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光学学报

多维度大容量超表面全息及光场变换

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摘要 超表面的设计与制造极大地推动了在片上紧凑光学系统中实现光场调控的应用。传统光学系统中的光学透镜、空间光调制器以及偏振光学元件虽具备光场调控的功能，但体积庞大、光场调控功能单一等因素限制了其应用。超表面为光场调控提供了新平台，有望解决传统光学元件和系统向微型化、集成化和多功能化发展的瓶颈。主要围绕超表面的多维度全息混合复用、二维/三维光场变换、矢量光场的产生与操控三方面进行介绍。最后，对超表面的未来发展趋势进行了展望。

关键词 超表面；多维度光场调控；全息成像；光束整形

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1 引 言

近些年来，超表面因其强大的光场调控能力引起了国内外研究人员的广泛关注。超表面可视为“降维”后的超材料，可表现出自然材料中不存在的电磁响应特性，它通常由单层亚波长尺寸的金属或介质纳米天线阵列构成，能够以亚波长分辨率对出射光的振幅、相位、偏振等多个物理量进行任意操控[1]。传统光学元件主要通过光在传播过程中的相位累积来调控光场，超表面则提供了一种通过光与超原子结构的相互作用，在亚波长距离内调控光场特性的新方法[2]。不仅如此，针对超表面的研究实现了平面光学的超薄化，利用超表面进行光场构造、操控的相关学科理论和功能应用已经成为了国际上竞相争夺的科技战略制高点。基于超表面对出射光的多物理量进行操控，能够实现光的异常折射[3-5]、光束整形[6-9]、超透镜[10-13]、全息成像[14-17]、增强现实[18-19]等功能应用。

如图 1 所示，研究者们提出了多维度超表面全息混合复用、二维/三维光场阵列产生、矢量光场的产生与操控等新原理和新方法，实现超表面由单一维度、单一功能到多维度、多功能应用的突破，解决传统光学元件和系统向微型化、集成化和多功能方向发展的瓶颈。研究成果在复杂波前调制、激光雷达、高密度全息存储、虚拟/增强现实、光信息处理、大容量光场调控等领域具有重要的理论价值和应用前景。

首先，研究人员利用多维度超表面全息混合复用的新原理，提出了多维度角度-偏振-空间位置、空/频域同时调制以及定量关联超表面全息混合复用。创造了多种崭新的全息算法设计，包括多维度合成谱法、定量关联振幅全息、地图索引的不规则面型全息算法等。该系列算法能与超表面光场调控机制相适配，实现多参量联合调控，突破了传统全息数学物理内涵，从而提高信息维度，解决算法赋能的挑战[20-22]。其次，提出了单片超表面产生二维/三维光场变换的新方法。通过介质超表面复振幅调控，实现二维独立可选择性衍射级次激发和能量分配。通过将达曼涡旋光栅、螺旋波带片和透镜因子相结合，实现空间拓扑电荷数可控的三维涡旋阵列和可控操纵，打破了传统空间复用局限性，解决系统集成度受限难题，信息容量提高三个数量级[23-25]。发展了达曼优化设计思想，采用纯相位调控实现了二维贝塞尔光束阵列的产生。同时，提出了空间逐点偏振调控新方案，该方案实现高阶矢量偏振光的产生，极大提高偏振态控制和演化性能，突破偏振调控模式单一、信道数有限的限制[26-27]。建立了超表面多通道矢量偏振调控新模型，揭示单层超表面琼斯矩阵调控规律，提出并验证不同偏振通道实现关联相位

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调制的可行性，实现12个偏振通道的7种不同偏振矢量全息的再现并提供三重信息加密维度。

本文将围绕利用超表面实现多维度全息混合复用、二维/三维光场变换以及矢量光场的产生与操控等方面展开讨论，并对超表面未来的发展趋势进行展望。

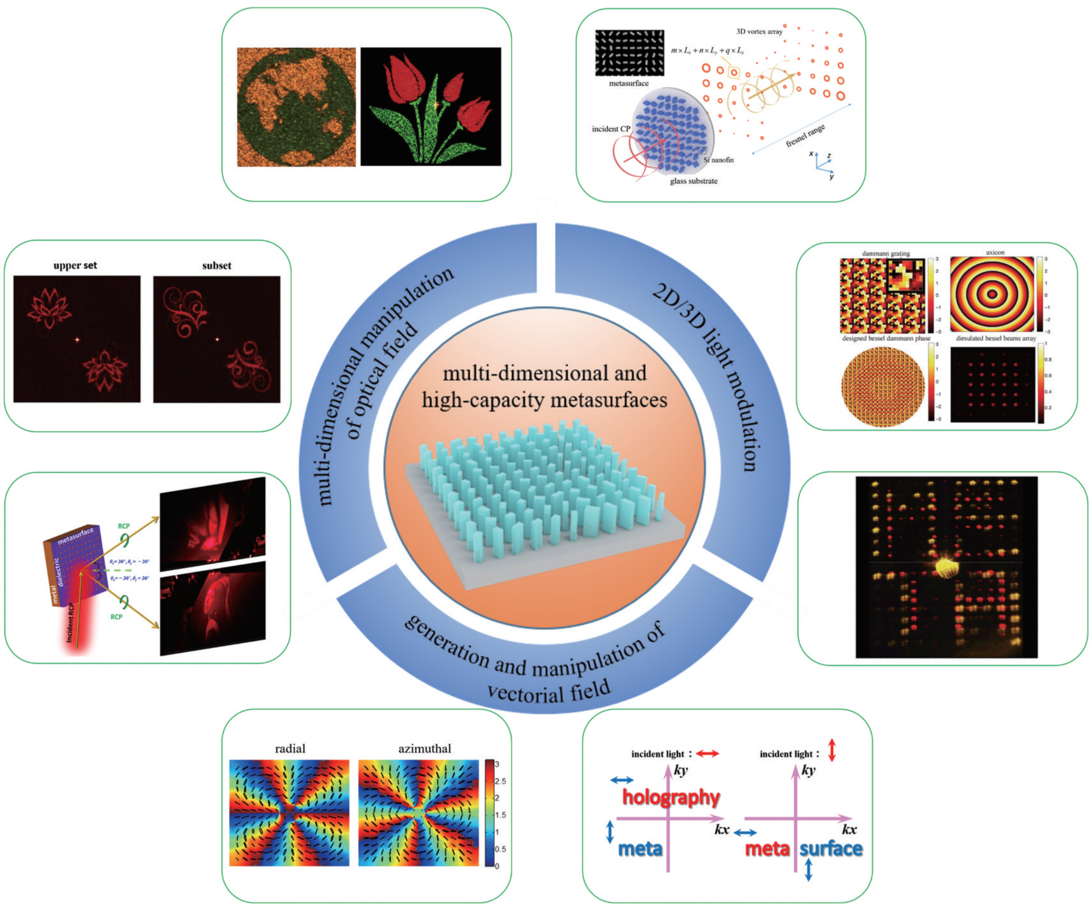

图1 超表面多维度调控（从上至下分别为多维度全息混合复用、二维/三维光场变换、矢量光场的产生与操控）

Fig. 1 Multi-dimensional manipulation of optical field based on metasurfaces (images from top to bottom are multi-dimensional holographic hybrid multiplexing, 2D/3D light field modulation, and vectorial light field generation and manipulation)

2 多维度全息混合复用

全息技术主要利用“干涉记录、衍射再现”的原理记录并恢复全部光场信息，可认为是实现复杂波前调制和重建的有力工具。然而，当前全息可刷新调制器件存在时空带宽积受限、再现像分辨率低、视场角小等不足之处。因此，迫切需要发展新的全息方法来拓展多维度全息，如扩大时空带宽积、提升全息算法的计算效率等。超表面具有亚波长像素的特征，每个像素都能对光场进行独立的调控，其各向异性的光学性质以及丰富多样的几何设计自由度有利于更精细的新型光场构造。对于各种光参量的联合调控研究揭示并发展一系列新型超表面全息显示和光学加密方法，取得重要的突破。

超表面最早的全息复用方法是使用定制的交叉纳米天线阵列组成的双折射超表面[28-31]，通过空间复用方案实现全息复用。然而，此类方案对特定全息再现像进行重建时，仅利用了部分像素所提供的相位分布信息，超表面的利用率较低。为了提高超表面全息的信息容量，研究者们提出几何相位超表面，实现了宽带、多参量全息复用。如图2(a)所示，通过设计基于金属棒形状纳米天线组成的几何相位超表面，利用其独特的手性选择性，将光场的相位分布信息编码到超表面中，使之具有多个自由度，该设计实现了偏振、位置、角度混合复用，从而提供了一种可见光和近红外波段的亚波长像素、超薄、大视场角、大容量、多种复用方式结合的全息复用方法。通过选择合适的入射光参量以及透射光参量作为图像再现的“密钥”，实现多幅图像的同时再现，提高超表面的信息容量和密度。在此基础上，探索在纯相位调制条件下，通过采用天线-介质-金属基底结构提高超表面的能量利用率，获得裸眼可观测的全息再现像，再现像的放大率可达540倍[20]。相比于传统全息复用方法，超表面具有宽带再现、大视场、高分辨率等优势。该工作指明了超表面全息复用的可行性，在紧凑的空间内执行大量并发任务，能够有效地增加通道数，可用于高密度的全息数据存储、光学信息处理等。

另一方面，光谱响应为设计超表面提供了新的自由度。通过改变超原子的几何形状、尺寸大小、材料特性和空间排布方式，影响其谐振模式和谐振强度，进而改变超表面的光谱响应特性，这些改变直观地体现在描述其透射、反射、吸收或其他物理量的光谱响应曲线中。通常，基于超表面的光谱调制在实现彩色印刷以及彩色全息等方面具有很大潜力[32-39]。与使用油墨或染料来着色的传统印刷方式相比，超表面彩色打印技术具有持久耐用、无环境污染、颜色丰富、色域广、分辨率高等优点[40-43]。超表面彩色打印技术能够在光学衍射极限下实现彩色显示。然而，此前报道的大多数彩色打印超表面无法重建全息图像，因为它们并不编码相位分布或深度信息。同样地，大多数超表面全息图也无法调制出射光的光谱响应，在非相干光照明下通常表现为随机且无特征的图案。为了进一步提高元超表面的信息容量并拓展其设计自由度，2019年，研究人员提出了在空域和频域同时调制的方法以实现单层超表面的彩色印刷与彩色全息。通过使用不同结构色对应的光谱响应的多种介质纳米天线作为基本组成单元来构建全介质超表面，实现了微纳全息技术与超表面的彩色印刷技术的结合。提出了基于彩色印刷模式下的彩色图案区域划分进行索引的全息算法，该算法可获得波长复用超表面全息图针对不同波长的相位分布。如图 2(b)所示，该全介质超表面能够同时调制超表面的光谱响应和出射波波前的空间相位分布，在白光照射下呈现出彩色图案，同时能够在特定波长相干激光的照射下，在远场分别重建不同的全息再现像，实现极低串扰的高质量彩色全息[21]。该工作创新性地利用几何相位和频谱解耦突破空域/频域难以同时调制的难题，为超表面提供了白光与相干光作用下的双工作模式。

作为另一个重要的设计自由度，光场的振幅信息同样可以用于全息图再现。为了简化设计加工的过程，超表面通常由随机分布孔阵列构成，用于记录二值全息图。此类超表面也被称为光子筛，能够有效操控出射光的振幅[44-46]。2019 年，研究者们发现利用智能算法的辅助可以显著地提升超表面光学调制的灵活性，并且利用全息图的冗余性可揭示不同振幅全息图之间的定量关联。如图 2(c)所示，Xu 等[22]基于改进的 GS 算法，生成了两幅具有定量关联的二值振幅全息图，通过将所得全息图编码于光子筛结构中，可在近红外波段得到清晰、低串扰的全息再现像。此方法不仅可以在傅里叶面上再现出完全不同的独立全息图，而且相比于遗传算法和粒子群算法等具有更高的计算速度与成像质量。同时，该方法从数学解空间角度出发，揭示了两幅独立全息图可以具备定量关联关系，可分别重建出不同的全息再现像。

基于多维度的全息混合复用能够实现多参量联合调控，突破传统全息数学物理内涵，从而提高信息的维度，解决算法赋能挑战。这类工作在双模式识别、大容量信息存储、光学加密、虚拟限制/混合现实等领域具有重要的应用价值。

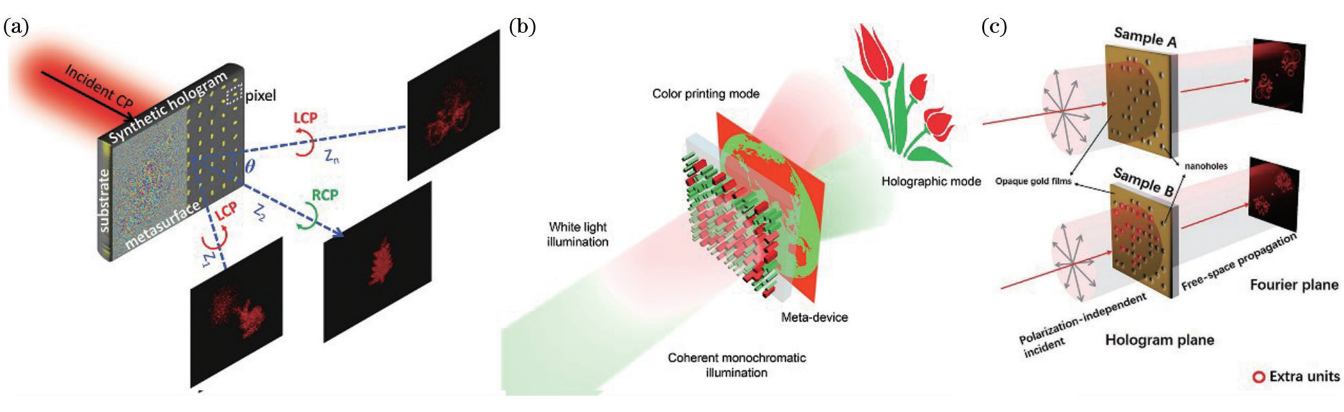

图 2　基于超表面的多参量联合调控。(a)宽带混合全息多路复用 Berry 相位超表面[20]；(b)单层超表面彩色印刷与彩色全息[21]；(c)基于光子筛的定量关联振幅全息[22]

Fig. 2　Multi-parameter joint control based on metasurfaces. (a) Broadband hybrid holographic multiplexing of Berry phase metasurfaces[20]; (b) color printing and color holography based on single layer metasurface[21]; (c) quantitative correlation amplitude holography based on photon sieve[22]

3　二维/三维光场变换

当前超表面研究已由单一功能应用逐步过渡到多功能应用。通过在同一超单元中嵌入多个不同几何形状、不同方位角朝向、不同共振峰位置的纳米天线，对入射光的波长和偏振实现选择性，实现功能复用。同时，也可采用空间复用的设计方案，对超表面进行空间区域划分，即在不同的空间区域针对某一特定波前调控功能进行设计。但是，为了减小不同信道之间的串扰、真正地扩大超表面的信息容量，需利用新的设计方法。

达曼光栅是对传统光栅的改进，通过对每个大周期内的相位分布进行优化设计，可在一维/二维衍射中

产生均匀以及可定制的强度分布[47-49]。超表面是实现达曼光栅的良好平台，一些基于达曼光栅原理的超表面被用于生成均匀点阵与涡旋光束阵列[25,48]。2018年，研究者们引入了共振飘移的思想，结合几何相位和传播相位的共同调制作用，通过改变构成介质超表面的矩形纳米柱的横截面和方位角排列，获取目标光场的振幅和动态相位映射规律，从而在单个像素内进行任意的复振幅调控。如图 3(a)所示，利用傅里叶模态法，通过确定超表面的周期，将选定的所有衍射级次对应的傅里叶级次进行叠加，并据此设定超表面各单元结构的复振幅信息，实现了对空间传播衍射级次的选择性激发[24]。该工作突破了传统光栅在正入射情况下无法灵活实现任意衍射级次的自由分配的瓶颈，并克服了双层超表面复振幅调控困难、仅适用于远红外或太赫兹波段的限制。

涡旋光束是一种具有螺旋相位波前的结构光束，它能够携带不同的轨道角动量(OAM)。携带不同OAM 的涡旋光束具备互相正交的特性，能够用于光操纵、光镊、大容量通信等场合[50-51]。传统生成涡旋光束的方法需要依赖涡旋相位片或者采用空间光调制器、分块光栅等，这些方法通常仅适用于窄带范围，并且系统庞大复杂，仅能产生有限数量具有特定拓扑电荷数的涡旋光。如图 3(b)所示，针对上述问题，研究人员将达曼涡旋光栅、涡旋波带片以及透镜因子合成涡旋光束相位分布图，并将其编码到单片纯相位调制的超表面，实现高效率、大容量三维涡旋光束产生(高达 125 个涡旋光束)，进而有望实现大容量涡旋光通信。特别地，各个衍射级次对应的涡旋光束的拓扑电荷数分布具有非常简明的规律，并可通过调控入射光的角动量实现主动调控[25]。该工作利用单片超表面实现三维涡旋阵列，克服了传统三维光束产生方案存在的体积大、元件多、系统笨重等弊端。此外，研究者们基于惠更斯超表面实现了二维无衍射贝塞尔光束阵列产生，通过将优化得到的达曼光栅相位和锥透镜相位叠加获得总相位分布，并将总相位分布编码于惠更斯超表面中，实现了与入射偏振无关的 5×5 贝塞尔光束阵列的产生[图 3(c)]，实验测得透射效率达到66.36%[23]。该方法具备普适性，易于和各类不同类型的光束如艾里光束、拉盖尔-高斯光束等相结合，在并行激光制造、分子传输和用于细胞检测的高效光学镊子等应用方面具有潜在的应用价值。

单片超表面产生二维/三维光场变换理论突破了传统空间复用的局限性，解决了系统集成度受限的难题，信息容量提高了三个数量级。通过将单片超表面与智能算法相结合，实现了衍射级次选择性激发、三维涡旋阵列以及大容量无衍射光束的产生。

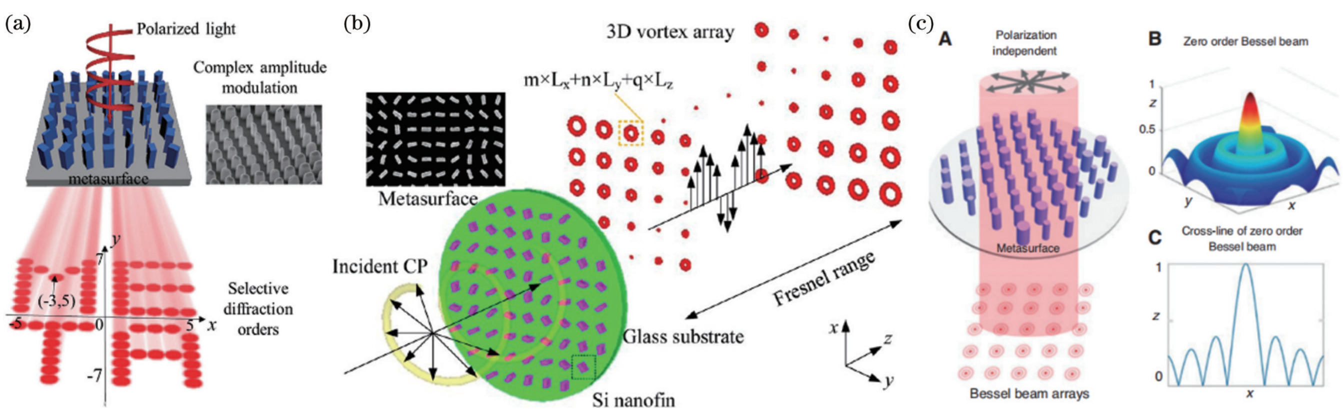

图 3 单片超表面产生二维/三维光场变换。(a)衍射级次可调的复振幅调制超表面[24]；(b)超表面生成涡旋光[25]；(c)基于惠更斯超表面产生高效率贝塞尔波束阵列[23]

Fig. 3 2D/3D optical field transformation by single metasurface. (a) Complex amplitude modulation metasurface with adjustable diffraction order[24]; (b) generation of vortex light by metasurface[25]; (c) generation of high-efficiency Bessel beam array based on Huygens metasurface[23]

4 矢量光场的产生与操控

偏振是光的基本属性之一。传统的偏振调制需要控制在正交方向上的电场振幅和相位延迟，从而实现偏振转换、分束、检测等应用。超原子由于能够用于人为的结构设计，具备各向异性的调控能力，能够克服自然界材料对偏振不敏感、双折射效率低等限制，极大地提高超表面器件的偏振控制和演化性能，实现偏振成像、偏振加密、矢量光束、偏振复用全息等应用[52-54]。

偏振态在空间上不均匀分布的偏振光束为矢量光束[55]。其中，径向偏振光束和角向偏振光束是柱矢量光束中最常见的两类。径向偏振光束聚焦时，在焦平面上有很强的纵向电场，所以它的聚焦光斑比线偏振光和圆偏振光的聚焦光斑更小。而角向偏振光束聚焦时，聚焦光斑中心强度为零，呈现出一种面包圈形状[56]。由于这些独特的物理特性，柱矢量光束被应用于粒子加速[57]、光学捕获[58-59]和超分辨成像[60-61]等领域。在这些应用的推动下，近年来研究人员提出了利

用 Sagnac 干涉仪[62]、布儒斯特棱镜的偏振选择特性[63]和空间光调制器[64]产生柱矢量光束的方法。但这些方法中存在着所用光学元件的体积较大和实验光路较为复杂等缺点，这限制了此类方法应用于微型化、紧凑型的光学系统中。针对上述问题，研究人员利用介质超表面的二维空间排布，实现如图 4(a)所示的空间非均匀偏振分布的高阶矢量光场产生。所设计的超表面由相同尺寸、方位角不同的非晶硅纳米柱构成。每个纳米柱可视为一个局域的半波片，将单个纳米柱在 xy 平面内绕 z 轴进行任意旋转即可实现对出射光束偏振方向的任意调控，从而实现适用于任意阶数的柱矢量光束的产生，并可通过改变入射光的偏振态，实现矢量光束空间逐点偏振态的改变。同时，可利用上述偏振调控方法，将偏振图像隐藏在矢量光场之中，实现图像加密功能[26]。

对于此前的全息偏振复用方法，通过改变入射光的偏振态仅能实现两幅独立图像的切换[65-66]。同时，全息再现像的偏振态分布都是均匀的，在设计的过程中并未考虑出射光的偏振态这一设计自由度，偏振通道数目有限。为此，研究者们创新性地开展了图 4(b)所示的超表面矢量全息显示与加密研究。基于矩形横截面的纳米柱结构，将双折射特性与偏振旋转矩阵相结合，将三个相位相关联的相位分布编码到三个独立偏振通道中，进而将多幅矢量全息图编码到同一超表面。研究了单层超表面琼斯矩阵调控机制，并验证了不同偏振通道实现关联相位调制算法的可行性。通过对入射光束和出射光束偏振态的选择，实现 12 个不同偏振通道的 7 种不同偏振图像的组合和复用，极大地提高全息图的信息容量，并提供了三重的信息加密维度，展示了一种实现高安全性的多通道矢量全息的新方法[27]。该方法揭示了单层超表面琼斯矩阵调控机制，并验证了不同偏振通道实现关联相位调制算法的可行性，可适用于各类偏振/相位调控的复杂波前产生与探测。这种完全的偏振控制方法可以在动态全息显示、可切换光学器件、数据存储和光学加密/防伪相关的前沿应用中发挥重要作用。

单层超表面的琼斯矩阵调控机制向不同偏振通道关联相位调制的发展，实现了多通道矢量调控和高阶矢量偏振光，极大地提高偏振控制和演化性能，解决了模式单一、信道数量受限的问题。

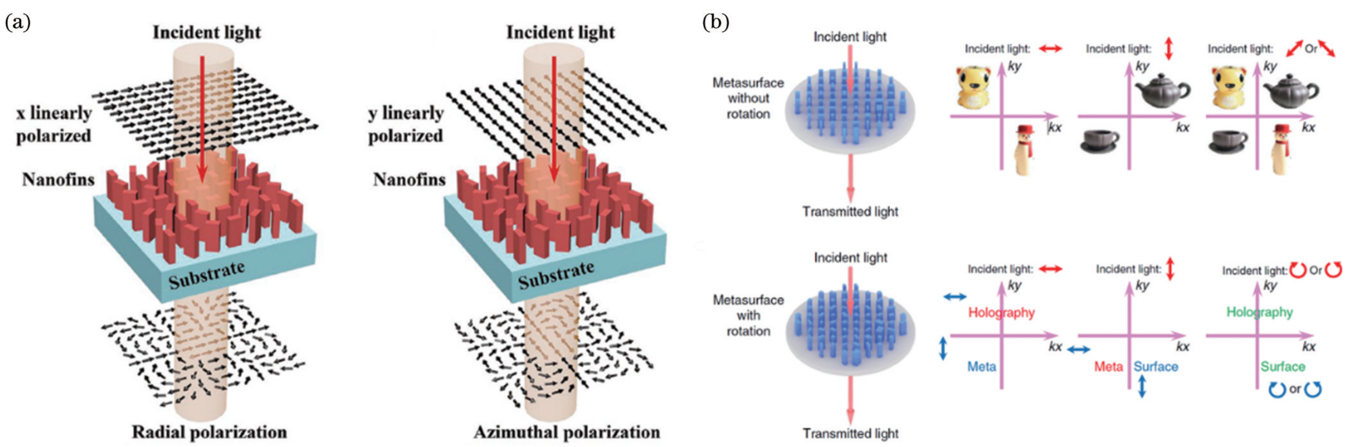

图 4　超表面琼斯矩阵调控机制。(a) 超表面的纳米级偏振操纵与加密[26]；(b) 超表面多通道矢量全息显示与加密[27]

Fig. 4　Jones matrix regulation mechanism of metasurface. (a) Nanoscale polarization manipulation and encryption of metasurface[26]; (b) metasurface multi-channel vectorial holographic display and encryption[27]

5　总结与展望

为了提升现有超表面光学元件性能或使其实现前所未有的新颖功能，多层超表面和级联超表面备受关注。其中，将多个超表面集成在一起形成的多层超表面常被用于实现复杂波前控制[67]、多光谱消色差超透镜[68]、图像区分[69]、具有双向功能的 Janus 超表面[70-72]、全光机器学习框架中的模式识别[73-74]等。研究者们提出了一种基于级联超表面全息术的全息密钥组合方法[75]。该方法中，当两张超表面相隔预设距离进行堆叠时，整个级联超表面系统能够产生一个不同于两张单层超表面全息图所对应再现像的全新再现像。此外，利用级联超表面全息术，针对平移和旋转的对准敏感度，研究人员提出了平移复用和旋转复用的概念，进一步扩大了级联超表面的信息容量。借助深度学习快速发展的契机，将深度学习算法与超表面设计过程相结合的方法在微纳结构设计[76-77]、全息成像[78]、光学感知与成像[79-80]以及光计算[81-82]等方面已展现出了良好的应用前景，能够获得常规设计方法难以实现的光学功能。针对这一研究领域，研究人员提出了一种物理驱动的衍射神经网络逆向设计级联的超表面结构。被设计的双层级联的超表面结构能够通过改变层间隔实现超大容量全息存储、加密和显示。在同等像素数情况下，利用两片复振幅超表面级联就能够实现超高密度的信息存储。

在二维/三维光场变换方面，研究者们对衍射级次

相关调控手段进行了更深入的研究。将广义涡旋光束的设计方法结合达曼涡旋优化，通过设置自定义的相位微分基本函数，实现了不同衍射级次的多种微分函数加减运算的直观光学展现[83]。同时，研究人员基于衍射级次的空间分布设计，实现了多层信息的交错呈现，可将平面内的图像信息转换为空间多平面信息，形成了具有深度的三维显示效果[84]。此外，研究者们将双相位编码方式引入超表面的设计过程中，提出了一种基于超表面对衍射级次的多参量调控方法，实现了衍射级次-相位分布-偏振共同调制[85-86]。该方法通过对衍射级次的操控，建立一种大容量、多通道、并行操作的光场调控方案，为多功能微型化光学系统的设计提供理论支持。

对于多维度混合全息，有研究人员提出了基于码分复用的动态超表面全息方法，并结合偏振复用利用单个超表面实现了多个独立通道的全息图像显示。该方法通过数字微镜产生特定强度分布的结构光束并将其照射到所设计的超表面上，即可准确再现预设全息图像。与频分复用与时分复用相比，码分复用允许多个用户在同一物理系统的同一时间传输独立的数据。该工作可以用于主动显示、结构照明、光学加密和存储中[87]。同时，研究者们利用超表面对出射光的多个物理量进行操控，通过选择不同入射/出射偏振态的组合实现了动态全斯托克斯矢量全息[88]。近年来，波长复用与其他复用如 OAM 复用、偏振复用等相结合的超表面全息方法被提出。通过正交结构光束和多种光参量的联合调控，引入定量关联机制以及其他信息复用技术，同时引入动态调控机制，拓展了多维度超表面全息器件的信息存储能力和应用的范围[89-90]，该方法在并行激光加工和激光通信方面有广阔前景。同时 OAM 全息具备高速传输海量信息的潜力。OAM 模式数在物理上是无限的，与高分辨率的超表面相结合可以为大容量全息设备和系统提供更广阔的发展空间。通过对 OAM 复用中编码的信息进行高帧率动态提取，可以实现三维全息图的再现以及数据的高帧率传输，这对进一步提高超表面的信息检索帧率、传输海量信息和提升光通信性能有着重要意义[91]。

综上所述，现代信息社会高速发展，人们对信息存储容量和存储速度的需求不断提升。未来超表面在信息传输、信息调制领域拥有着广阔的应用空间。超表面作为新一代变革性的光学器件，为动态传输、虚拟现实和增强现实技术提供了广阔的平台。但当前超表面在可调超表面加工和物理机制方面还面临诸多挑战，对加工工艺和物理机制仍需探索。例如在 mm^2 量级乃至 cm^2 量级的大口径器件加工中保持高精度对现有工艺是一个巨大的挑战。可调超表面的调节频率低[92-94]，使其刷新速度以及灵活性受到限制。动态超表面在应用方面也存在设计复杂度高和串扰大的问题。相信，随着超表面工艺和理论的不断突破与发展，超表面将替代传统光学器件，在真彩色显示、全息防伪、加密解密、动态传输、虚拟现实和增强现实方面大放异彩。

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Multi-Dimensional and High-Capacity Metasurface Holography and Light Modulation

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Abstract

Significance Metasurfaces are usually composed of arrays of metallic or dielectric nano-antennas. They can arbitrarily manipulate the amplitude, phase, as well as polarization of light with sub-wavelength resolution. These features make metasurfaces represent powerful abilities for manipulating multi-dimensional optical fields. Hence, the metasurfaces have attracted much attention in the research on new generation of optical devices. The design and fabrication of metasurfaces have greatly promoted the applications of optical field manipulation in compact optical systems. Although the optical lens, spatial light modulator, and polarization optical element in the traditional optical system have the ability to manipulate the optical field, their applications are limited due to their large size and single function of optical field manipulation. While, metasurfaces provide a new platform for tailoring the optical field, which is expected to solve the bottleneck of traditional optical components and systems towards miniaturization, integration, and multi-functional processes.

In recent years, metasurfaces have attracted great interest as novel kinds of flat artificial function devices due to their unusual physical properties. They are usually composed of a single layer of sub-wavelength nanostructures, which can arbitrarily control the amplitude, phase, polarization, and other fundamental properties of the emitted light with sub-wavelength resolution. While conventional optical elements control the optical field mainly through the phase accumulation of light during propagation, metasurfaces provide a new way to control the light field properties at subwavelength distances through the interaction of light with meta-atoms. As a burgeoning research field, metasurfaces have shown great promise for novel design in a great number of device applications such as flat lenses, wave plates, beam deflectors, switchable surface plasmon polariton couplers, high-resolution 3D holography, and augment reality (AR).

New principles and new methods such as holographic hybrid multiplexing, 2D/3D optical field modulation, as well as the generation and manipulation of vectorial field based on metasurfaces proposed have overcome the bottleneck challenges of traditional optical components and systems towards miniaturization, integration, and versatility. The research results have important theoretical value and application prospects for complex wavefront modulation, lidar, high-density holographic storage, AR/VR, optical information processing, large-capacity light field regulation, and other fields.

Progress The earliest holographic multiplexing method of metasurfaces used birefringent metasurfaces composed of custom crossover nanoantenna arrays for holographic multiplexing through a spatial multiplexing scheme. Our research group demonstrated a new principle of multi-dimensional metasurface holographic hybrid multiplexing. We proposed multi-dimensional angle-polarization-spatial position, space/frequency domain simultaneous modulation, and quantitatively correlated metasurface holographic hybrid multiplexing. A variety of new holographic algorithms have been created, including multi-dimensional synthesis spectroscopy, quantitative correlation amplitude hologram, irregular surface holographic algorithm, and map index. Such algorithms can adapt to the manipulation of optical fields based on metasurfaces and realize the joint regulation of multiple parameters, which breaks through the connotation of traditional holographic mathematical physics. Meanwhile, they can also improve the information dimension and solve the challenges of algorithm empowerment.

The current metasurface research has gradually shifted from single function to multifunctional application. At the same time, the design scheme of spatial multiplexing can also be used to divide the spatial area of the metasurface, namely, to design the regulation function of a specific wave front in different spatial regions. However, in order to alleviate the crosstalk between different channels, the real expansion of the information capacity of metasurfaces requires new design methods. To this end, our research group proposed a new method to produce 2D/3D optical field transformation from monolithic metasurfaces. We realized 2D selective diffraction with customized energy distribution based on complex amplitude manipulation provided by metasurfaces. Meanwhile, a 3D vortex array with controllable topological charge number has been successfully demonstrated by combining Dammann vortex grating and spiral Dammann zone plate with lens factor. Such a method may break the limitation of traditional spatial multiplexing, solve the problem of limited system integration, and increase the information capacity by three orders of magnitude.

Polarization is one of the fundamental properties of light. The conventional methods of polarization modulation require controlling the amplitude and phase delay of the electric field in the orthogonal polarization components to enable polarization conversion, beam splitting, detection, and other applications. Artificially designed meta-atoms have the ability to solve the restrictions of natural materials such as insensitive to polarization and low birefringence. They can greatly improve the capabilities of polarization modulations based on metasurfaces. A new scheme of tailoring the vectorial field pixel-by-pixel was proposed to realize the generation of high-order vector beams which greatly improved the performance of polarization modulation.

Conclusions and Prospects As a new generation of transformative optical devices, metasurfaces will provide a broad platform for dynamic transmission, VR, and AR technologies. Meanwhile, the adjustment frequency of the tunable metasurfaces is low, which limits its refresh speed and flexibility. Dynamic metasurfaces also have the problem of high design complexity and large crosstalk in their applications. However, it is believed that with the continuous breakthroughs and developments of metasurface technology and theory, metasurface will replace traditional optical devices and excel in true color display, holographic anti-counterfeiting, encryption and decryption, and dynamic transmission.

Key words metasurface; multi-dimensional optical field manipulation; holography; beam shaping