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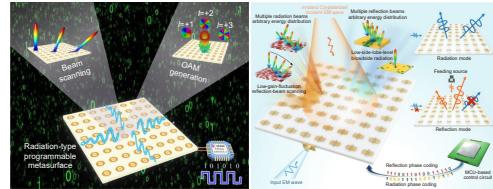
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电磁超表面对辐射波的调控与应用

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摘要: 电磁超材料由亚波长尺寸的人工单元结构周期或非周期排列组成, 可以实现天然材料不具备的奇特性质。超表面作为二维特殊形式超材料, 具有剖面低、易集成、低成本等优点。随着有源器件、传感元件与智能算法的引入, 超表面进一步实现了对电磁波的实时可编程与智能调控。目前多数电磁超表面研究致力于反射波或透射波调控, 事实上, 电磁超表面对辐射波同样具有强大的调控能力。本文系统介绍电磁超表面调控辐射波幅度、相位、极化等维度的相关研究进展, 以超表面与馈源的集成方式和超表面对辐射波的调控原理为分类依据, 重点介绍折叠阵超表面、法布里-珀罗超表面、漏波超表面和辐射式超表面, 对应空间馈电、表面波馈电、缝隙耦合馈电、同轴馈电等方式, 从无源与有源两个角度介绍这四类超表面对辐射波的调控机理与应用, 最后对电磁超表面调控辐射波的未来研究方向进行展望。

关键词: 电磁超表面; 辐射波; 电磁波调控**中图分类号:** TN82**文献标志码:** A

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Manipulations and applications of radiating waves using electromagnetic metasurfaces

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Abstract: Electromagnetic metamaterials are composed of sub-wavelength artificial unit cells with periodic and aperiodic arrangements, which can achieve peculiar properties that natural materials do not have. As the two-dimensional metamaterials, metasurfaces have the advantages of low profile, easy integration and low cost. With the introduction of active elements, sensing elements and intelligent algorithms, metasurfaces further realize real-time programmable and intelligent control of electromagnetic waves. At present, most electromagnetic metasurfaces researches are devoted to the manipulation of reflecting waves and transmitting waves. In fact,

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electromagnetic metasurfaces also have the strong regulation ability for radiating waves. This paper will introduce the research progress of metasurfaces in regulating the amplitude, phase, polarization of radiating waves systematically. Based on the integration of metasurfaces and feeds and the regulation principle of metasurfaces on radiating electromagnetic waves, this paper focuses on folded array metasurfaces, Fabry-Perot metasurfaces, leaky wave metasurfaces and radiation-type metasurfaces, corresponding to space wave feeding, surface wave feeding, gap coupling feeding, coaxial feeding. The regulation mechanism and applications of these four types of metasurfaces on radiating waves are introduced from the perspectives of passive and active. Finally, the future research directions of electromagnetic metasurfaces in regulating radiating waves are prospected.

Keywords: electromagnetic metasurfaces; radiating waves; electromagnetic wave control

1 引言

超材料由亚波长尺寸的人工电磁单元构成。与自然界中天然材料不同,超材料的特性主要取决于基本电磁单元的结构与排列方式。通过精心设计基本单元结构,其对外部电磁场的响应可以被人为改变。得益于这一特性,超材料可以实现天然材料不具备的电磁特性,例如负介电常数^[1]、负磁导率^[2]、负折射率^[3]等。然而,超材料通常需要单元的三维空间排布来实现特定的电磁功能,这不可避免地带来了损耗高、体积庞大、重量大、加工困难等问题,使其难以走向更广阔的实际工程应用。

超表面作为二维形式超材料,对电磁波的调控不再依赖于单元的三维空间排布,而是利用电磁波在超表面二维界面上产生突变相位/幅度来实现对入射电磁波的自由调控,相比于三维超材料,其具有体积小、剖面低、易集成、低损耗等优点。近年来,超表面已被广泛研究并实现了对电磁波的各种调控与应用,例如相位调控^[4]、全息成像^[5-6]、雷达散射截面 (radar cross section, RCS) 缩减^[7-9]、极化转换^[9-13]、吸波^[10,14-15]等。同时,机器学习、深度学习因其强大的数据挖掘和表征能力被引入超表面的设计流程,使超表面对电磁波的复杂调控进一步被探索,在极化复用、纳米打印、全息成像等领域具有良好应用前景^[16-18]。

上述超表面均具有固定结构,加工完成后其功能和特性就已确定,因此可统称为“无源超表面”。在实际应用场景中,例如无线通信、宽带吸波、电磁隐身等,往往需要超表面具有动态调节电磁波的能力,根据入射波的不同频率、功率、极化等实现不同的功能。基于此类需求,研究人员通过在无源超表面结构上集成有源器件(例如开关二极管^[14-15,19-20]、变容二极管^[20-22]、光电二极管^[23-26]等),进一步实现了有源超表

面。通过引入数字编码表征方式和现场可编程门阵列 (field programmable gate array, FPGA) 或单片机 (microcontroller unit, MCU) 提供外部馈电偏置以改变有源器件的状态,有源超表面可以对电磁波表现出不同的电磁响应,进而实现多种电磁功能的动态、实时与可编程调控^[27-29]。除此之外,可进一步引入传感器件与智能算法实现智能超表面,建立环境变量与超表面编码之间的联系,从而实现不同电磁功能的自主决策与自适应切换^[30-31]。

由于上述超表面研究主要关注对空间电磁波的反射与透射调控,在辐射波调控应用中,这些超表面仅能作为次级惠更斯源,需要结合外置的初级馈源,以反射阵或透射阵形式工作。然而,外置馈源的引入不仅会带来明显的溢出损耗以及边缘衰减,而且会导致系统整体剖面升高,集成度降低。因此,如何实现具有直接、高效调控辐射电磁波能力的低剖面、高集成度超表面成为研究热点。本文主要讨论电磁超表面调控辐射波领域的相关工作,其工作频段主要集中在微波频段,依据超表面与馈源的集成方式不同及超表面对辐射电磁波的调控原理不同,将超表面划分为折叠阵超表面、法布里-珀罗超表面、漏波超表面和辐射式超表面四类,从无源与有源两个角度介绍这四类超表面对辐射波的调控机理与应用。

2 折叠阵超表面

2.1 无源折叠阵超表面

传统反射阵天线通常由馈源和反射阵列 (reflectarray, RA) 组成^[32-34],由于馈源与 RA 之间需要一定的距离,天线的剖面通常较高。为了降低剖面,提高集成度,Pilz 和 Menzel^[35]在 1998 年提出了折叠式反射阵天线 (folded reflectarray antenna, FRA),该天

线由波导喇叭馈源、中心集成馈电的 RA 和平行于 RA 的偏振片组成。根据射线追踪路径可以推出折叠式反射阵天线的高度 H 仅为原反射阵列焦距 f 的二分之一。文献 [36] 和 [37] 使用基片集成波导 (substrate integrated waveguide, SIW) 缝隙阵代替喇叭馈源, 进一步降低了结构剖面。然而, 上述研究仅关注低剖面、低副瓣、高增益天线的实现, 对辐射电磁波的调控能力仍较为单一。

随着超表面对电磁波调控能力的不断发掘, 利用超表面代替传统反射阵的 FRA 开始被广泛研究。得益于超表面对辐射电磁波的相位、极化等多维度调控, 基于超表面的 FRA 不仅可以实现上述研究中的高性能天线, 还可以实现诸如波束扫描、多波束、RCS 缩减等功能。由于超表面在天线结构中既作为反射面又作为相位补偿器, 是至关重要的一部分, 因此本文将此类工作统称为折叠式反射阵超表面。例如, 文献 [38] 和 [39] 分别设计了两款折叠式反射阵超表面, 分别用于对圆极化波和线极化波的 RCS 缩减, 如图 1(a)、(b) 所示。图 1(a) 为棋盘格型超表面, 能够反射左旋圆极化波 (left circular polarization, LCP) 并透射右旋圆极化波 (right circular polarization, RCP), 令相邻两个棋盘单元间的反射相位差接近 π , 对超表面进行 1 比特相位编码, 从而实现 RCS 缩减。另外,

也可以引入聚焦和漫散射超表面, 同时实现带外的高吸波性能以及带内交叉极化波的散射性能, 如图 1(b) 所示。2018 年, Shen 等人 [40] 在微波频段通过 3 比特相位编码超表面实现携带轨道角动量 (orbital angular momentum, OAM) 的贝塞尔波束 (图 1(c)), 后来, Miao 等人 [41] 采用“准 I 型”单元的超表面实现高效率极化转换与全相位覆盖。基于改进型纯相位傅里叶变换法, 在不需体积庞大的物理透镜进行傅里叶变换的情况下, 将相应的透镜相位轮廓被加载到超表面上以实现所需的立方相位分布, 最终实现低剖面太赫兹艾里波束发生器 (图 1(d))。

上述折叠式反射阵超表面中, 超表面作为下层的主反射面, 能够对辐射波进行自由调控, 但是上层的极化选择表面仅对某一极化方向的波全透射或全反射, 并不能对相位进行调控。为了进一步增强折叠式超表面对辐射波的相位调控, 研究人员提出了折叠式透射阵超表面构型, 用超表面替代上层的极化选择表面, 这样超表面可以同时透射波进行相位补偿和极化转换。图 2(a) 展示了一种圆极化折叠式透射阵超表面 [42], 其由三部分组成: 用于极化转换的底层超表面、用于相位调制和极化选择的顶层超表面、位于底层超表面中心的馈源。由射线追踪路径可以推出, 折叠式透射阵超表面的高度 H 仅为焦距 f 的三分之一, 进一步降

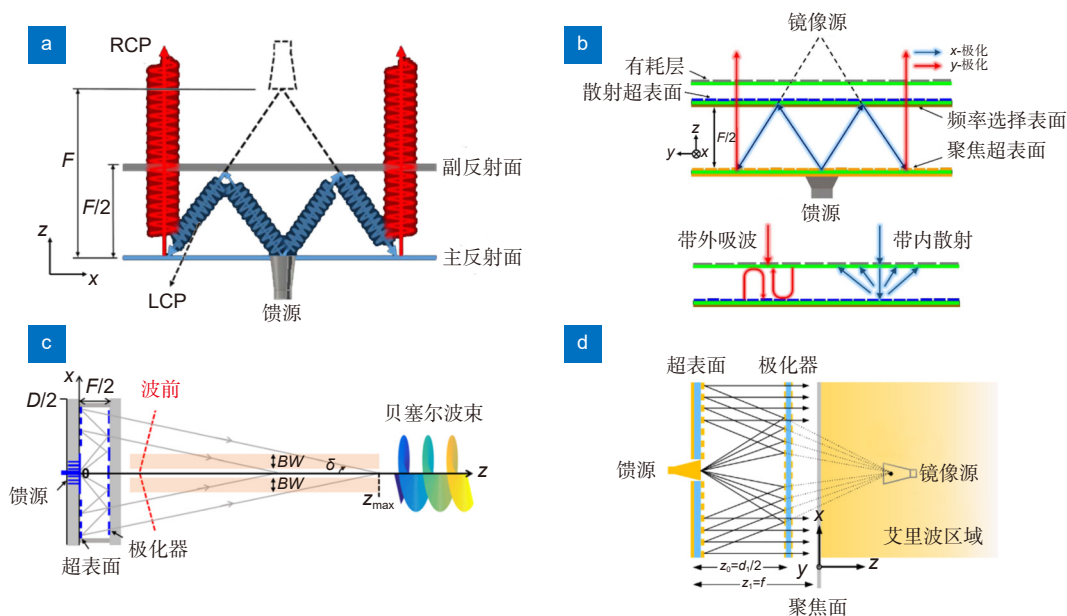


图 1 无源折叠式反射阵超表面原型。(a) 圆极化波 RCS 缩减 [38]; (b) 线极化波 RCS 缩减 [39]; (c) 贝塞尔波束产生器 [40]; (d) 艾里波束产生器 [41]

Fig. 1 Passive folded reflectarray metasurface prototype. (a) RCS reduction for CP wave [38]; (b) RCS reduction for LP wave [39]; (c) OAM beam generator [40]; (d) Airy beam generator [41]

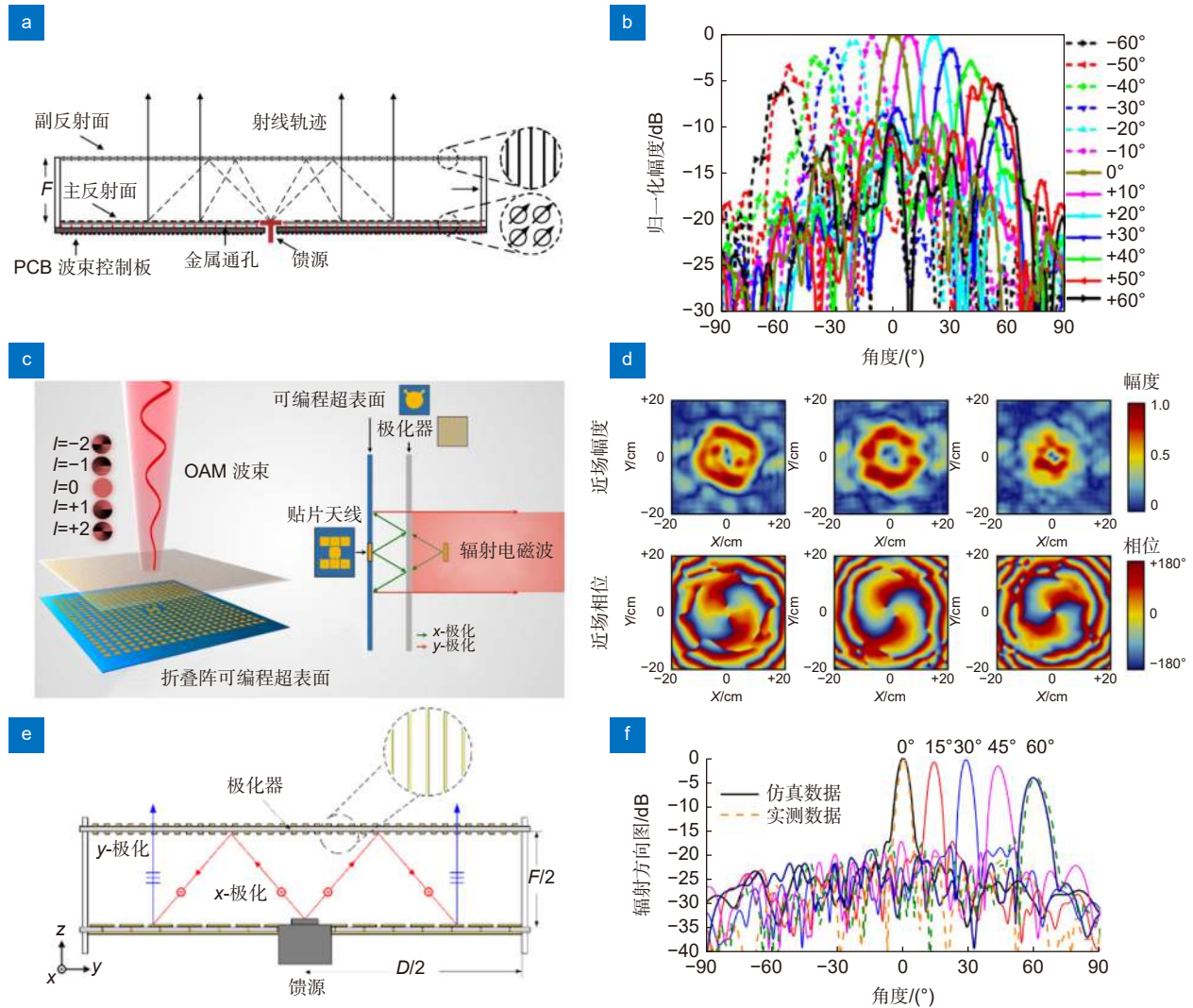


图 3 有源折叠阵超表面。(a) 用于波束扫描^[48]; (b) 实测辐射方向图; (c) 用于产生 OAM 波束^[49]; (d) 2 阶 OAM 波束近场幅度和相位分布图; (e) 用于波束偏折^[50]; (f) 仿真和实测归一化辐射方向图

Fig. 3 Active folded metasurface. (a) Programmable folded metasurface for beam scanning^[48]; (b) Measured radiation pattern; (c) Active folded metasurface for OAM beam generation^[49]; (d) Near-field amplitude and phase distribution for $l=+2$; (e) Active folded metasurface for beam steering^[50]; (f) Simulated and measured normalized radiation patterns

(图 5(b))。在此基础上, 还利用 1 比特相位编码超表面对带外来波实现 RCS 缩减。针对带内 RCS 缩减问题, 文献 [57] 设计了一款 F-P 超表面, 上层采用吸波表面实现带内 RCS 缩减, 下层设计了集成变容二极管的超表面单元, 在可调频段内实现高增益波束, 如图 5(c) 所示。进一步, 文献 [58] 提出了一种基于变容二极管的散射波可重构 F-P 超表面 (图 5(d)), 对带内的共极化来波实现 -40° 到 40° 的波束扫描, 对交叉极化来波起到 RCS 缩减功能, 对馈源的辐射波实现高增益定向辐射, 在雷达探测领域和低可观测平台中具有应用前景。

4 漏波型超表面

4.1 无源漏波型超表面

前两节所述的折叠式超表面和 F-P 超表面均是调控由馈源辐射的空间波, 通过使电磁波在上下两层表面发生多次反射以降低结构剖面并进行相位补偿。除调控空间波外, 超表面还具有调控表面波的能力。通过调整表面阻抗, 可以将表面波转化为空间辐射波并同时实现对辐射波的波前调控, 这类超表面可统称为漏波超表面。相比于大型平面阵列存在复杂的馈电系统、较高的插入损耗等, 漏波超表面通常采用表面波

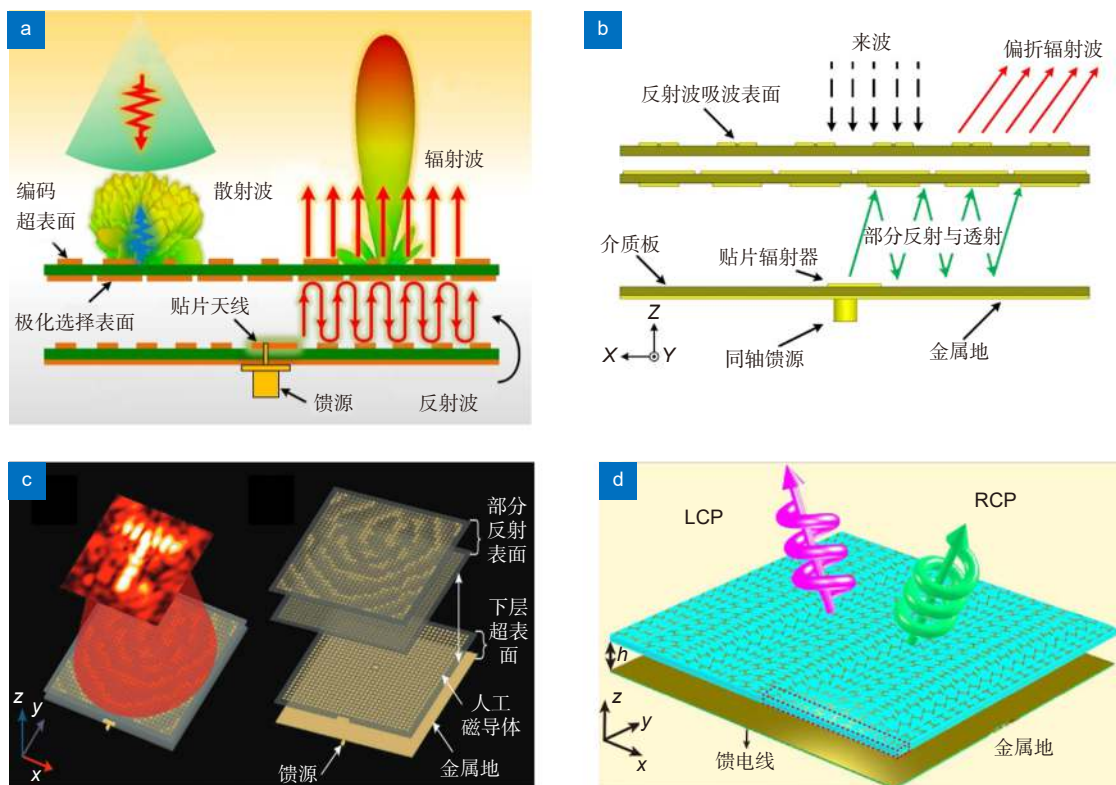


图 4 无源 F-P 超表面。(a) 低散射 F-P 编码超表面^[51]；(b) RCS 缩减 F-P 超表面^[52]；
(c) F-P 超表面实现二维全息成像^[53]；(d) F-P 超表面实现双圆极化辐射^[54]

Fig. 4 Passive F-P metasurface. (a) Low-scattering F-P coding metasurface^[51]; (b) F-P metasurface for RCS reduction^[52];
(c) F-P metasurface for 2D holographic imaging^[53]; (d) F-P metasurface for dual circularly polarized radiation^[54]

馈电技术，避免了复杂馈电网络的设计与优化。

根据漏波超表面的表面阻抗是否均匀分布，可以将超表面分为两类：均匀漏波超表面和非均匀漏波超表面（非均匀漏波超表面常被称为“全息超表面”）。图 6(a) 展示了一种均匀漏波超表面^[59]，由交错排列的金属贴片组成，通过设计开槽宽度以及周期长度，保持大角度波束扫描的同时，降低副瓣电平和主瓣宽度。文献 [60] 研究了多层介质结构均匀超表面的辐射特性（图 6(b)），通过比较 1/3/5 层介质构成的超表面的辐射特性，发现随着层数的增加，扫描角度变宽的同时也会引起增益降低。

全息超表面的设计思路来源于光学全息成像，通过计算馈源产生的辐射场与目标场之间的干涉图案，设计非均匀分布表面阻抗来匹配这种干涉图案，从而使馈源辐射出的波经过全息超表面调制后转化为目标辐射波。对于全息图像的重建，研究人员探索了各种复用方式，包括同时控制幅度和相位实现极化和频率的复用^[61-62]，调制复振幅实现空间和频谱的复用^[63]，

加密偏振相关的 OAM 加密全息法^[64-65] 等。2016 年，Li 等人^[66] 设计了一款双功能全息超表面（图 6(c)）。该超表面由各向同性的矩形贴片单元组成，通过相互正交的端口激励，可以分别实现相同偏振下的双波束扫描和正交偏振下的单波束扫描，且两种功能相互独立。此类双功能频率扫描装置在新型雷达系统、前视成像系统、计算成像系统等方面具有巨大的应用潜力。2021 年，Shen 等人^[67] 使用开槽圆形贴片张量单元（图 6(d)），通过表面阻抗叠加方法，使两个独立的单极子天线端口分别激励出左旋圆极化的一阶涡旋波和右旋圆极化的零阶贝塞尔波束，具有低剖面、紧凑尺寸和平面集成的特点。

4.2 有源漏波型超表面

在有源漏波型超表面的研究方面，Wu 等人^[68] 设计了一款集成波导时空编码漏波超表面天线。每个超表面单元集成一个 PIN 二极管，并通过 FPGA 加载不同的 1 比特时空编码矩阵，可以在频率和空间维度上

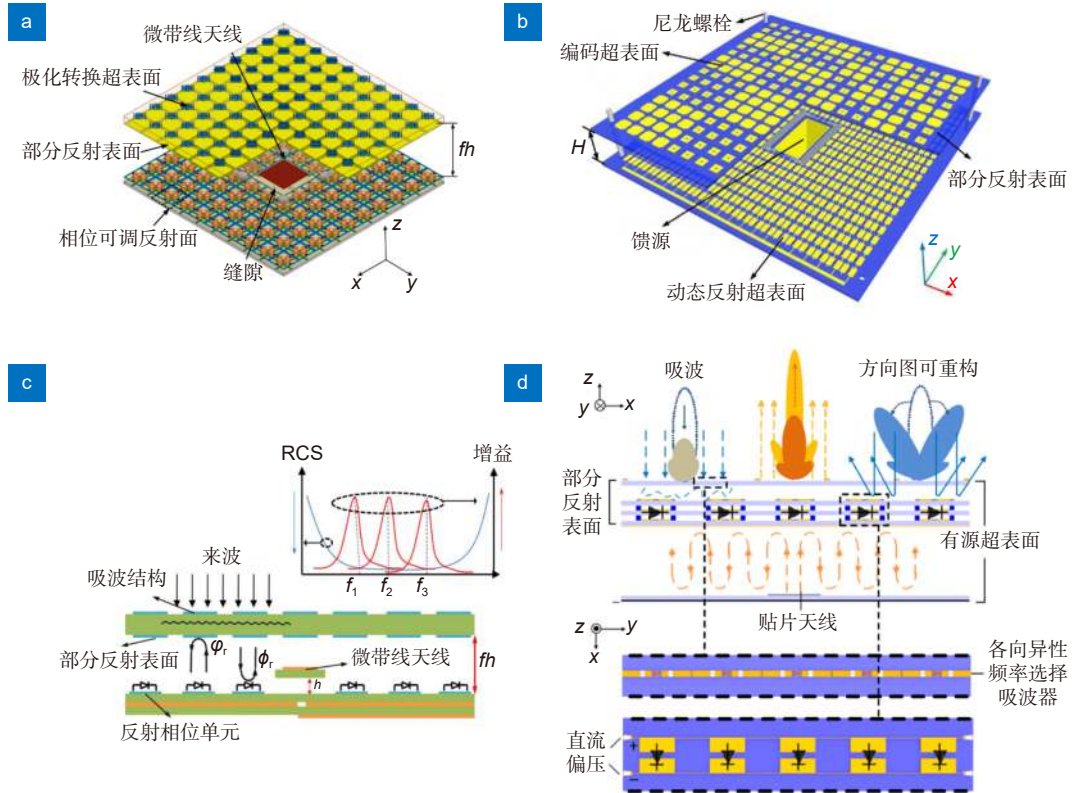


图 5 有源 F-P 超表面。(a) 频率可重构 F-P 超表面^[55]；(b) 双频段可重构 F-P 超表面^[56]；(c) 带内 RCS 缩减 F-P 超表面^[57]；(d) 散射方向图可重构 F-P 超表面^[58]

Fig. 5 Active F-P metasurface. (a) Frequency reconfigurable F-P metasurface^[55]; (b) Dual-band reconfigurable F-P metasurface^[56]; (c) F-P metasurface for in-band RCS reduction^[57]; (d) Reconfigurable scattering patterns F-P metasurface^[58]

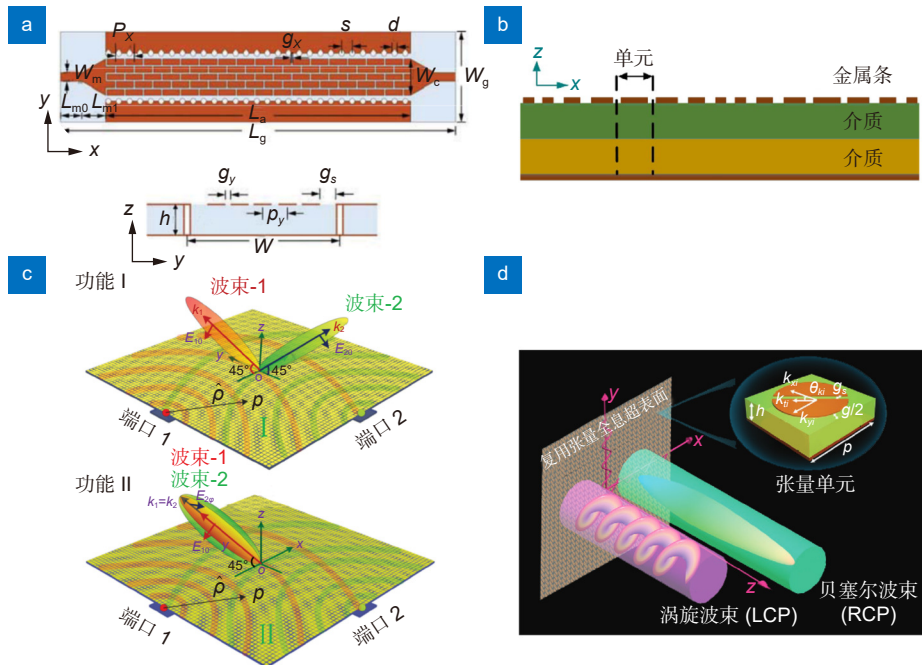


图 6 无源漏波超表面。(a) 大角度均匀漏波超表面^[59]；(b) 多层均匀漏波超表面^[60]；(c) 双功能全息超表面^[66]；(d) 复用张量全息超表面^[67]

Fig. 6 Passive leaky-wave metasurface. (a) Wide-angle uniform leaky-wave metasurface^[59]; (b) Multilayer uniform leaky-wave metasurface^[60]; (c) Dual-functional holographic metasurface^[66]; (d) Multiplexing tensor holographic metasurface^[67]

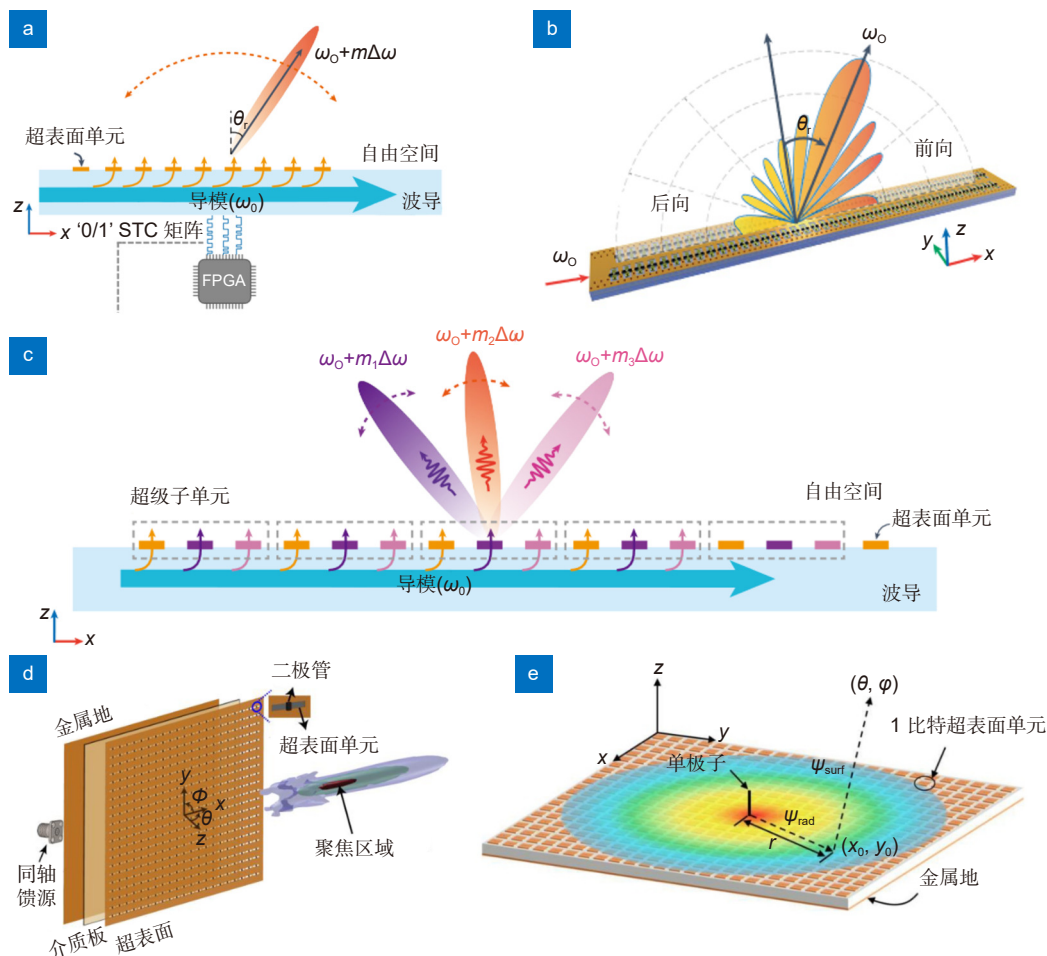


图 7 有源漏波型超表面。(a) 无边带辐射漏波型超表面^[68]; (b) 基频波束扫描; (c) 多谐波独立调控; (d) 动态近场聚焦全息超表面^[69]; (e) 动态波束全息超表面^[70]

Fig. 7 Active leaky-wave metasurface. (a) Sideband-free leaky-wave metasurface^[68]; (b) Fundamental-frequency beam scanning; (c) Multi-harmonic independent control; (d) Dynamic near-field focusing holographic metasurface^[69]; (e) Dynamic beam holographic metasurface^[70]

对辐射波进行灵活调控。通过优化时空编码矩阵, 只有满足相位匹配条件的谐波频率可辐射到自由空间, 而其他非期望谐波频率(边带)由于和自由空间及波导动量不匹配而被抑制(图 7(a))。另外, 利用时间平均效应在基频处形成等效正弦幅度分布, 从而在基频实现高增益辐射和动态波束扫描, 如图 7(b)所示。通过采用空分复用技术实现多谐波独立调控(图 7(c)), 可应用于多目标探测和多用户通信等场景。文献[69]设计了一种动态近场聚焦可重构全息超表面(图 7(d)), 在不使用移相器和功率放大器的情况下实现了波束聚焦, 在无线输电和成像等方面具有潜在的应用价值。同样, 文献[70]设计了一种 1 比特可编程全息超表面(图 7(e)), 可以实现一维和二维的波束扫描动态切换, 满足单脉冲雷达对运动目标跟踪的要求。

5 辐射式超表面

5.1 无源辐射式超表面

从超表面与馈源的集成方式来看, 上述折叠式超表面与 F-P 超表面均属于空间馈电, 而漏波超表面属于表面波馈电, 将馈源辐射出的电磁波从表面波转化到空间波。这三种超表面的设计过程中, 超表面与馈源的高度集成一定程度上影响了辐射波的直接调控性能。为了解决这一问题, metantenna 采用传统天线的缝隙耦合或同轴馈电方式, 将超表面直接作为天线的辐射口径, 超表面子阵列作为阵列天线的辐射单元, 用馈源激励整个子阵列。在此基础上通过特征模分析(characteristic mode analysis, CMA)等理论, 最终实现增益提升、带宽拓展、副瓣降低等性能^[71-74]。

除此之外, 为了实现阵元级别对电磁波的独立调控能力, 2020年, Xu等人^[75]提出一种集成馈源式的编码超表面阵列天线(图8(a)), 利用了超表面与馈源的耦合效应, 不仅有效缩减了辐射阵元的尺寸, 同时基于超表面的调相能力实现了对辐射波前灵活调控。然而, 这种强耦合设计相对复杂, 且对系统的装配精度要求高, 难以拓展到大规模应用。

相较于metantenna的馈源对超表面子阵列进行馈电, 文献[76]提出了直接调控辐射波的辐射式超表面, 将超表面单元作为天线的阵元, 对每个单元进行馈电。作者基于此思想设计了一款相位和极化调控的辐射式超表面, 如图8(b)所示。在这一设计中, 超表面单元采用双开口谐振环结构, 通过旋转单元, 能够同时直接辐射出左旋/右旋圆极化波, 分别带有 $-\alpha/\alpha$ 角的几何相位。另外, 可通过引入相位延迟线(phase-delay meta-line, PDML)使辐射波携带 β 角的传输相位, 最终两种正交圆极化波分别携带 $-\alpha+\beta/\alpha+\beta$ 的辐射相位, 为实现不同极化下的不同辐射功能提供了一种可行解决方案。进一步, 文献[77]中提出调整单元谐振环开

口与金属臂的相对角度来引入谐振相位, 实现以任意幅度比、相位、极化的调控(图8(c))。利用不同的极化状态, 提出了一种具有高效信道串扰抑制和信息加密功能的新MIMO天线, 此外还设计了一个能量可控的路由器和一个低剖面超表面全息图。最近, Wang等人^[78]设计了一种纯相位辐射式超表面, 采用双e型结构实现 2π 全相位覆盖, 引入远场重构算法实现了能量可调的多波束通信、大角度偏折和波束赋形, 可以根据具体场景的需求高效准确地计算超表面所需的相位分布。进一步, 文献[79]将两个e型单元交错排列, 如图8(d)所示, 通过调整各自的旋转角度, 利用多重几何相位干涉实现解耦的全相位调制。此外, 还引入远场复振幅反演方法, 实现精确的能量分配和复杂形式的波束赋形, 为复振幅超表面在小型化和高度集成的多功能系统中的实际应用奠定基础。相比于传统波束扫描天线需要复杂馈电网络或数字电路, 辐射式超表面可将超表面单元直接作为具有移相能力的辐射阵元, 不仅能够简化对辐射波的调控成本与复杂度, 且具有更高的调控自由度。

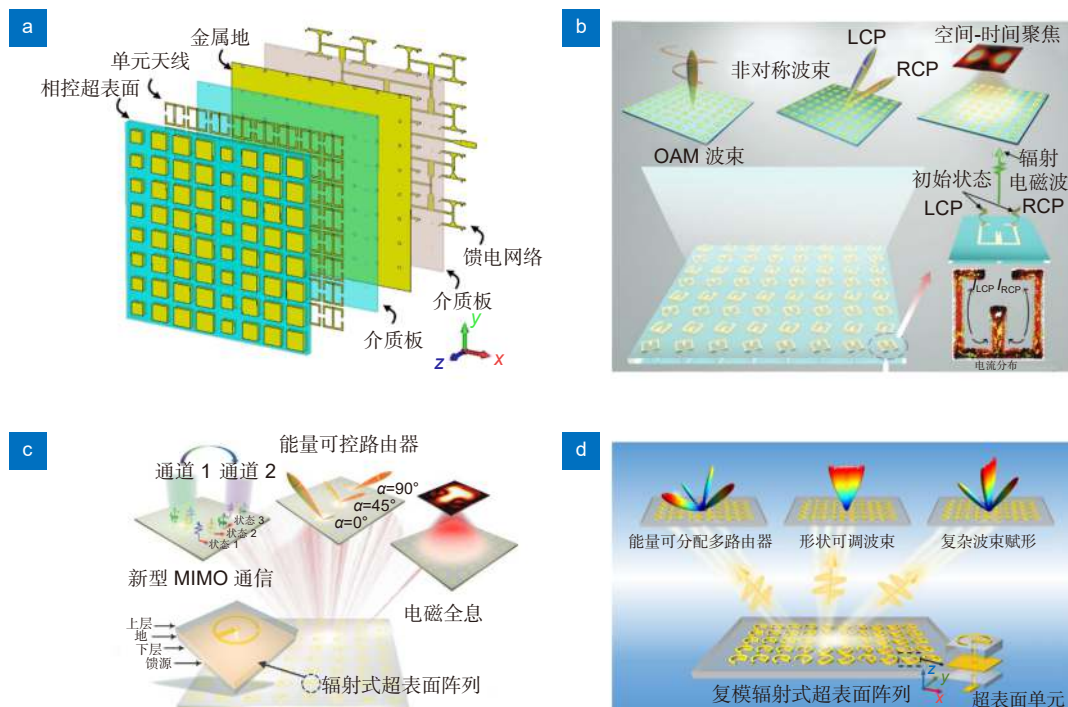


图8 无源辐射式超表面。(a) 集成馈源式编码超表面^[75]; (b) 相位和极化调制辐射式超表面^[76];

(c) 幅度、相位和极化调制辐射式超表面^[77]; (d) 复振幅调制辐射式超表面^[79]

Fig. 8 Passive radiation-type metasurface. (a) Integrated coding-metasurface^[75]; (b) Phase- and polarization-modulated radiation-type metasurface^[76]; (c) Amplitude-, phase- and polarization-modulated radiation-type metasurface^[77]; (d) Complex-amplitude modulated radiation-type metasurface^[79]

5.2 有源辐射式超表面

由于辐射式超表面的概念近两年才提出, 目前有源辐射式超表面的研究相对较少。2022年, Bai 等人^[80]提出可编程辐射式超表面, 如图 9(a)所示。将馈电网络和可编程超表面直接集成, 在每个单元上加载两个 PIN 二极管实现 1 比特相位编码, 采用集成的串并联混合微带网络对具有初始加权幅度和相位分布的顶层超表面单元进行激励。使用这种超表面实现 -45° 到 45° 单波束扫描和产生 $+1/+2/+3$ 阶 OAM 波束, 验证了超表面的可编程实时调控性能, 可用于低成本车载或机载共形无线通信系统。最近, Tian 等人^[81]在辐射式超表面的基础上, 利用单个可编程超表面实现了对辐射波和带内同极化反射波的直接、动态和集成控制 (图 9(b))。在超表面单元上分别集成两个 PIN 二极管和两个变容二极管, 能够动态选择只辐射电磁波或只反射带内同极化入射波, 并同时辐射相位和反射相位进行动态调制, 实现了任意能量分布的多波束、低增益波动的反射波束扫描和低旁瓣宽边辐射等功能, 能够适用于无线通信和雷达探测等多种应用的高集成度、多任务和智能无线系统。

6 总结与展望

本文系统介绍了近年来利用超表面对辐射波进行直接调控的研究现状, 重点介绍了折叠阵超表面、法布里-珀罗超表面、漏波超表面和辐射式超表面四类辐射波调控超表面。相较于反射式/透射式超表面需要外置馈源所导致的溢出损耗高、剖面高以及集成度低等问题, 本文中介绍的工作旨在将馈源与超表面高

度集成以降低结构剖面, 简化馈电网络, 同时实现对辐射波各个维度的调控, 为后续设计低剖面、小型化、集成化的辐射波调制器件与系统提供了新的视角。超表面在直接调控辐射波的领域仍存在很多机遇和挑战, 未来可从以下几个方面进行进一步研究和探讨:

1) 大规模有源辐射式超表面研究。相比于折叠阵超表面、法布里-珀罗超表面与漏波超表面, 辐射式超表面由馈源直接激励超表面单元从而实现对辐射波的直接调控, 不存在空间溢出损耗、表面波-空间波转换等问题, 具有辐射效率高、超表面-馈源低耦合等优势。未来可进一步探索有源辐射式超表面的大规模实现, 构造可调单元数目、状态更多的辐射式超表面, 以期提供一种更灵活、更精准、更高效且成本更低的辐射电磁波调控方案。

2) 超表面对辐射电磁波的智能调控研究。在有源超表面研究中, 智能超表面已展现出强大的电磁波自适应调控能力。未来可借鉴此类工作, 将超表面的辐射功能与外界环境进行感知与匹配, 实现辐射波的自适应与智能调控, 在多普勒雷达、万物互联、卫星通信等领域均有广泛潜在应用价值。

3) 超表面对辐射电磁波的系统级调控研究。近年来, 时域超表面的相关工作^[82-83]实现了对相位、幅度等电磁物理特征的时间域调制, 并在此基础上衍生了新体制无线通信系统。此外, 超表面还在雷达探测系统方面具有广泛的应用潜力。目前对超表面的系统级研究是一大热点, 因此可进一步探索基于辐射波调控超表面的高效、高集成度通信与雷达系统, 进一步推动超表面走向实际工程应用。

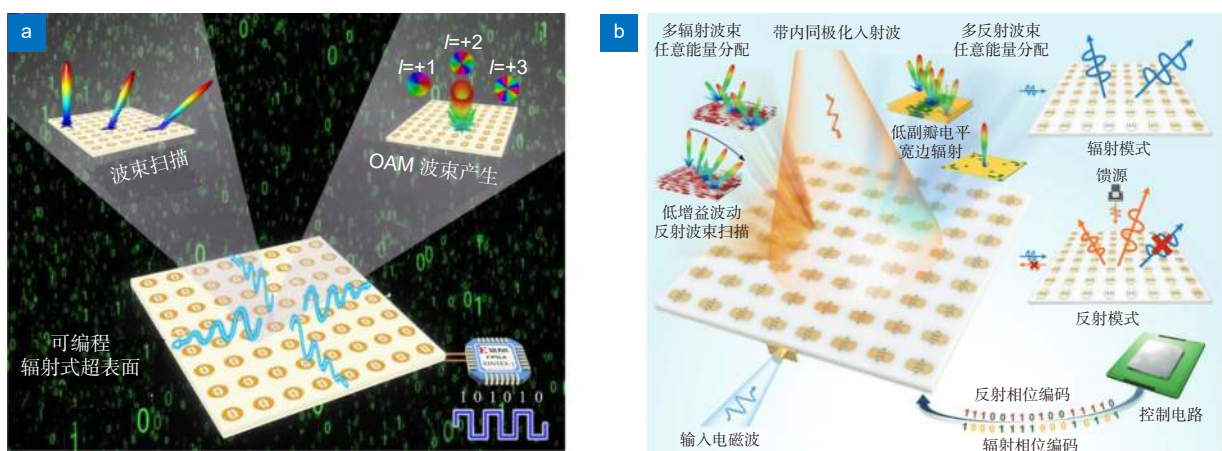


图 9 有源辐射式超表面。(a) 可编程辐射式超表面^[80]; (b) 辐射和反射集成超表面^[81]

Fig. 9 Active radiation-type metasurface. (a) Programmable radiation-type metasurface^[80], (b) Radiations and reflections integrated metasurface^[81]

利益冲突: 所有作者声明无利益冲突

参考文献

- [1] Pendry J B, Holden A J, Stewart W J, et al. Extremely low frequency plasmons in metallic mesostructures[J]. *Phys Rev Lett*, 1996, **76**(25): 4773–4776.
- [2] Pendry J B, Holden A J, Robbins D J, et al. Magnetism from conductors and enhanced nonlinear phenomena[J]. *IEEE Trans Microw Theory Techn*, 1999, **47**(11): 2075–2084.
- [3] Smith D R, Padilla W J, Vier D C, et al. Composite medium with simultaneously negative permeability and permittivity[J]. *Phys Rev Lett*, 2000, **84**(18): 4184–4187.
- [4] Li X, Ma X L, Luo X G. Principles and applications of metasurfaces with phase modulation[J]. *Opto-Electron Eng*, 2017, **44**(3): 255–275.
李雄, 马晓亮, 罗先刚. 超表面相位调控原理及应用[J]. *光电工程*, 2017, **44**(3): 255–275.
- [5] Xu P, Xiao Y F, Huang H X, et al. Dual-wavelength hologram of high transmittance metasurface[J]. *Opt Express*, 2023, **31**(5): 8110–8119.
- [6] Wang X S, Wu J L, Wang R X, et al. Reconstructing polarization multiplexing terahertz holographic images with transmissive metasurface[J]. *Appl Sci*, 2023, **13**(4): 2528.
- [7] Heidari M, Sedighy S H, Amirhosseini M K. RCS reduction using grounded multi-height multi-dielectrics metasurfaces[J]. *Sci Rep*, 2023, **13**(1): 3069.
- [8] Ha T D, Zhu L, Alsaab N, et al. Optically transparent metasurface radome for rcs reduction and gain enhancement of multifunctional antennas[J]. *IEEE Trans Antennas Propag*, 2023, **71**(1): 67–77.
- [9] Faraz Z, Kamal B, Ullah S, et al. High efficient and ultra-wideband polarization converter based on I-shaped metasurface for RCS reduction[J]. *Opt Commun*, 2023, **530**: 129101.
- [10] Dutta R, Mitra D, Ghosh J. Dual-band multifunctional metasurface for absorption and polarization conversion[J]. *Int J RF Microw Comput Aided Eng*, 2020, **30**(7): e22200.
- [11] Loncar J, Grbic A, Hrbar S. A reflective polarization converting metasurface at X-band frequencies[J]. *IEEE Trans Antennas Propag*, 2018, **66**(6): 3213–3218.
- [12] Lin B Q, Huang W Z, Guo J X, et al. A high efficiency ultra-wideband circular-to-linear polarization conversion metasurface[J]. *Opt Commun*, 2023, **529**: 129102.
- [13] Wang J J, Zhu Q H, Dong J F. Research progress of electromagnetic properties of tunable chiral metasurfaces[J]. *Opto-Electron Eng*, 2021, **48**(2): 200218.
王金金, 朱邱豪, 董建峰. 可调谐手征超表面电磁特性研究进展[J]. *光电工程*, 2021, **48**(2): 200218.
- [14] Liu J Y, Duan Y P, Zhang T, et al. Dual-polarized and real-time reconfigurable metasurface absorber with infrared-coded remote-control system[J]. *Nano Res*, 2022, **15**(8): 7498–7505.
- [15] Ghosh S, Srivastava K V. A polarization-independent broadband multilayer switchable absorber using active frequency selective surface[J]. *IEEE Antennas Wirel Propag Lett*, 2017, **16**: 3147–3150.
- [16] Krasikov S, Tranter A, Bogdanov A, et al. Intelligent metapotonics empowered by machine learning[J]. *Opto-Electron Adv*, 2022, **5**(3): 210147.
- [17] Yang Y, Zhang X H, Liu K F, et al. Complex-amplitude metasurface design assisted by deep learning[J]. *Annal Phys*, 2022, **534**(9): 2200188.
- [18] Yang Y, Zhang X H, Liu K F, et al. Exploring the limits of metasurface polarization multiplexing capability based on deep learning[J]. *Opt Express*, 2023, **31**(10): 17065–17075.
- [19] Luo Z J, Ren X Y, Zhou L, et al. A high-performance nonlinear metasurface for spatial-wave absorption[J]. *Adv Funct Mater*, 2022, **32**(16): 2109544.
- [20] Liang J C, Zhang L, Cheng Z W, et al. Flexible beam manipulations by reconfigurable intelligent surface with independent control of amplitude and phase[J]. *Front Mater*, 2022, **9**: 946163.
- [21] Zhang X G, Yu Q, Jiang W X, et al. Polarization-controlled dual-programmable metasurfaces[J]. *Adv Sci*, 2020, **7**(11): 1903382.
- [22] Zhang X G, Jiang W X, Cui T J. Frequency-dependent transmission-type digital coding metasurface controlled by light intensity[J]. *Appl Phys Lett*, 2018, **113**(9): 091601.
- [23] Zhang X G, Tang W X, Jiang W X, et al. Light-controllable digital coding metasurfaces[J]. *Adv Sci*, 2018, **5**(11): 1801028.
- [24] Zhang X G, Jiang W X, Jiang H L, et al. An optically driven digital metasurface for programming electromagnetic functions[J]. *Nat Electron*, 2020, **3**(3): 165–171.
- [25] Zhang X G, Sun Y L, Yu Q, et al. Smart doppler cloak operating in broad band and full polarizations[J]. *Adv Mater*, 2021, **33**(17): 2007966.
- [26] Zhang X G, Sun Y L, Zhu B C, et al. A metasurface-based light-to-microwave transmitter for hybrid wireless communications[J]. *Light Sci Appl*, 2022, **11**(1): 126.
- [27] Chen L, Ma Q, Luo S S, et al. Touch-programmable metasurface for various electromagnetic manipulations and encryptions[J]. *Small*, 2022, **18**(45): 2203871.
- [28] Ke J C, Dai J Y, Zhang J W, et al. Frequency-modulated continuous waves controlled by space-time-coding metasurface with nonlinearly periodic phases[J]. *Light Sci Appl*, 2022, **11**(1): 273.
- [29] Wang S R, Chen M Z, Ke J C, et al. Asynchronous space-time-coding digital metasurface[J]. *Adv Sci*, 2022, **9**(24): 2200106.
- [30] Chen B W, Wang X R, Li W L, et al. Electrically addressable integrated intelligent terahertz metasurface[J]. *Sci Adv*, 2022, **8**(41): eadd1296.
- [31] Zhu R C, Wang J F, Fu X M, et al. Deep-learning-empowered holographic metasurface with simultaneously customized phase and amplitude[J]. *ACS Appl Mater Interfaces*, 2022, **14**(42): 48303–48310.
- [32] Huang J. Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept[C]//*IEEE Antennas and Propagation Society International Symposium. 1995 Digest*, Newport Beach, 1995: 582–585. <https://doi.org/10.1109/APS.1995.530086>.
- [33] Javor R D, Wu X D, Chang K. Design and performance of a microstrip reflectarray antenna[J]. *IEEE Trans Antennas Propag*, 1995, **43**(9): 932–939.
- [34] Abd-Elhady M, Hong W, Zhang Y. A Ka-band reflectarray implemented with a single-layer perforated dielectric substrate[J]. *IEEE Antennas Wirel Propag Lett*, 2012, **11**(1): 600–603.
- [35] Pilz D, Menzel W. Folded reflectarray antenna[J]. *Electron Lett*, 1998, **34**(9): 832–833.
- [36] Jiang M, Hong W, Zhang Y, et al. A folded reflectarray antenna with a planar SIW slot array antenna as the primary

- source[J]. *IEEE Trans Antennas Propag*, 2014, **62**(7): 3575–3583.
- [37] Yang J W, Shen Y Z, Wang L N, et al. 2-D scannable 40-GHz folded reflectarray fed by SIW slot antenna in single-layered PCB[J]. *IEEE Trans Microw Theory Techn*, 2018, **66**(6): 3129–3135.
- [38] Wang S J, Xu H X, Wang M Z, et al. A low-RCS and high-gain planar circularly polarized cassegrain meta-antenna[J]. *IEEE Trans Antennas Propag*, 2022, **70**(7): 5278–5287.
- [39] Xu J, Xu H X, Luo H L, et al. A low-RCS folded reflectarray combining dual-metasurface and rasorber[J]. *IEEE Antennas Wirel Propag Lett*, 2022, **21**(12): 2462–2466.
- [40] Shen Y Z, Yang J W, Meng H F, et al. Generating millimeter-wave Bessel beam with orbital angular momentum using reflective-type metasurface inherently integrated with source[J]. *Appl Phys Lett*, 2018, **112**(14): 141901.
- [41] Miao Z W, Hao Z C, Jin B B, et al. Low-profile 2-D THz airy beam generator using the phase-only reflective metasurface[J]. *IEEE Trans Antennas Propag*, 2020, **68**(3): 1503–1513.
- [42] Yang J, Chen S T, Chen M, et al. Folded transmitarray antenna with circular polarization based on metasurface[J]. *IEEE Trans Antennas Propag*, 2021, **69**(2): 806–814.
- [43] Li G W, Ge Y H, Chen Z Z. A compact multibeam folded transmitarray antenna at Ku-band[J]. *IEEE Antennas Wirel Propag Lett*, 2021, **20**(5): 808–812.
- [44] Li T J, Wang G M, Cai T, et al. Broadband folded transmitarray antenna with ultralow-profile based on metasurfaces[J]. *IEEE Trans Antennas Propag*, 2021, **69**(10): 7017–7022.
- [45] Chen J H, Li G W, Ge Y H, et al. A broadband circularly polarized multi-beam folded transmitarray antenna[J]. *Int J RF Microw Comput Aided Eng*, 2022, **32**(7): e23161.
- [46] Fan C, Che W Q, Yang W C, et al. A novel PRAMC-based ultralow-profile transmitarray antenna by using ray tracing principle[J]. *IEEE Trans Antennas Propag*, 2017, **65**(4): 1779–1787.
- [47] Li T J, Wang G M, Li H P, et al. Circularly polarized double-folded transmitarray antenna based on receiver-transmitter metasurface[J]. *IEEE Trans Antennas Propag*, 2022, **70**(11): 11161–11166.
- [48] Wang Z L, Ge Y H, Pu J X, et al. 1 bit electronically reconfigurable folded reflectarray antenna based on p-i-n diodes for wide-angle beam-scanning applications[J]. *IEEE Trans Antennas Propag*, 2020, **68**(9): 6806–6810.
- [49] Liu B Y, Wong S W, Tam K W, et al. Multifunctional orbital angular momentum generator with high-gain low-profile broadband and programmable characteristics[J]. *IEEE Trans Antennas Propag*, 2022, **70**(2): 1068–1076.
- [50] Li T, Wang R, Sun J W, et al. Characteristic modes-inspired polarization twisting metasurface element for 1-bit folded reflectarray[J]. *IEEE Antennas Wirel Propag Lett*, 2022, **21**(11): 2254–2258.
- [51] Dai J Y, Tang W K, Yang L X, et al. Realization of multi-modulation schemes for wireless communication by time-domain digital coding metasurface[J]. *IEEE Trans Antennas Propag*, 2020, **68**(3): 1618–1627.
- [52] Umair H, Latif T B A, Yamada Y, et al. Tilted beam fabry–perot antenna with enhanced gain and broadband low backscattering[J]. *Electronics*, 2021, **10**(3): 267.
- [53] Li H, Li Y B, Shen J L, et al. Low-profile electromagnetic holography by using coding fabry–perot type metasurface with in-plane feeding[J]. *Adv Opt Mater*, 2020, **8**(9): 1902057.
- [54] Yang P, Yang R, Li Y C. Dual circularly polarized split beam generation by a metasurface sandwich-based fabry–perot resonator antenna in Ku-band[J]. *IEEE Antennas Wirel Propag Lett*, 2021, **20**(6): 933–937.
- [55] Long M, Jiang W, Gong S X, et al. Low-RCS frequency reconfigurable antenna with polarization conversion metasurface and phase tunable reflector[C]//2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, 2017: 1921–1922. <https://doi.org/10.1109/APUSNCURSINRSM.2017.8073003>.
- [56] Bai L, Zhang X G, Wang Q, et al. Dual-band reconfigurable metasurface-assisted Fabry–Pérot antenna with high-gain radiation and low scattering[J]. *IET Microw Antennas Propag*, 2020, **14**(15): 1933–1942.
- [57] Huang C, Pan W B, Ma X L, et al. A frequency reconfigurable directive antenna with wideband Low-RCS property[J]. *IEEE Trans Antennas Propag*, 2016, **64**(3): 1173–1178.
- [58] Zhang J H, Liu Y, Jia Y T, et al. High-gain fabry–Pérot antenna with reconfigurable scattering patterns based on varactor diodes[J]. *IEEE Trans Antennas Propag*, 2022, **70**(2): 922–930.
- [59] Liang J R, Liu J H. A conductor-backed coplanar waveguide leaky-wave antenna with metasurface[C]//2020 IEEE Asia-Pacific Microwave Conference, Hong Kong, China, 2020: 947–949. <https://doi.org/10.1109/APMC47863.2020.9331618>.
- [60] Pandi S, Balanis C A, Birtcher C R. Analysis of wideband multilayered sinusoidally modulated metasurface[J]. *IEEE Antennas Wirel Propag Lett*, 2016, **15**(1): 1491–1494.
- [61] Wang Q, Zhang X Q, Plum E, et al. Polarization and frequency multiplexed terahertz meta-holography[J]. *Adv Opt Mater*, 2017, **5**(14): 1700277.
- [62] Guan C S, Liu J, Ding X M, et al. Dual-polarized multiplexed meta-holograms utilizing coding metasurface[J]. *Nanophotonics*, 2020, **9**(11): 3605–3613.
- [63] Lin Z M, Huang L L, Xu Z T, et al. Four-wave mixing holographic multiplexing based on nonlinear metasurfaces[J]. *Adv Opt Mater*, 2019, **7**(21): 1900782.
- [64] Wu L W, Xiao Q, Gou Y, et al. Electromagnetic diffusion and encryption holography integration based on reflection–transmission reconfigurable digital coding metasurface[J]. *Adv Opt Mater*, 2022, **10**(10): 2102657.
- [65] Xiao Q, Ma Q, Yan T, et al. Orbital-angular-momentum-encrypted holography based on coding information metasurface[J]. *Adv Opt Mater*, 2021, **9**(11): 2002155.
- [66] Li Y B, Cai B G, Cheng Q, et al. Isotropic holographic metasurfaces for dual-functional radiations without mutual interferences[J]. *Adv Funct Mater*, 2016, **26**(1): 29–35.
- [67] Shen Y Z, Xue S, Dong G Q, et al. Multiplexing tensor holographic metasurface with surface impedance superposition for manipulating multibeam with multimodes[J]. *Adv Opt Mater*, 2021, **9**(22): 2101340.
- [68] Wu G B, Dai J Y, Cheng Q, et al. Sideband-free space–time-coding metasurface antennas[J]. *Nat Electron*, 2022, **5**(11): 808–819.
- [69] Yurduseven O, Smith D R, Fromenteze T. Design of a reconfigurable metasurface antenna for dynamic near-field focusing[C]//2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, 2018: 1707–1708. <https://doi.org/10.1109/APUSNCURSINRSM.2018.8609076>.

- [70] Tian Y C, Han J Q, Ma X J, et al. Design of 1-bit programmable holographic metasurface for monopulse radar applications[C]//2021 IEEE MTT-S International Wireless Symposium, Nanjing, 2021: 1–3. <https://doi.org/10.1109/IWS52775.2021.9499630>.
- [71] Li T, Chen Z N. Wideband sidelobe-level reduced Ka -band metasurface antenna array fed by substrate-integrated gap waveguide using characteristic mode analysis[J]. *IEEE Trans Antennas Propag*, 2020, **68**(3): 1356–1365.
- [72] Wang J F, Li Y, Jiang Z H, et al. Metantenna: when metasurface meets antenna again[J]. *IEEE Trans Antennas Propag*, 2020, **68**(3): 1332–1347.
- [73] Lv Y H, Wang R, Wang B Z, et al. Anisotropic complementary metantenna for low sidelobe radiation and low in-band Co-polarized scattering using characteristic mode analysis[J]. *IEEE Trans Antennas Propag*, 2022, **70**(11): 10177–10186.
- [74] Zhang P, Zhang X M, Li L. An optically transparent metantenna for RF wireless energy harvesting[J]. *IEEE Trans Antennas Propag*, 2022, **70**(4): 2550–2560.
- [75] Xu P, Jiang W X, Cai X, et al. An integrated coding-metasurface-based array antenna[J]. *IEEE Trans Antennas Propag*, 2020, **68**(2): 891–899.
- [76] Xu P, Tian H W, Jiang W X, et al. Phase and polarization modulations using radiation-type metasurfaces[J]. *Adv Opt Mater*, 2021, **9**(16): 2100159.
- [77] Xu P, Tian H W, Cai X, et al. Radiation-type metasurfaces for advanced electromagnetic manipulation[J]. *Adv Funct Mater*, 2021, **31**(25): 2100569.
- [78] Wang Y Z, Pang C, Wang Q M, et al. Phase-only compact radiation-type metasurfaces for customized far-field manipulation[J]. *IEEE Trans Microw Theory Techn*, 2023, **71**(9): 4119–4128.
- [79] Mu Y H, Pang C, Wang Y Z, et al. Complex-amplitude radiation-type metasurface enabling beamform-controlled energy allocation[J]. *Photon Res*, 2023, **11**(6): 986–998.
- [80] Bai X D, Zhang F L, Sun L, et al. Radiation-type programmable metasurface for direct manipulation of electromagnetic emission[J]. *Laser Photon Rev*, 2022, **16**(11): 2200140.
- [81] Tian H W, Xu L, Li X, et al. Integrated control of radiations and in-band Co-polarized reflections by a single programmable metasurface[J]. *Adv Funct Mater*, 2023, **33**(36): 2302753.
- [82] Zhao J, Yang X, Dai J Y, et al. Programmable time-domain digital-coding metasurface for non-linear harmonic manipulation and new wireless communication systems[J]. *Nat Sci Rev*, 2019, **6**(2): 231–238.
- [83] Chen M Z, Tang W K, Dai J Y, et al. Accurate and broadband manipulations of harmonic amplitudes and phases to reach 256 QAM millimeter-wave wireless communications by time-domain digital coding metasurface[J]. *Nat Sci Rev*, 2022, **9**(1): nwab134.

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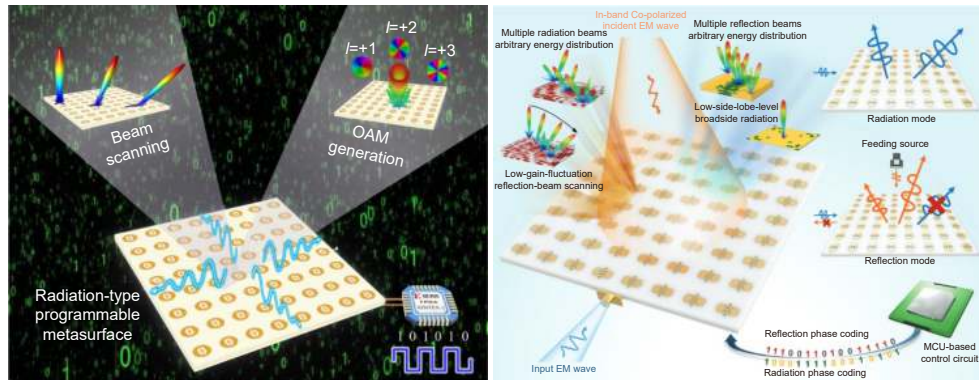
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Manipulations and applications of radiating waves using electromagnetic metasurfaces

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Schematic diagram of active radiation-type metasurface

Overview: Metamaterials are composed of basic electromagnetic unit cells with sub-wavelength size. Different from natural materials, the properties of metamaterials depend mainly on the structure and arrangement of electromagnetic unit cells. This characteristic can be used to flexibly design metamaterials with unique properties such as negative permittivity, negative permeability, and negative refractive index. As the two-dimensional form of metamaterials, metasurfaces utilize the abrupt phase/amplitude generated by the sudden change of electromagnetic waves on the interface of metasurface to achieve the free control of the incident electromagnetic waves, thus having the advantages of easy design, low profile, and low loss. In recent years, the manipulation of electromagnetic waves by metasurfaces has been widely studied and applied by researchers, such as holographic imaging, radar cross section reduction, polarization conversion, absorption, etc. In practical application scenarios, such as wireless communication, broadband absorption, electromagnetic stealth, etc., metasurfaces are often required to have the ability to dynamically adjust electromagnetic waves, and achieve various functions according to specific working frequency, powers, and polarizations of incident waves. Based on such requirements, researchers have achieved dynamic regulation of metasurfaces by loading active elements on metasurfaces. Active metasurfaces can control the state of active elements through the feeding layer to achieve different phase coverage and amplitude regulation, so that metasurfaces can achieve dynamic switching between multiple functions, improve the ability to modulate electromagnetic waves, and promote the in-depth application and development of the metasurfaces in various fields. In the above work, metasurfaces mainly achieve various electromagnetic functions by regulating reflecting and transmitting waves, metasurface itself is only used as a secondary feed, and additional primary feed is needed, which not only produces overflow loss and edge attenuation, but also leads to increase in the overall profile of the system and decrease in the integration. In fact, electromagnetic metasurfaces also have the strong regulation ability for radiating waves. The feed-integrated metasurfaces solve the above problems due to its ingenious design ideas. Based on the integration of metasurfaces and feeds and the regulation principle of metasurfaces on radiating electromagnetic waves, this paper systematically introduces various types of metasurfaces and their related applications for the direct control of radiating waves from passive to active aspects, such as folded reflectarray/transmitarray metasurfaces, Fabry-Perot metasurfaces, leaky wave metasurfaces and radiation-type metasurfaces, corresponding to air feeding, surface wave feeding, gap coupling feeding, coaxial feeding. The related works of these types of feed-integrated metasurfaces are systematically introduced. Finally, the related researches in this field are summarized and prospected.

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