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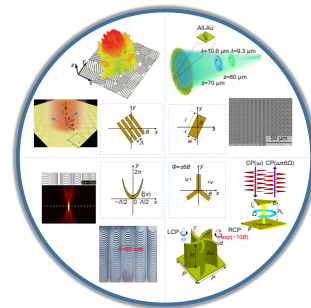
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全金属超表面在电磁波相位调控中的应用及进展

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摘要: 全金属超表面是由亚波长金属单元所组成的结构阵列, 其在调控电磁波相位方面展现出了效率高、带宽大等特点, 并且相较于金属-介质混合型超表面, 全金属超表面具有优良的热学和机械性能, 如耐高温、强度大、延展性好等, 这使得其可以应用于高温高压等极端复杂环境中。本文对近年来全金属超表面取得的研究进展进行了简要的归纳总结, 主要介绍了其在构建高效、多功能平面光学器件以及多频谱电磁隐身中的应用, 并对其未来的发展方向进行了展望。

关键词: 全金属超表面; 几何相位; 电磁隐身; 高效率

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Applications and progress of all-metal metasurfaces in phase manipulation of electromagnetic waves

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Abstract: All-metal metasurfaces are structural arrays composed of sub-wavelength metal units, which exhibit high efficiency and large bandwidth in phase manipulation of electromagnetic waves. Compared with metal-dielectric hybrid metasurfaces, all-metal metasurfaces have excellent thermal and mechanical properties, such as high-temperature resistance, high strength, and good ductility, which enable them to be applied in extremely complex environments such as high temperature and high pressure. In this paper, we briefly summarize the recent research progress based on all-metal metasurfaces. We mainly introduce their applications in the construction of highly efficient and multi-functional planar optical devices as well as multi-spectrum electromagnetic stealth, and provide

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an outlook of the future direction of its development.

Keywords: all-metal metasurface; geometric phase; electromagnetic stealth; high efficiency

1 引言

超表面是一种可以在亚波长范围内对电磁波的振幅、相位以及偏振态等光学属性进行灵活调控的人工二维结构, 它突破了超材料三维结构的限制, 有利于光学系统向轻量化、微型化方向发展。2011年, 美国哈佛大学 Capasso 教授团队提出了广义折反射定律, 通过调节 V 型金属天线的夹角和臂长, 产生了一定的相位梯度, 从而实现了光的异常折反射现象^[1]。该工作引发了学术界对平面光学的研究热潮, 使得基于超表面的电磁波相位调控技术得到了快速发展, 涌现出一系列的新型功能器件与应用, 如光聚焦与成像^[2-5]、全息显示^[6-8]、涡旋光束发生器^[9-12]等。

2013年, Monticone 等人根据理论分析与计算得到, 超薄透射型超表面的理论效率极限为 25%^[13], 而实际加工出的器件效率通常不足理论极限值的一半, 这极大限制了超表面的应用。因此, 如何提高超表面的工作效率成为研究人员关注的重点话题。有学者采用多层超表面来提高两种圆偏振光之间的偏振转换效率^[14-21], 突破了单层透射型超表面的效率极限, 但这也增加了材料的厚度和结构复杂度。随后, 为了摆脱金属结构的欧姆损耗问题, 研究人员采用低损耗的高折射率介质材料来构造超表面^[22-29], 从而显著提高了器件的工作效率。除此之外, 采用反射式设计也可以显著提高超表面器件的效率。常用的反射式设计方式为金属-介质-金属 (metal-insulator-metal, MIM) “三明治”构型^[30-35], 包括顶层的金属天线、中间介质层, 以及底层的金属反射衬底。利用该方法, 可以使超表面的工作效率达到 80% 以上。2018年, 研究人员提出一种新的反射式超表面, 该结构由亚波长金属光栅和金属反射衬底组成, 是一种全金属化的超表面。他们利用几何相位原理调控电磁波散射, 结合金属材料低辐射特性, 在红外波段同时实现了极低的反射率与辐射率, 并构建了高效率的全息器件^[36]。相较于 MIM 型设计, 全金属超表面避免了由法布里-珀罗谐振腔引起的谐振模式, 降低了光波反射时金属结构的欧姆损耗, 从而进一步提高了超表面的工作效率和带宽^[37]。此外, 金属材料通常具有优良的机械、热

学等性能, 如强度大、韧性好、耐高温、良好的导电导热性等。这使得全金属超表面不仅能够多物理场调控中发挥重要作用, 还有望应用于高温高压等极端复杂环境中。

全金属超表面在电磁波调控方面所表现出的优异性能, 使其广泛用于各类光学器件与应用^[38-44]。本文对近年来基于全金属超表面的电磁波相位调控技术进行归纳总结, 首先介绍了基于全金属超表面构建的高效率平面光学器件, 然后阐述了全金属超表面在电磁隐身领域中的应用, 最后进行总结并对全金属超表面的未来发展趋势进行展望。

2 全金属超表面器件与应用

全金属超表面是由亚波长金属单元所组成的结构阵列, 其调控电磁波相位的方式同其他超表面一样, 包括共振相位、几何相位以及传播相位等^[45]。目前, 使用最广泛的是基于几何相位原理进行设计, 常见的几种单元结构如图 1 所示, 分别为光栅结构、纳米砖结构、悬链线结构以及多重旋转对称结构等^[36-37, 46-51]。值得一提的是, 电磁波与全金属结构相互作用的物理过程可以通过悬链线模型解释^[37, 46, 52-53]。通过控制光栅和纳米砖结构的取向角可以产生二倍于取向角的相位延迟, 从而实现局域相位调控。随着悬链线光学的发展, 将全金属设计和悬链线结构结合, 则可以实现电磁波相位的高效连续调控。之后, 广义几何相位的出现进一步丰富了超表面光场调控的自由度, 利用具有多重旋转对称性的单元结构可以产生数倍于旋转角的相位延迟。目前, 全金属超表面已被广泛应用于各类光学器件的设计, 如偏振转换、全息显示以及涡旋光束发生器等。此外, 得益于金属材料优良的热学、力学等特性, 其在电磁隐身领域也发挥出了重要作用, 下面将围绕这两类应用展开详细描述。

2.1 全金属超表面在平面光学器件中的应用

几何相位型超表面在各类平面光学器件中应用广泛^[54], 该类超表面最大的优势在于其设计简单, 并且产生的几何相移与波长无关, 基于该原理研究人员设计出了一系列宽带的全金属超表面功能器件。2018年, 研究人员通过控制亚波长金属光栅的取向

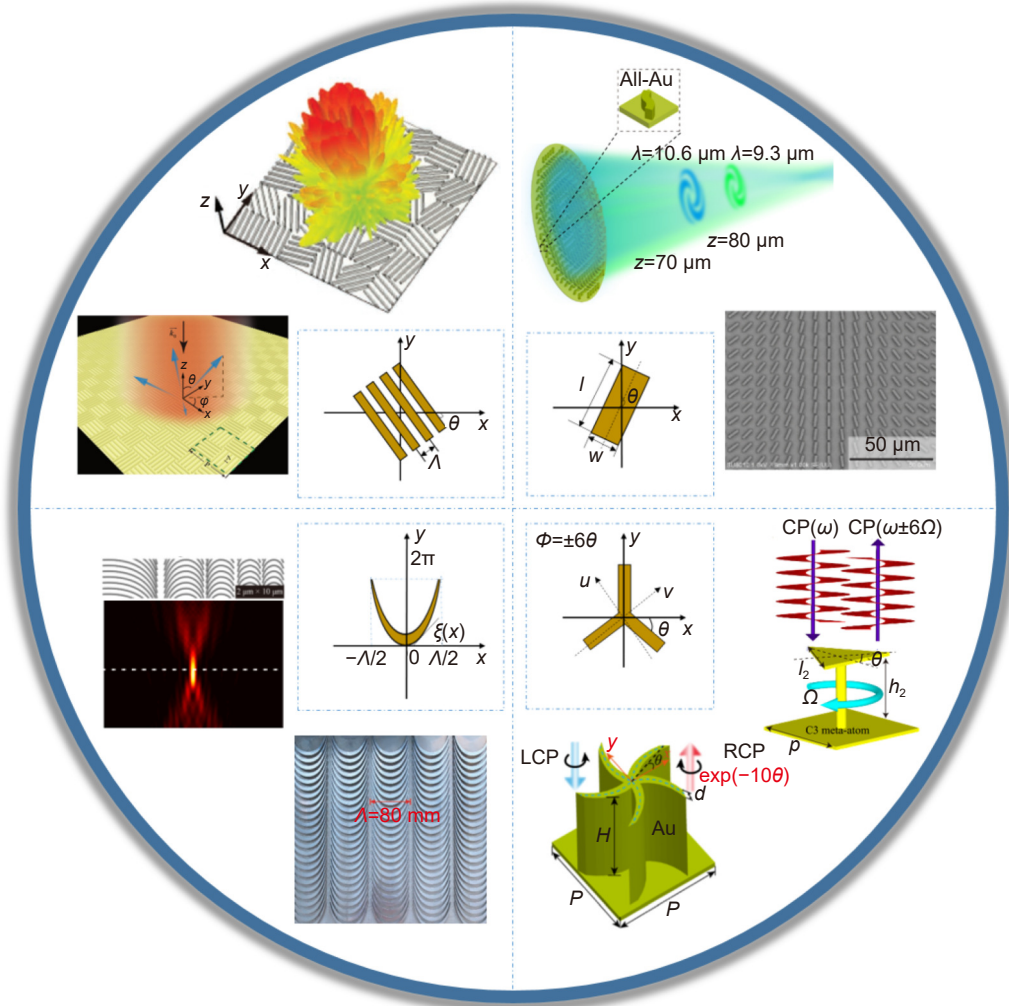


图 1 常见的几何相位型单元结构及全金属超表面。第一、二象限展示了金属纳米砖和金属光栅单元结构以及基于其设计的电磁隐身器件^[36,46]、全息显示器件^[37]、涡旋光束发生器^[47]；第三象限展示了悬链线型金属单元结构以及基于其设计的圆偏振光分束器^[48]、光聚焦器件^[49]；第四象限展示了具有多重旋转对称性的单元结构以及基于广义几何相位设计的波前调控器件^[50]、旋转多普勒频移探测器件^[51]

Fig. 1 Schematic diagram of the typical geometric phase-type building blocks and all-metal metasurfaces. The first and second quadrants show the metallic nanobrick and grating unit structures and the designed electromagnetic stealth devices^[36,46], holographic display device^[37], and vortex beam generator^[47]; the third quadrant shows a catenary metal unit structure and the designed circularly polarized beam splitter^[48], optical wave focusing device^[49]; the fourth quadrant shows the unit structure with multi-fold rotational symmetry and the designed wavefront modulation device^[50] and rotational Doppler effect detector^[51]

角在红外波段实现了电磁波的高效散射，与此同时他们还制备了全息显示效率超过 80% 的反射式全息器件^[36]。如图 2(a) 所示，用于构建超表面的金属光栅单元在宽波段内表现出了超高的反射率和偏振转换效率。上述全金属超表面不仅工作效率高，而且加工简单。为节省成本，研究人员采用激光直写和传统光刻技术，通过在光刻胶或者硅、石英等基底上刻蚀出目标结构，然后镀一定厚度的金属层，得到超表面样品。尽管通过该方法制备的超表面并不是理想的全金属结构，但

金属层的厚度远大于趋肤深度，可以实现与全金属结构相同的光学功能，因此可以将其视为全金属结构。随后，2019 年他们采用金属砖作为单元结构，同样利用几何相位原理实现了宽带和高效的电磁波前操纵^[37]。如图 2(b) 所示，在圆偏振光入射的情况下，所设计的单元结构在 9.5~11.5 μm 的波长范围内，交叉偏振反射率达到 94%。相较于 MIM 型结构，全金属结构呈现出更高的偏振转换效率和更大的带宽。进一步，通过控制金属单元的空间取向实现 0-2π 的相位

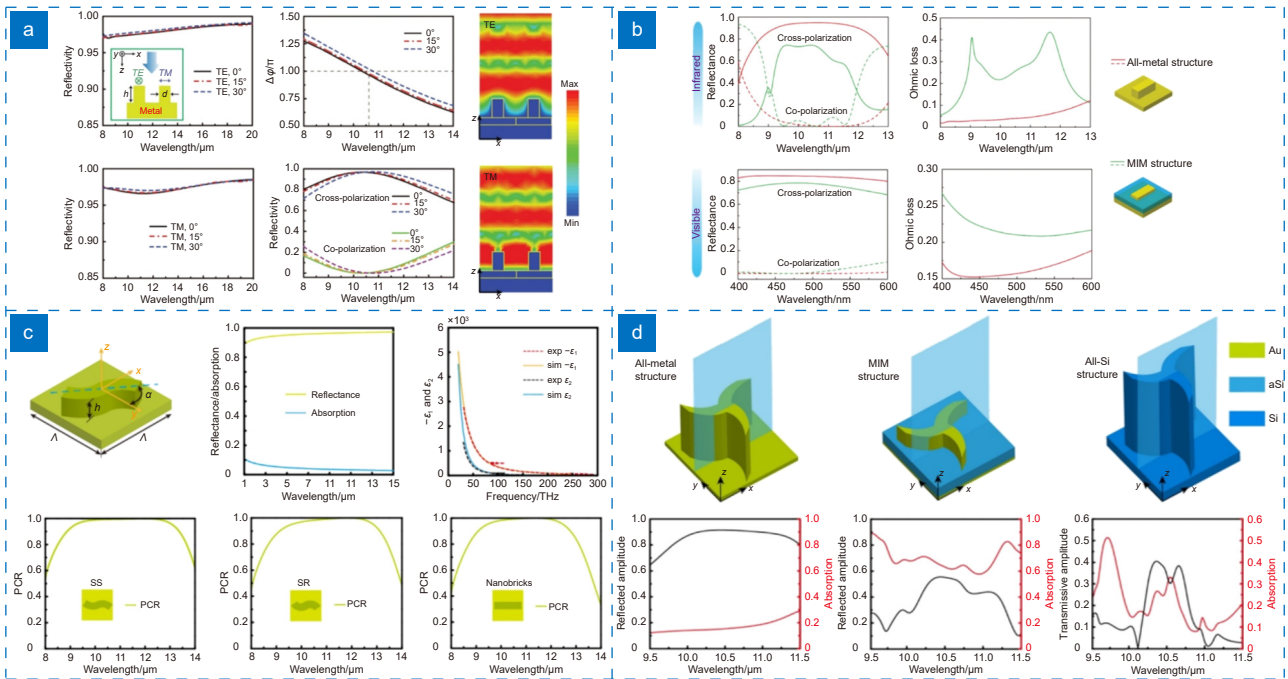


图 2 不同金属单元结构的仿真结果。(a) 金属光栅的仿真结果^[36]; (b) 金属纳米砖的仿真结果及其与 MIM 结构的对比^[37]; (c) S 型单元结构的仿真结果^[47]; (d) 不同 C3 结构的仿真对比^[50]

Fig. 2 Simulation results of different metal unit structures. (a) Simulation results of metal gratings^[36]; (b) Simulation results of metal nanobricks and comparison with MIM-type structure^[37]; (c) Simulation results of S-type unit structure^[47]; (d) Simulation comparison of different C3 structures^[50]

调控, 并实验验证了高效的光束偏转和全息显示功能。2020 年, 研究人员在此单元结构的基础上设计了一种由 S 型纳米砖组成的全金属超表面^[47], 通过对比另外两种单元结构, 发现 S 型金属结构具有更高的平均偏振转换效率及更大的工作带宽, 如图 2(c) 所示。2021 年, 研究人员提出了广义几何相位理论, 并指出利用全金属结构设计可以显著提高器件的效率^[51]。随后, Cai 等人对此进行了实验验证, 利用广义几何相位原理设计了高效率的全息器件。如图 2(d) 所示, 相比于 MIM 结构和全介质结构, 全金属结构展现出更高的效率和更大的带宽^[50]。在微波波段, Luo 等人利用二重和三重旋转对称性的全金属结构, 分别得到了两倍和六倍的旋转多普勒频移, 证明了高阶几何相位可以放大旋转多普勒频移^[51]。

上述全金属超表面均是通过离散的单元结构来构建, 这会导致波前采样不足从而影响器件的工作效率以及信噪比^[56]。Pu 等人于 2015 年提出了悬链线结构光学^[57], 为连续精准地调控电磁波相位提供了一种行之有效的方法, 随之涌现出一系列高效、宽带的平面光学器件与应用^[58-60]。随着悬链线光学的发展, 研究人员将全金属设计与悬链线结构相结合, 开发出了更

为高效的平面光学器件。图 3(a) 所示为基于金属悬链线结构设计的圆偏振波分束器^[48], 该器件能够将入射的线偏振光高效地分离为左旋圆偏振光和右旋圆偏振光并使其偏转到预定的角度, 分束效率高达 92%。同时, 通过向悬链线凹槽注入酒精实现了工作频率从 10.5 GHz 到 8.5 GHz 的连续调谐。在可见光波段, Tang 等人基于悬链线结构提出了一种全金属超表面, 以此来实现高效和宽带的光聚焦功能^[49], 如图 3(b) 所示。所设计的超透镜分别可以实现衍射受限和亚衍射极限聚焦, 工作带宽几乎覆盖整个可见光谱, 相较于二元相位超透镜, 通过悬链线结构设计实现了更高的聚焦效率并更好地抑制了杂散光。

利用全金属超表面进行光学多参量调控, 可以实现一系列多功能光学器件^[61-69]。Du 等人采用铝纳米砖结构, 利用其取向简并性提供连续的振幅调制以及二元的相位调控, 通过点源算法优化出铝纳米砖的取向分布进而匹配目标振幅和相位, 如图 4(a) 所示, 同时实现了近场灰度显示和三维全息成像^[70], 如图 4(b) 所示。Zhang 等人采用 SP 光刻技术制备了一种用于实现彩色打印和全息成像的超薄全金属超表面^[71], 如图 4(c) 所示, 根据匹配得到的振幅分布, 在

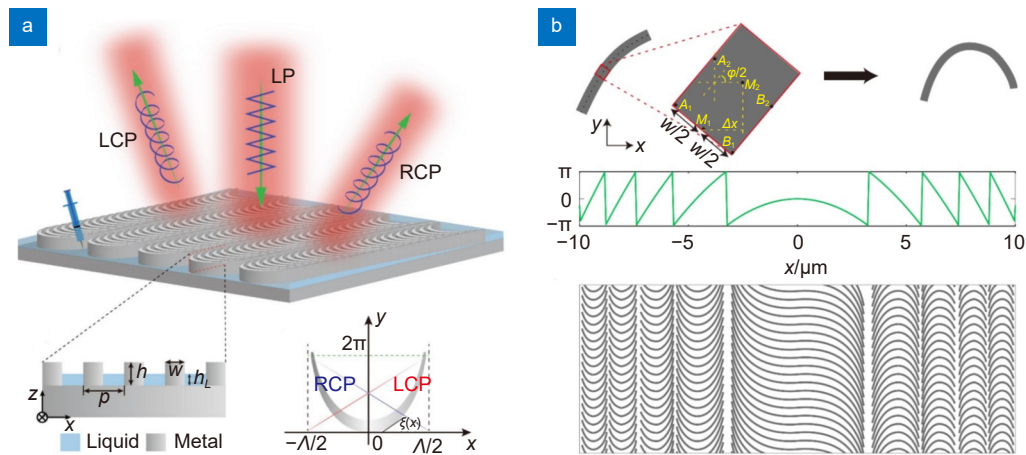


图 3 基于悬链线结构的全金属超表面。(a) 圆偏振波分束器^[48]; (b) 聚焦透镜^[49]
 Fig. 3 All-metal catenary metasurfaces. (a) Circular polarized beam splitter^[48]; (b) Focusing lens^[49]

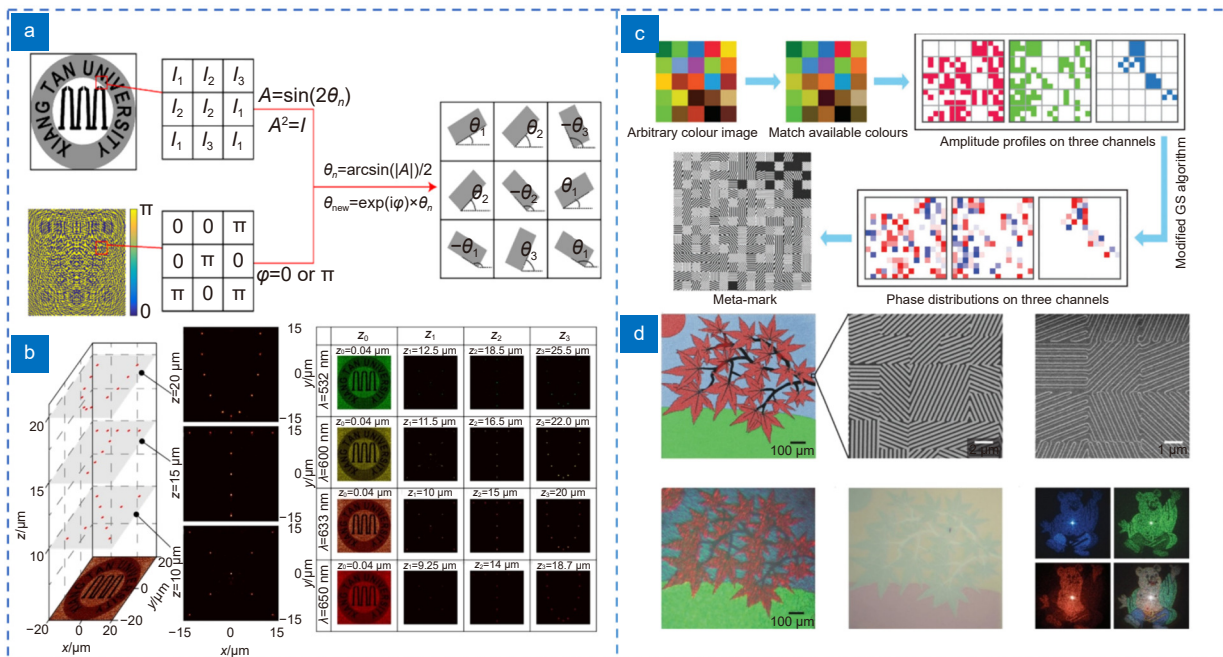


图 4 基于全金属超表面的多功能器件。(a, b) 利用复振幅调控同时实现近场灰度显示和三维全息成像^[70];
 (c, d) 利用全金属超表面实现的结构色全息器件^[71]

Fig. 4 Multifunctional devices based on all-metal metasurfaces. (a, b) Simultaneous near-field grayscale display and three-dimensional holographic imaging enabled by complex amplitude modulation^[70]; (c, d) Simultaneous full-color printing and holography enabled by all-metal metasurface^[71]

Gerchberg-Saxton 算法下优化得到相位分布, 再将不同通道的相位信息进行编码。在宽带非相干光源的照明下, 打印图像会随着观察角度发生变化, 并且利用入射光的偏振态可以实现虚假颜色与真实颜色的转换。在相干光源的照明下, 该器件在远场可以实现全息显示, 并且通过解密三个不同波长的全息图可以得到加密后的信息, 如图 4(d) 所示。Cheng 等人提出一种用于实现偏振转换的全金属超表面^[72], 通过调整纳米砖结构的几何参数, 不仅实现了线偏振态到其正交偏振态的转换, 在 356.5~536.5 THz 范围内偏振转换效率超过 90%, 而且实现了线偏振态到圆偏振态的转换, 在 336.5~544.5 THz 范围内其偏振消光比的绝对值大于 10 dB。

目前, 全金属超表面已被应用于太赫兹波操纵、3D 制造、多物理场调控等。2022 年, Wang 等人采用金属开口谐振环结构设计了一种宽带、高效的多功能太赫兹超表面^[73], 如图 5(a) 所示。该结构能够将入射的圆偏振光转化为手性相反的圆偏振光, 在 0.8-1.65 THz 范围内转换效率超过 95%。进一步, 通过控

制开口谐振环的取向角实现了反射波相位的控制, 如图 5(b) 所示。图 5(c) 和 5(d) 为聚焦及涡旋光束产生的仿真结果, 表明该器件具有良好的波前操纵能力。2022 年, Zhu 等人利用 3D 打印在微波波段制备了一种全金属超表面, 以实现双频圆偏振波的转换^[74]。当左旋圆偏振光入射时, 该器件不仅可以通过垂直调整单元结构的位置产生所需要的传播相移, 将低频入射光转化为右旋圆偏振光并偏转到特定角度, 还可以与通过旋转金属单元引入的几何相移相结合, 将高频入射的左旋圆偏振光以另一角度进行反射。此外, 全金属超表面能够在多物理场调控中发挥重要作用。例如在 2019 年, Cui 等人基于铝材料制备了一种可同时调控电磁波与声波的超表面^[75], 如图 5(e) 所示, 所设计的开口谐振环结构在 50-100 mm 的波长范围内相位响应超过了 300°, 振幅响应均在 0.99 以上。基于此, 分别对多波束产生、漫反射以及波束偏转等功能进行了验证, 如图 5(f-h) 所示。相较于 MIM 型超表面, 该器件采用全金属材料设计, 在降低制造难度的同时, 也满足了实际应用中高强度、延展性好以及耐高温等

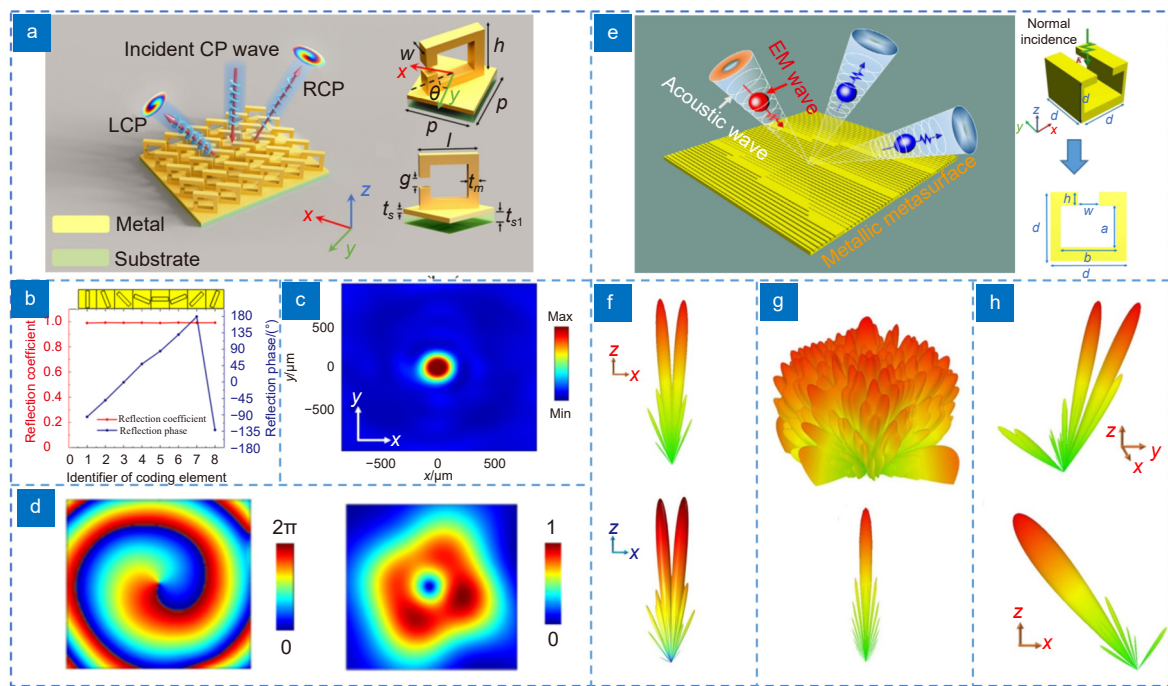


图 5 基于开口谐振环结构的全金属超表面。(a) 太赫兹全金属超表面示意图^[73];
(b-d) 太赫兹超表面的仿真结果, 包括异常反射、聚焦、涡旋光束产生^[74];
(e) 同时操纵电磁波和声波的超表面^[75];
(f-h) 针对电磁波和声波的多波束产生、漫反射以及波束偏转计算结果^[75]

Fig. 5 All-metal metasurfaces based on split-ring resonators. (a) Schematic diagram of the terahertz metasurface^[73]; (b-d) Simulation results of the terahertz metasurface, including anomalous reflection, focusing, vortex beam generation^[74]; (e) All-metal metasurface for simultaneous manipulation of electromagnetic waves and acoustic waves^[75]; (f-h) Calculations results of multiple-beam generation, scattering diffusion, and beam steering for both electromagnetic waves and acoustic waves^[75]

物理属性要求。

2.2 全金属超表面在电磁隐身方面的应用

电磁隐身, 即利用材料对电磁波的吸收和反射特性, 借助目标“大气窗口”的波长选择性来实现隐身或者伪装。近年来, 基于超表面强大的电磁波调控能力, 涌现出了一系列超薄隐身材料与器件^[76-80]。传统的金属-介质混合超表面多工作于同一频谱, 难以实现多频段兼容^[81-82], 并且其结构难以在复杂的工程环境中实际应用。为了克服这一难题, 研究人员基于全金属结构设计了多种超表面和超材料器件, 实现了多频谱兼容的电磁伪装。

2018年, 研究人员提出一种由亚波长金属光栅组成的相位梯度超表面, 通过调控电磁波散射, 并结合金属材料在红外波段的低辐射特性, 在 8-14 μm 波段同时实现了超低的镜面反射率和发射率^[36]。如图 6(a) 所示, 在电磁波以不同角度入射时, 实验加工的样品在 10~14 μm 波段的相应镜面反射率均低于 0.1, 并且从红外热像仪的测试结果中可以看到样品具有超低的热辐射, 证明该结构有望应用于激光与热红外的兼容隐身。在此工作基础上, 2019年他们结合漫反射原理, 在微波波段设计了一种全金属超表面^[46], 分别在 6°、20°、30°三种入射角下测量器件的反射信号, 证明了该结构在大入射角和宽频谱下的高效雷达散射截面 (radar cross section, RCS) 抑制能力。

进一步, 他们还验证了该超表面的耐高温和低热辐射特性, 如图 6(b) 所示。值得一提的是, 研究人员发现金属光栅间的电场分布满足悬链线函数, 基于此建立了悬链线模型解释了电磁波与厚金属光栅相互作用的物理过程, 推动了悬链线光学的进一步发展。

2020年, 基于全金属超表面, Feng 等人提出了一种分层超材料以实现激光-热红外-微波的兼容隐身, 如图 7(a) 所示^[83]。该结构由顶层的全金属超表面阵列和底层的微波吸收器组成。金属超表面能够将入射的 1.06 μm 激光散射到其他方向进而抑制其回波信号。同时, 结构在 3~5 μm 和 8~14 μm 的红外大气窗口具有极低的发射率。超表面阵列间留有 μm 级宽度的间隙, 使得微波几乎能够全部透射进而被底层的吸波材料高效吸收。仿真结果表明, 在入射角不超过 40°时, TE 和 TM 偏振光在 7~12.7 GHz 的频率范围内吸收效率均超过 90%。进一步, 他们于 2022 年又提出了一种大面积的跨尺度分层超材料^[84], 同时实现了双波长激光、热红外以及微波的多频谱兼容隐身, 所设计的器件可以通过纳米压印技术进行大面积低成本制造。如图 7(b) 所示, 采用的结构设计在上述工作类似, 也是由全金属超表面阵列和微波吸收器组成。其中超表面能够同时将 1.06 μm 和 10.6 μm 波长的激光散射到其他方向使得镜面反射率缩减至 0.2, 同时金属结构表面还可以保持不超过 0.2 的红外发射率。入射的微波通过金属超表面阵列后被下方的吸波材料吸收, 实

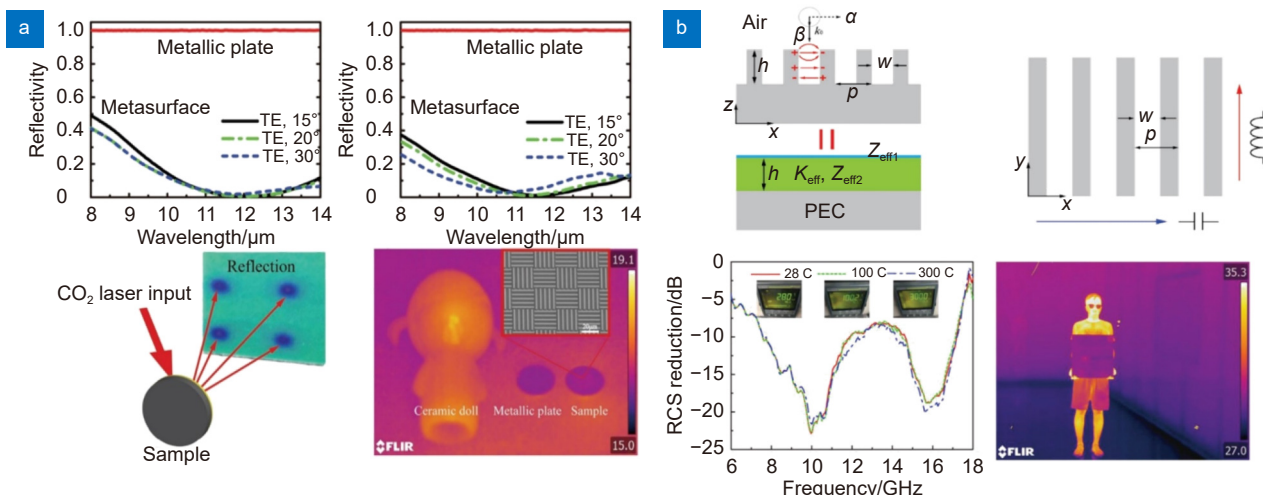


图 6 基于全金属超表面的激光-红外和微波-红外隐身技术。(a) 激光-红外兼容隐身材料的测试结果^[36];

(b) 厚金属光栅的等效电路模型及微波-红外兼容隐身材料的高温 RCS 和红外辐射测试结果^[46]

Fig. 6 Laser-infrared and microwave-infrared stealth technology based on all-metal metasurface. (a) Measurement results of the laser-infrared compatible stealth materials^[36]; (b) Equivalent circuit model of the thick metal grating and measured high-temperature RCS and infrared radiation of the microwave-infrared compatible stealth materials^[46]

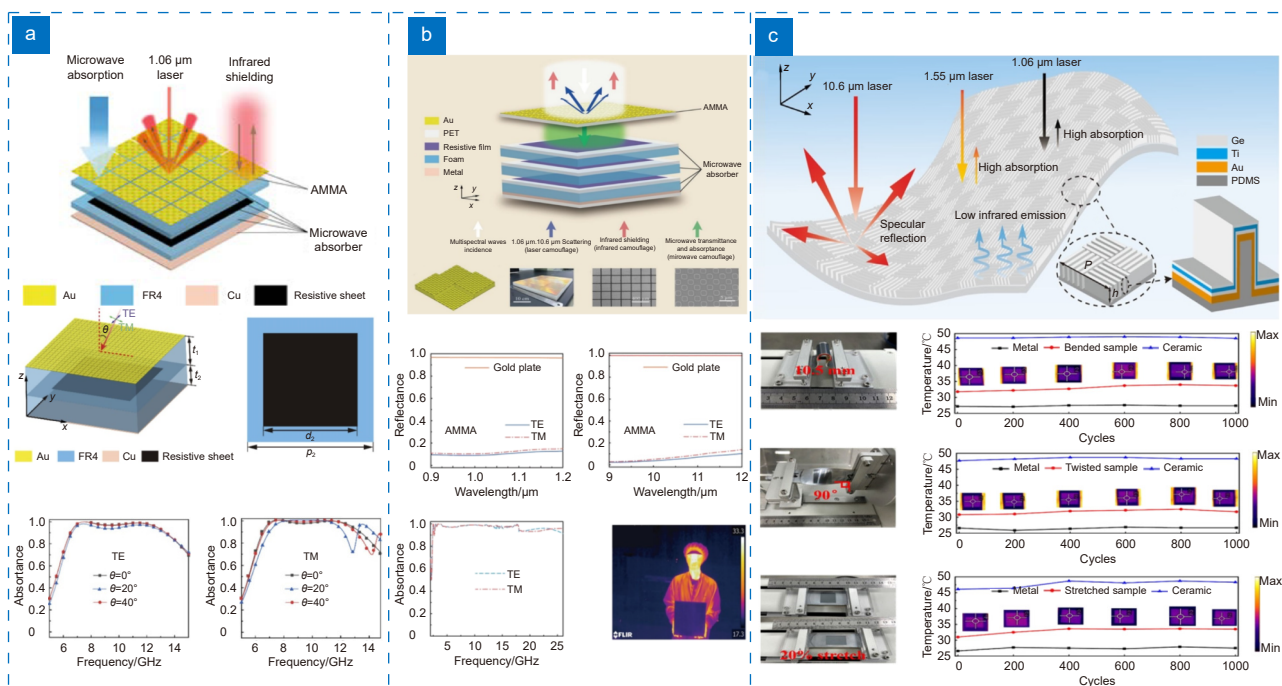


图 7 基于全金属超表面建立的多频谱兼容隐身超材料。(a) 激光-红外-微波隐身兼容的分层超材料示意图及仿真结果^[83]；(b) 大面积跨尺度分层超材料示意图及实验测试结果^[84]；(c) 多波长激光-红外兼容的柔性金属超表面示意图及实验测试结果^[85]

Fig. 7 Multispectral compatible stealth metamaterials based on all-metal metasurfaces. (a) Schematic diagram and simulation results of the hierarchical metamaterial for laser-infrared-microwave compatible stealth^[83]; (b) Schematic diagram of the large-area and multiscale hierarchical metamaterials and experimental test results^[84]; (c) Schematic diagram and experiment results of the flexible metallic metasurface for multi-wavelength lasers and infrared compatible stealth^[85]

验结果表明在 2.7-26 GHz 的超宽带范围内吸收效率超过 90%。考虑到隐身材料作为蒙皮时经常需要曲面贴合, Huang 等人将金属反射层加工在 PDMS 衬底上, 实现了一种柔性金属超表面^[85], 如图 7(c) 所示。该结构基于相消干涉原理实现了 1.06 μm 和 1.55 μm 激光的高效吸收。与此同时, 设计的棋盘型超表面结构可以调控 10.6 μm 激光散射从而降低其镜面反射率, 最终同时实现三波长激光 (1.06 μm、1.55 μm、10.6 μm) 的低反射, 实验测得的反射率分别为 0.017、0.13、0.17。该金属结构在 3~5 μm 和 8~14 μm 波段依然保持低的热辐射特性, 平均发射率分别为 0.19 和 0.11。除此之外, 该材料还表现出超疏水性等特点, 为多频谱兼容隐身提供了有效手段。

3 总结与展望

近年来, 国内外学者在基于全金属超表面的电磁波相位调控技术方面开展了广泛和深入的研究, 设计并制备了一系列新型功能器件与材料。综合来看, 全金属超表面表现出了加工简单、机械性能好等优势, 并且具有高效率、宽带等特点, 有望为实现下一代集

成化、平面化光学器件及多频谱兼容的电磁隐身材料提供方案。

尽管全金属超表面在近年来得到了广泛关注和长足的发展, 但仍然面临着许多机遇与挑战。光波所携带的信息非常丰富, 如振幅、相位以及偏振态等, 进一步开发光学多参量调控, 有望实现多维度信息复用; 其次, 金属材料普遍具有优良的热学、力学、电学等性能, 如何充分发挥全金属结构的优势并探索其在多物理场调控中的应用还有待进一步研究; 最后, 目前全金属超表面同样面临无法动态调控的问题, 在未来实现更多更复杂功能的同时, 发展动态可调谐的手段将能够丰富其应用场景。

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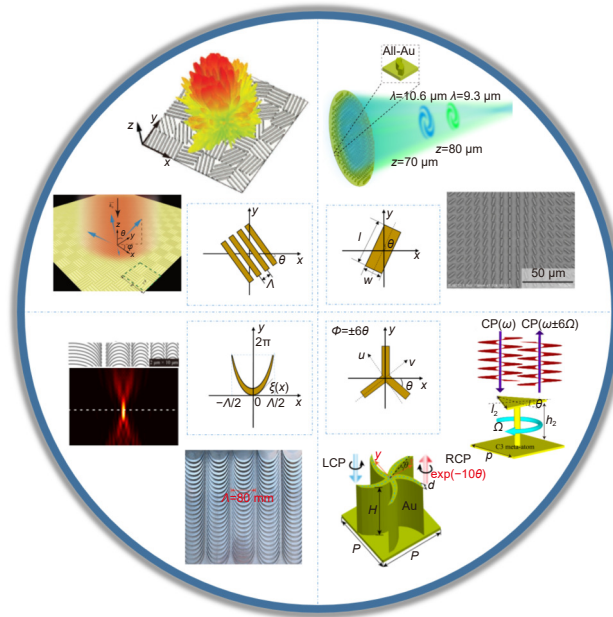
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Applications and progress of all-metal metasurfaces in phase manipulation of electromagnetic waves

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Schematic diagram of the typical geometric phase-type building blocks and all-metal metasurfaces

Overview: Classical optical devices use changes in the refractive index of material or surface shape to accumulate the optical path difference like lenses and prisms, thus converging, diverging, and deflecting the light beam. To overcome these limitations of the large size and heavy weight of classical optical devices, researchers have proposed a new structure known as metasurfaces, an array of artificial designs at subwavelength scales. Metasurfaces can change the amplitude and phase of electromagnetic waves at interfaces, which provides a means to realize novel optical phenomena and the planarization and lightweight of optical devices. As a result, a series of metasurface-based flat devices have been demonstrated in the past few decades, including beam deflectors, holographic displays, vortex beam generators, etc. However, the efficiency of the initially designed functional devices based on metasurfaces is too low and is greatly limited in practical applications. To improve efficiency, low-loss dielectric materials with high refractive indexes are used to design metasurfaces, and the working efficiency is significantly improved. Additionally, metal-insulator-metal hybrid reflective metasurfaces can remarkably enhance efficiency. A new reflective metasurface composed of all-metal structures has been proposed recently. All-metal metasurfaces exhibit higher energy efficiency and larger operating bandwidth in phase modulation than metal-insulator-metal structures. Besides, since metallic materials generally have excellent thermal and mechanical properties, such as high-temperature resistance, high strength, and good flexibility, all-metal metasurfaces have the potential for applications in highly complex environments such as high temperatures and high pressures. All-metal metasurfaces have been applied in various fields of holographic display, beam deflection, electromagnetic invisibility, etc. In this paper, we focus on the applications of all-metal metasurfaces in planar optical devices and electromagnetic stealth and provide an outlook on its future development direction.

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