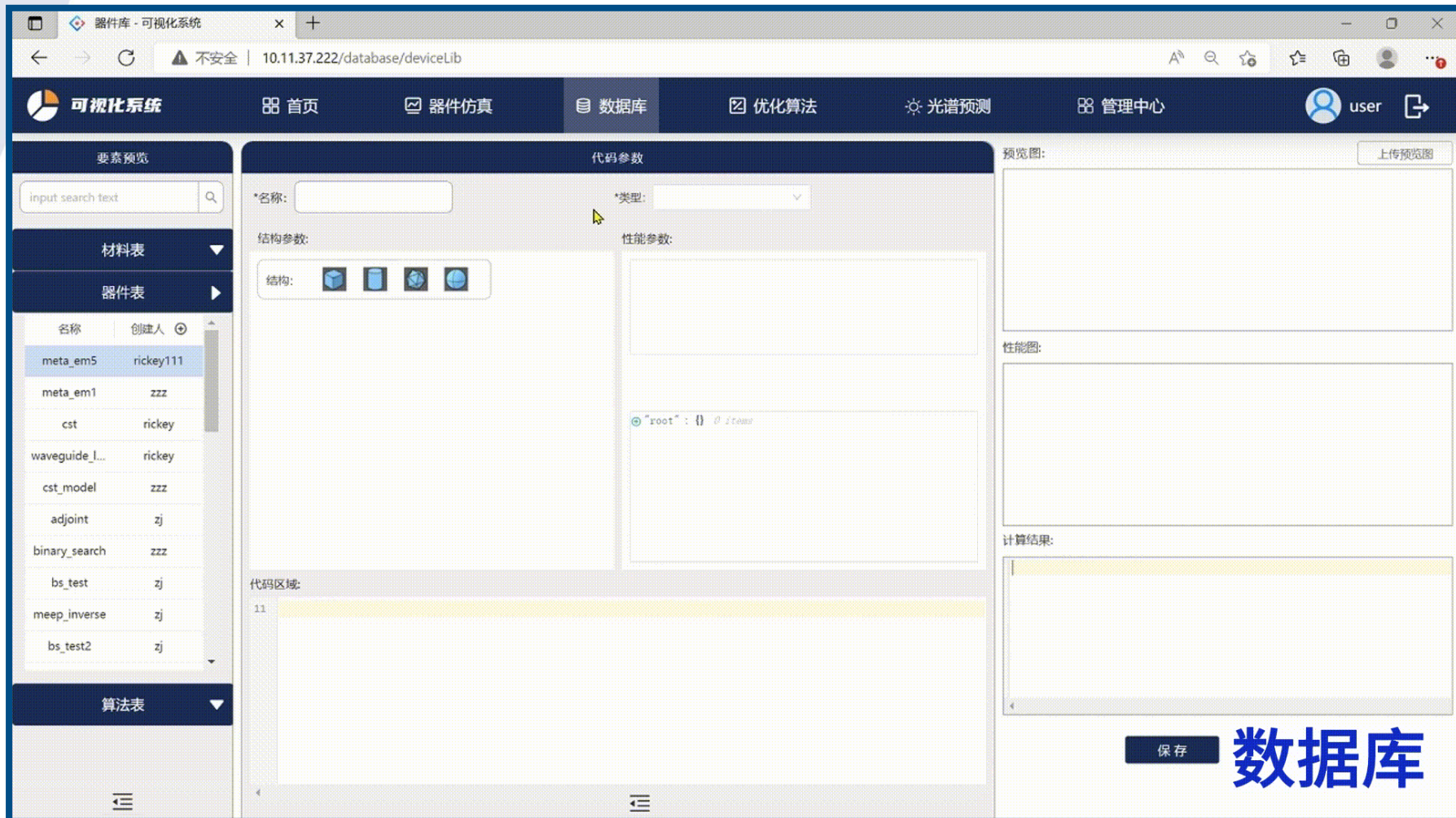
举一个很简单的例子。我们把一个高斯函数的数据上传到ChatGPT，让它对数据进行拟合，并得到半高全宽。



这是ChatGPT对数据的拟合：



自研智能设计软件平台



The screenshot displays the ISEE software interface, specifically the '数据库' (Database) section. The browser address bar shows '10.11.37.222/database/deviceLib'. The interface includes a navigation menu with options like '首页', '器件仿真', '数据库', '优化算法', '光谱预测', and '管理中心'. The main content area is titled '代码参数' (Code Parameters) and features a search bar, a table of parameters, and a code editor.

名称	创建人
meta_em5	rickey111
meta_em1	zzz
cst	rickey
waveguide_l...	rickey
cst_model	zzz
adjoint	zj
binary_search	zzz
bs_test	zj
meep_inverse	zj
bs_test2	zj

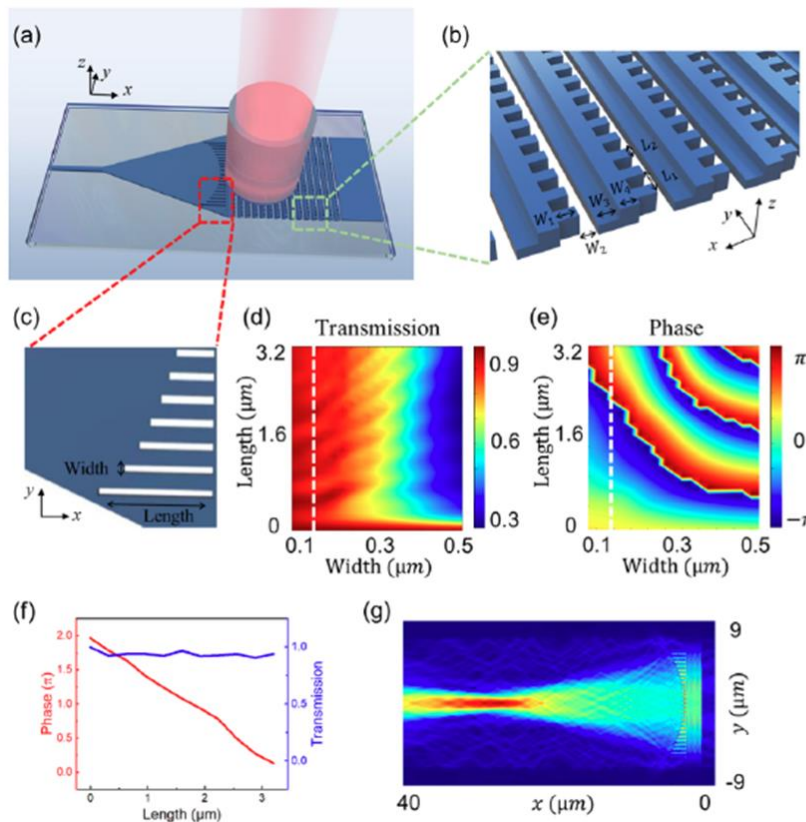
The '代码区域' (Code Area) shows a code snippet:

```

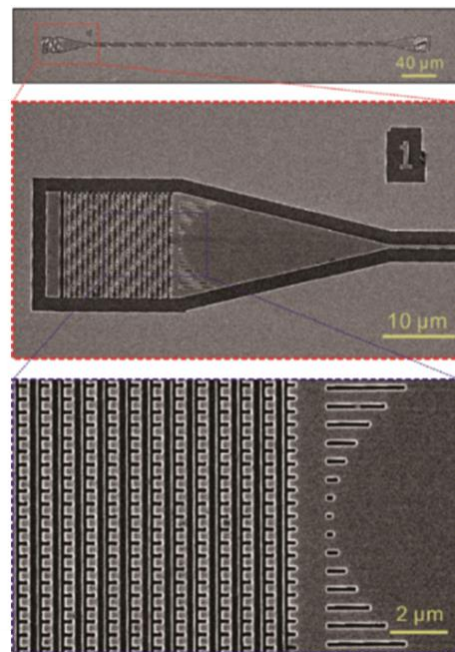
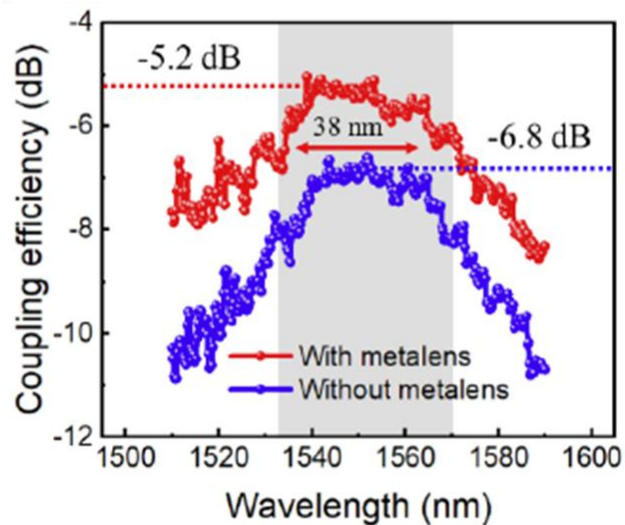
"root" : {} @ 21mm
    
```

At the bottom right, there is a '保存' (Save) button and a large '数据库' (Database) label.

垂直光栅耦合器

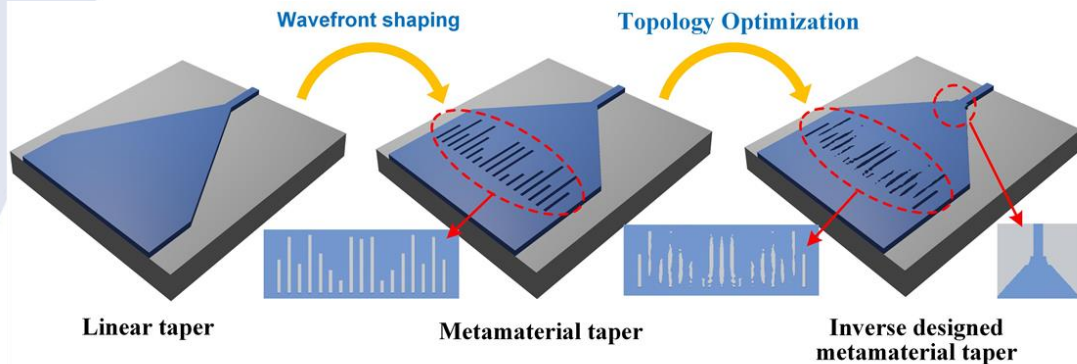


✓ 长度仅45 μm , 总体插损5.2dB

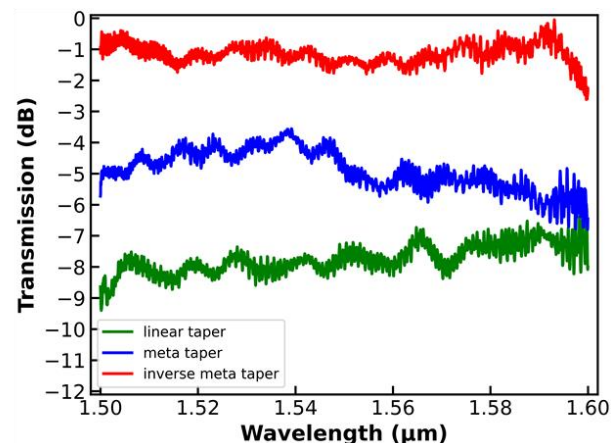
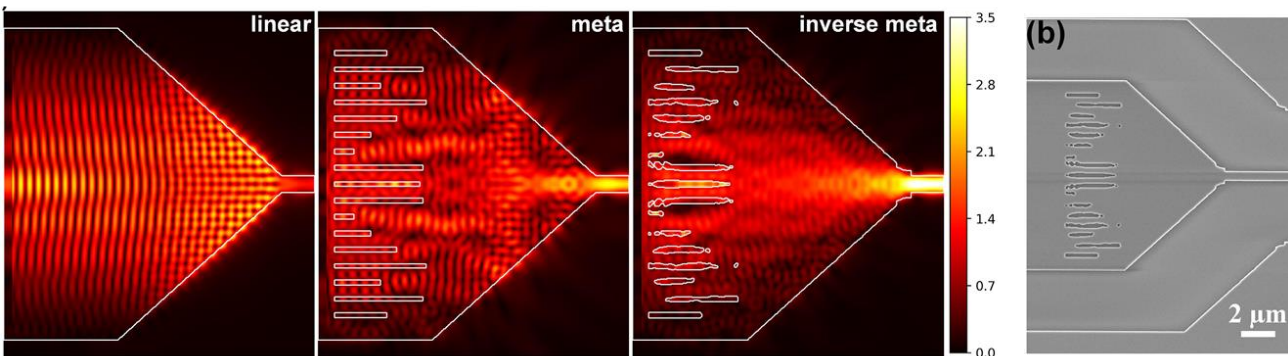


Optics Express, 30, 20 (2022)

片上超表面透镜初始设计+拓扑优化



- ✓ 常规结构片上超表面透镜到自由形状片上超材料taper
- ✓ 相比于常规线性结构长度小2个数量级



Nanophotonics, 12, 6 (2023)

目录

一、背景介绍

二、超构表面中多自由度调控

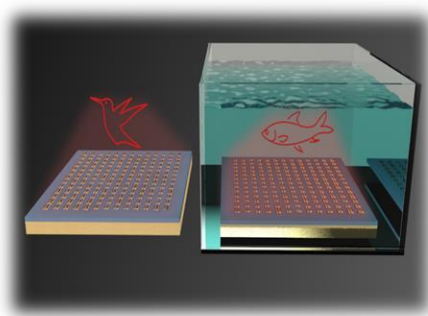
三、微纳器件智能逆向设计



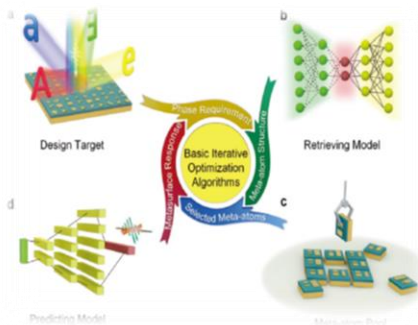
四、总结与展望

总结与展望

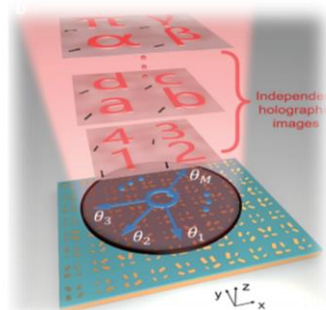
- ❑ The development of multifunctional devices through multiple degrees of freedom control in metasurfaces, including wavelength, polarization and dynamic control.
- ❑ A statistical data-driven model is proposed to link the structural parameters and the target performance, realizing multifunctional metasurface lenses and holograms.
- ❑ By introducing the correlated noise with least squares estimation and noncorrelated noise with a random distribution, new independent polarization channels can be created and thus push the limit of polarization multiplexing.



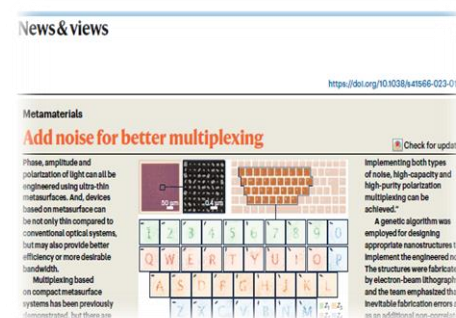
Advanced Materials
33(21), 2005864 (2021)



Advanced Materials,
34(16), 2110022 (2022)



Science 379(6629),
294-299 (2023)



Nature Photonics 17(4),
294-294 (2023)

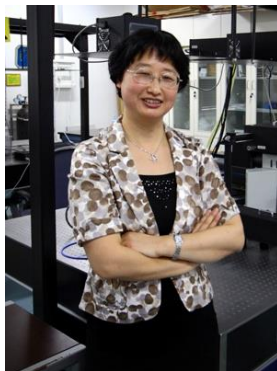
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Nanjing University



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Nanjing University



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- 美国东北大学：Yihao Xu & Lin Deng



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