



# 从超振荡透镜到超临界透镜: 超越衍射极限的光场调制

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**摘要:** 以超振荡透镜和超临界透镜为典型代表的平面超透镜是一种利用光场调控方式实现远场超衍射极限聚焦和成像的光学元件。通过精密调控各衍射结构单元之间的干涉效应, 可以在焦平面上局部区域内获得高于系统最高空间频率的电场振荡, 从而实现对衍射焦斑横向和轴向尺寸的可控调节。与传统的光学透镜相比, 平面超透镜具有聚焦能力强, 结构紧凑, 设计自由度大, 利于集成等优点。因其远场超衍射极限的光场调控能力, 受到衍射光学和纳米光子学领域人员的广泛关注和研究。本文介绍了平面超衍射极限透镜光场调控的原理和设计方法。对超振荡透镜和超临界透镜的研究现状及其在远场光学超分辨成像领域的应用进行了分析和讨论, 最后对该领域面临的问题及其拓展方向作了展望。

**关键词:** 超振荡透镜; 超临界透镜; 超分辨成像; 衍射光学

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## From super-oscillatory lens to super-critical lens: surpassing the diffraction limit via light field modulation

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**Abstract:** Super-oscillatory lens (SOL) and super-critical lens (SCL) are the typical representatives of planar meta-lens which could achieve sub-diffractive focusing and imaging in far field by means of light field modulation. Through precisely modulating the interference effect of each diffractive unit, the electromagnetic wave could be oscillated faster than its maximum frequency components in a certain region of the target plane, and then the focal spot size is controllable in lateral and longitudinal directions. Compared with the traditional optical lens, the planar metalens is much more attractive in the fields of diffractive optics and nanophotonics due to its distinct advantages of powerful focusing capabilities, compact configuration, higher design freedom and the integratable properties, etc. In this review, we briefly introduce the field modulation mechanism and design principle of planar metalens. The research advances of the super-oscillatory lens and super-critical lens, as well as their applications in far-field label-free super-resolution imaging, are discussed in detail. In addition, a perspective about the future outlook of planar metalens is summarized. Since the planar metalens has powerful capability in manipulating the light field, the rapid development in various applications would be gradually realized in the near future.

**Keywords:** super-oscillatory lens; super-critical lens; super-resolution imaging; diffractive optics

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## 1 引言

成像分辨率决定了人们认识世界的深度和广度。在众多成像技术中, 光学显微成像技术是最直观、最方便, 也是应用最广泛的成像方式。由于光的波动性的本质, 其成像分辨率受到衍射极限的限制。1873 年 Abbe 首次阐述了光学显微镜存在一个无法逾越的分辨率极限, 可以表示为  $0.5\lambda/NA$ , 其中  $\lambda$  为照明光的波长,  $NA$  为光学系统的数值孔径<sup>[1]</sup>。1896 年, Rayleigh 进一步指出非相干成像条件下物理两点分辨率的瑞利判据<sup>[2]</sup>, 即显微成像系统可分辨的两点最小距离等于光学系统聚焦艾里斑(Airy spot)的半径( $0.61\lambda/NA$ )<sup>[3]</sup>。对应于可见光波段, 成像分辨率的极限大约在 200 nm 左右。采用更短波长的紫外照明光和高数值孔径的浸没透镜系统, 虽然可以一定程度上提高光学系统的聚焦和成像能力, 但却为实际应用提出了特殊的要求和困难。随着科学技术的不断发展, 生物学、材料学、精密加工制备等各个领域对成像分辨率提出了越来越高的要求。如何突破光学仪器的分辨率极限, 实现纳米尺度的光学成像, 具有非常重要的科学和工程意义, 同时也是一个非常具有挑战性的任务。从阿贝衍射极限提出以来的 140 余年里, 科研人员和光学工程师们针对该问题进行了大量的研究探索, 并相继提出多种超分辨成像技术<sup>[4-12]</sup>, 主要包括基于消逝场操控的近场技术和基于传播场调控的远场技术两大类, 如图 1<sup>[4]</sup>。

目前已知的最早突破衍射极限的可行方案是 Edward Synge 于 1928 年提出的近场扫描光学显微镜

(NSOM)的概念<sup>[13]</sup>。但受技术水平的限制, 直到 1984 年才首次在实验中实现了光学领域近场扫描光学显微成像<sup>[14]</sup>。目前该技术是实验室中应用最广泛的光学超分辨成像技术之一, 其成像分辨率取决于扫描探针的孔径, 最高可以实现 10 nm~20 nm 的分辨能力<sup>[15]</sup>。2000 年, 英国帝国理工学院的 Pendry 提出, 利用具有负介电常数和负磁导率的材料构建的超透镜, 通过在近场区域同时收集调控传播场和消逝场分量, 理论上可以实现无物理极限的成像效果<sup>[16]</sup>。2005 年加州大学伯克利分校的 Zhang Xiang 等人利用具有负介电常数的银膜构建了 superlens 系统, 在 365 nm 光照下成功实现了 89 nm 分辨率的近场成像效果<sup>[17-21]</sup>。基于微球系统的光学显微技术是近年来兴起的又一个有代表性的超分辨成像技术<sup>[22-33]</sup>。以新加坡国立大学 Hong Minghui 教授和英国曼彻斯特大学 Li Lin 教授为代表的众多研究小组已经在该方向上作了大量的研究工作, 并在科研成果的产业转化方面作了大量的努力, 其中以新加坡的 Phoas Technology 和英国曼彻斯特的 Nanopsis 公司为典型代表。Wang Zengbo 等人将其超分辨成像原理归因于光子纳米喷射效应(photonic nanojet)<sup>[22, 34]</sup>。根据微球本身的物理性质, 实验环境以及样品本身的特征条件, 微球纳米显微技术可以实现最高<20 nm 的全光谱超分辨成像能力, 同时其工作距离可以扩展到几百纳米的尺度。基于表面等离子体(surface plasmon)消逝场的近场光刻成像技术近年来发展迅速<sup>[35-39]</sup>。传统光刻成像技术要实现 50 nm 以下分辨率时, 需采用深紫外的照明光源, 导致光学系统复杂, 现有材料和工艺难以兼容等诸多问题。2015 年, 中国科学院光电技

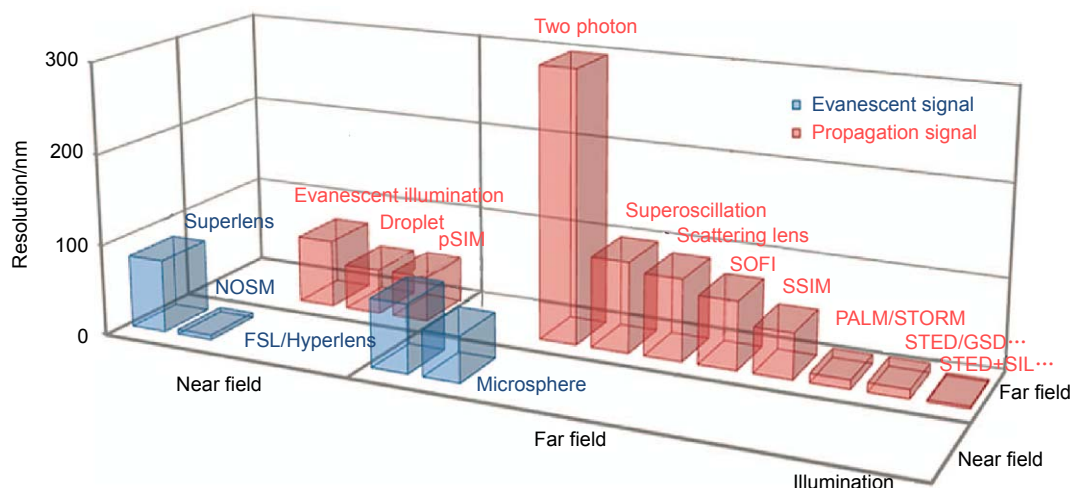


图 1 典型光学超分辨成像技术及其分辨率对比<sup>[4]</sup>。

Fig. 1 Comparison between typical optical super-resolution techniques and their corresponding imaging resolutions<sup>[4]</sup>.

术研究所的研究人员创造性地把表面等离子体技术引入到光学光刻领域,利用长波长的普通光刻光源实现了高陡直度、高深宽比的超衍射极限光刻成像能力,目前已经可以达到 22 nm 的成像分辨率<sup>[40]</sup>。

基于近场操控的显微技术虽然可以实现纳米尺度的光学超分辨成像,但由于其近场操作的本质要求,使得其应用范围受到一定的限制,且成像过程中对样品会有较大的影响。超分辨荧光显微成像技术是近年来发展最成功的光学纳米成像技术之一<sup>[8, 41-59]</sup>。该类技术以受激辐射损耗成像(stimulated emission depletion microscopy, STED),光激活局域显微成像(photo-activated localization microscopy, PALM),随机光学重建显微成像(stochastic optical reconstruction microscopy, STORM),光学涨落超分辨成像(super-resolution optical fluctuation imaging, SOFI),以及饱和结构光照明显微成像(saturated structured illumination microscopy, SSIM)等技术为典型代表。由于在超分辨荧光显微成像技术领域的重大贡献,2014年, Betzig, Hell 和 Moerner 三位科学家获得了诺贝尔化学奖。不同于 NSOM 等近场技术,该类成像技术可以实现远场的超衍射极限成像。利用荧光分子的选择性激活或淬灭,可以对经过荧光分子标定的生物样品实现 20 nm~50 nm 的超分辨成像,其成像过程完全不需要消逝场的参与,可以方便地与传统显微镜集成。但是该类技术的成像过程依赖于荧光分子的非线性响应,需要用荧光分子对待成像样品进行标定,使得其适用范围一般只局限于生物学和医学领域。

1952 年意大利物理学家 Toraldo di Francia 提出可以通过在光学系统中引入圆对称同心环带分布的二元振幅型或者相位型光瞳滤波器,对光场波前的相位和强度进行调制,来实现对聚焦艾里斑的压缩,从而提高光学系统横向和轴向聚焦能力<sup>[60]</sup>。但光瞳滤波器本质上并不会对光学系统的带限函数实现拓展,在聚焦平面上也不会出现大于系统最高空间频率的光场振荡,所以并不能实现严格意义上的超分辨聚焦和成像。此外,传统的光瞳滤波器只改变光瞳平面内光场的振幅或相位,其聚焦和成像功能一般还是依靠光学系统中的体材料折射透镜来实现,增加了系统的复杂度,不利于当前光学技术向集成化和轻量化发展的趋势<sup>[61-68]</sup>。作为平面衍射光学元件典型代表的菲涅耳波带片(FZP)具有尺寸紧凑、重量轻、加工方便等诸多优点。此外,菲涅耳波带片还具有与传统体材料折射透镜相

反的色散特性,两者组合形成折衍混合系统可以用来消色差。但与传统光学透镜类似,菲涅耳波带片的远场聚焦和成像无法突破衍射极限的限制。

探索研究完全基于光场调控的超衍射极限聚焦和成像技术,获得更加锐利的衍射聚焦光斑以及亚波长的无衍射光针,在超分辨成像、高精密激光加工、高密度光存储等各个领域都有重要的应用价值。本综述将围绕超衍射极限平面透镜的研究现状,主要对超振荡透镜和超临界透镜的研究进展进行总结,并结合本研究组的理解和认识对该研究领域未来发展趋势进行展望。

## 2 平面超衍射透镜及其常用设计方法

区别于传统的光瞳滤波器和菲涅耳波带片对光场的调制原理,2006 年英国布里斯托大学的 Berry 等人从理论上指出,利用特殊设计的光学微纳结构对传输光场的干涉现象精密调制,完全可以在远场实现超越衍射极限的光学聚焦光斑,并把该现象命名为光学超振荡<sup>[69,70]</sup>。光学超振荡的物理属性来源于多个空间频率较低的光场叠加,在相长干涉(constructive interference)或者相消干涉(destructive interference)的调制下,形成局域快速振荡光场的现象。该局域振荡频率可以远大于光场最高空间频率,并在局域空间形成最小特征尺寸小于光学衍射极限的聚焦光斑。该理论提出后,迅速引起国际上衍射光学领域研究人员的广泛关注<sup>[71-92]</sup>,其中以英国南安普顿大学、新加坡国立大学以及中科院光电技术研究所的研究小组最具代表性。

2014 年新加坡国立大学的 Huang Kun 等人在 Berry 理论的基础之上进一步细化并提出了超振荡判据( $0.38\lambda/NA$ )的概念,对聚焦光斑给出定量的理论界限,如图 2 所示<sup>[85]</sup>。光学聚焦光斑尺寸图被瑞利衍射极限(Rayleigh criterion,  $0.61\lambda/NA$ )和超振荡极限(super-oscillation criterion,  $0.38\lambda/NA$ )分成三部分。小于超振荡判据的蓝紫色区域会发生光学超振荡现象,理论上可以实现无限小的聚焦光斑,但其旁瓣的强度会随着主瓣尺寸的减小而呈指数的增强,同时入射光的能量利用效率也急剧下降,对实际应用有很大的影响。在大于瑞利衍射极限的橙色区域,虽然旁瓣的影响可以忽略不计,但却无法实现超衍射极限的调制效果。只有在介于超振荡判据和瑞利极限之间的天蓝色区



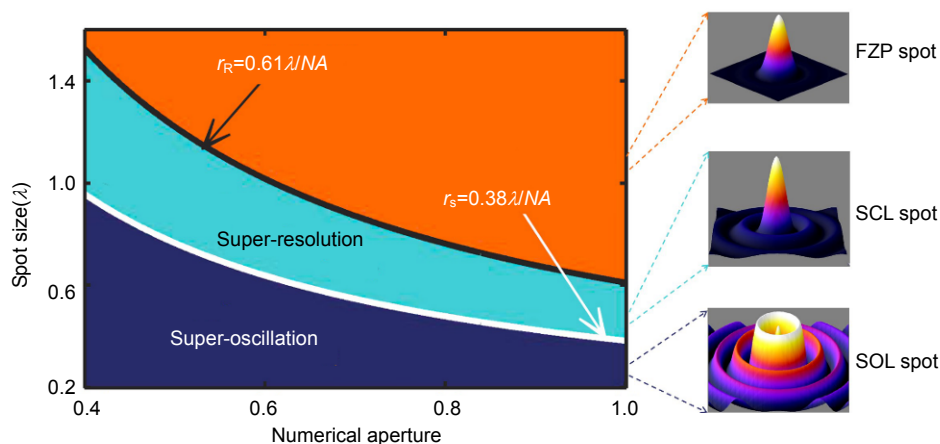


图 2 平面衍射透镜聚焦光斑尺寸被瑞利判据( $0.61\lambda/NA$ )和超振荡判据( $0.38\lambda/NA$ )分成亚分辨、超分辨和超振荡三个区域, 分别对应图中的橙色、天蓝色和蓝紫色三个部分; 右侧插图分别为各个区域所对应的典型光斑强度分布示意图<sup>[85]</sup>。

Fig. 2 The focal spot size of planar diffractive lens could be divided into three parts by Rayleigh (black) and super-oscillation (white) criteria, including sub-resolved (orange), super-resolution (cyan) and super-oscillation (dark blue). The insets in the right side are the field distributions of the focal spots for three typical diffractive lenses<sup>[85]</sup>.

域, 在实现超衍射极限的聚焦的同时, 可以有效抑制旁瓣的影响, 其焦深也可以根据需要进行灵活设计, 为实际应用提供了极大的便利。因此, 他们把焦斑尺寸趋近于超振荡判据( $0.38\lambda/NA$ ), 同时具有大于传统透镜的焦深( $2\lambda/NA^2$ )而能够形成光针效应, 这样的平面衍射透镜定义为超临界透镜(supercritical lens, SCL)<sup>[87, 90, 91]</sup>。

传统的光学透镜聚焦是利用光在折射率不同的两种媒介界面处发生的折射现象来实现的, 通过调整透镜的曲率, 可以实现对传播场聚焦效应的调控。而衍射光学元件的工作本质是通过调制各衍射次波源在设计焦斑平面的光场强度和相位分布, 来实现符合设计的光学效应。超振荡透镜和超临界透镜本质上也是一种经过优化设计的衍射光学元件, 其聚焦特性完全可以通过利用各种衍射理论和优化算法, 对各同心环带的位置和宽度的参数设计优化来实现。衍射理论主要包括标量衍射理论和矢量衍射理论。对于低数值孔径的平面透镜, 可以采用标量衍射理论来准确计算其衍射场分布。然而, 标量衍射理论忽略了入射光的偏振特性, 标量衍射积分所描述的聚焦光场也没有体现出电场的偏振特性。而实际情形入射光的偏振态可能对聚焦光场的结构和偏振特性产生显著影响, 尤其对于高数值孔径的平面透镜, 标量理论所得到的结果与实际偏差较大而不再适用<sup>[93-99]</sup>。

为了精确描述聚焦光场的振幅、相位和偏振态等特征, 需要借助于矢量衍射理论来充分考虑不同偏振

态入射光场的矢量特性, 矢量瑞利-索莫菲衍射理论和矢量德拜-沃尔夫衍射积分理论是最常用的理论研究方法<sup>[85-87, 100-102]</sup>。

结构设计优化过程常用的方法主要包括优化算法(optimization algorithms)和优化免疫算法(optimization-free algorithms)两类。前者主要以粒子群优化算法(particle swarm optimization, PSO)和基因遗传算法(genetic algorithms, GA)为代表, 其中粒子群优化算法应用最为广泛<sup>[80, 84, 103]</sup>。粒子群优化算法属于进化算法的一种, 和模拟退火算法类似, 从随机解出发, 通过迭代寻找最优解。通过与预先设定的目标函数进行对比来评价解的品质。这种算法具有实现容易、精度高、收敛快的优点, 在衍射光学元件的设计中被研究者们广泛采用。但该类优化算法共同的缺陷是无法揭示结构内在的物理属性, 对于每个结构单元在聚焦平面上所起到的作用和做出的贡献无法清晰地描述, 限制了对平面超透镜的设计的灵活性。2014年新加坡国立大学的 Huang Kun 等人提出一种优化免疫(optimization-free)设计方法, 预先设定聚焦焦斑的位置和强度分布特性, 通过数值求解包含每一个环带位置和宽度信息的非线性方程的方式来得到平面衍射透镜的设计参数, 把超振荡优化设计过程转化成求解符合目标值的非线性解的逆过程, 如图 3 所示<sup>[85]</sup>。该方法比常用的粒子群优化等算法能极大地提高平面衍射透镜的设计速度, 同时由于其物理思路清晰, 每个结构单元的实际贡献明确, 适合用来设计各种具有特殊

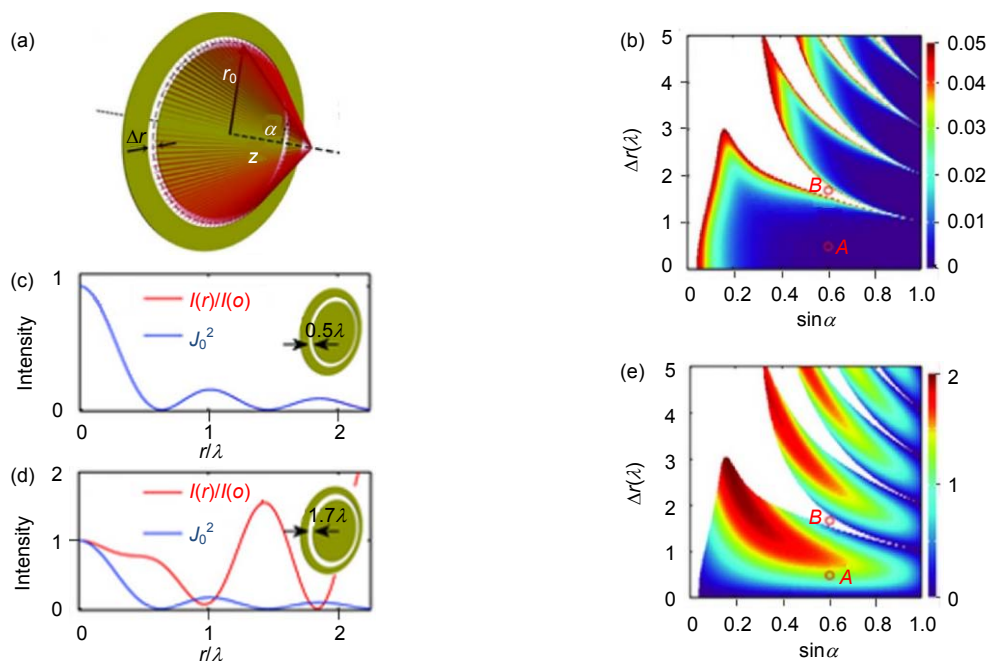


图3 不同宽度和数值孔径的单个环带在固定焦平面上( $z=20\lambda$ )的衍射效应. (a) 半径  $r_0$ 、宽度  $\Delta r$  的单环衍射示意图. (b) 单环带在焦平面上的聚焦特性和零阶贝塞尔函数的均方根差与单环宽度和半径的关系. (c),(d) 对应于图(b)中的 A 和 B 两点的单环衍射一维强度分布与零阶贝塞尔函数的对比. (e) 强度调制系数与环带宽度和数值孔径的关系<sup>[85]</sup>.

Fig. 3 The diffraction effect at a certain plane( $z=20\lambda$ ) for a single belt with different widths and numerical apertures. (a) Illustration of the diffraction effect of a single belt with its radius  $r_0$  and width  $\Delta r$ . (b) Root-mean-square error (RMSE) between the diffracting intensity at the target plane and its corresponding zero-order Bessel function for different widths and radius of a single belt. (c), (d) The line profiles of the diffraction intensities at the positions A and B in Fig. 3(b), with its corresponding zero-order Bessel function with the same numerical apertures. (e) The dependence of the amplitude modulation coefficient on the width and radius of the single belt<sup>[85]</sup>.

衍射光学效应的结构器件。

### 3 超振荡透镜

在 Berry 的超振荡理论的基础之上, 2007 年, 英国南安普顿大学的 Zheludev 小组利用金属衍射屏上准周期排列的纳米孔阵, 在实验中成功观测到了半高全宽  $0.39\lambda$  的远场亚波长聚焦现象, 如图 4 所示<sup>[71, 73]</sup>。同时当观察面沿  $Z$  方向移动时, 在衍射区不同位置上都可以观察到超衍射极限的聚焦现象<sup>[78]</sup>。他们把该超衍射极限聚焦过程归因于准周期排列的纳米孔阵对激发光的超振荡调制效应<sup>[82]</sup>。由于该过程发生在远场区域, 无须消逝场的参与, 可以使用传统的光学显微收集和成像系统来观测表征。2009 年, 该团队进一步提出可以利用多个长椭球波函数(prolate spheroidal wave functions)构造出局部视场区域内任意大小的超衍射聚焦斑, 如图 5 所示。他们采用 26 个长椭球函数, 理论上在  $20\lambda$  的工作距离上构造了聚焦尺寸  $<0.21\lambda$  的超衍射聚焦斑光场分布<sup>[79]</sup>。但由于准周期结构和满足长椭球

函数的掩模结构的加工异常复杂, 制约了其实际应用。

2012 年该研究小组利用超振荡原理, 通过算法优化的方式成功地设计并制备出了二元振幅圆对称同心环带结构的平面超透镜, 并命名为超振荡透镜(superoscillatory lens)<sup>[74, 80]</sup>。在该工作中, 他们利用  $640\text{ nm}$  波长的线偏振相干光作为激发光源, 在油浸介质中  $10\text{ }\mu\text{m}$  的工作距离处得到了  $185\text{ nm}$  ( $0.29\lambda$ ) 的超衍射极限聚焦斑。通过把该超振荡透镜与共焦成像系统相结合, 利用其远场超衍射极限的聚焦能力, 在实验上实现了  $105\text{ nm}$  的远场成像分辨率(图 6)。超振荡透镜虽然采用与传统光瞳滤波器类似的同心环带结构, 但调制特性显著不同。通过精密调制各环带衍射光场之间超振荡现象所带来的相消干涉效应, 在焦平面上一定区域内, 可以实现带限函数的振荡速度远大于系统最高傅里叶频谱分量的现象, 从而实现无物理极限的聚焦能力。但受限于超振荡原理的本质, 其超衍射极限聚焦斑的周围无法避免会产生强度很高的衍射旁瓣光场分布, 如图 6(d)所示。当主瓣尺寸逐渐减小时, 其

旁瓣会快速增强, 对后期的成像应用过程带来显著的影响。

此后, 该研究组又分别提出了对线偏振光和圆偏

振光响应的光针形超振荡透镜。2016 年, 他们利用一维超振荡透镜实现了单光子的量子超振荡效应。2017 年, 利用衍射效应不同级次之间的叠加进一步实现了

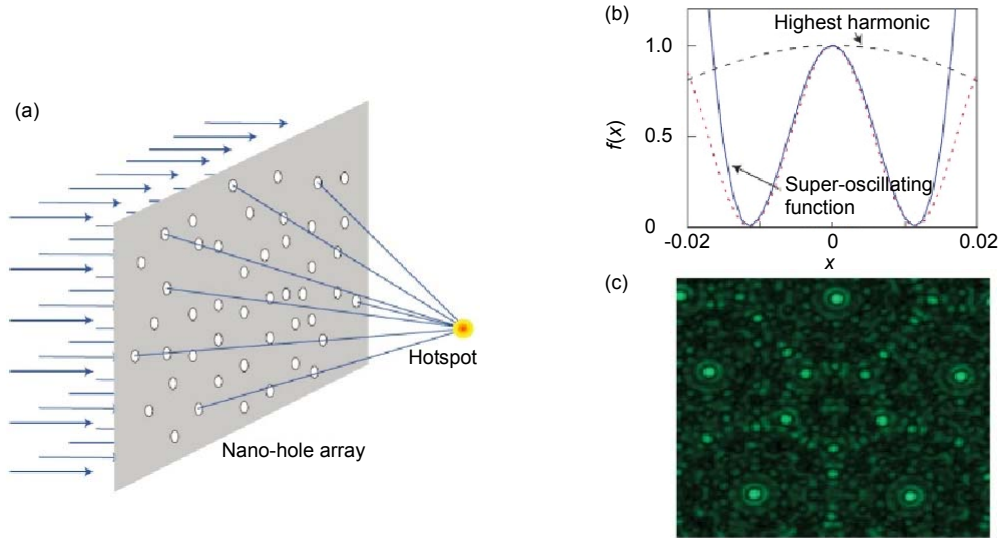


图 4 (a) 纳米孔阵的远场超衍射极限聚焦效应示意图. (b) 超振荡效应产生大于频谱最高傅里叶分量的电场振荡. (c) 由准周期纳米孔阵衍射产生的亚波长超振荡焦斑实验图<sup>[82]</sup>.

Fig. 4 (a) Generation of a sub-diffractive hotspot by nanoholes array in an opaque screen. (b) The comparison between the super-oscillating functions with its highest harmonic Fourier component. (c) The experimental results of the subwavelength super-oscillating focal spot by a quasi-periodical holes array<sup>[82]</sup>.

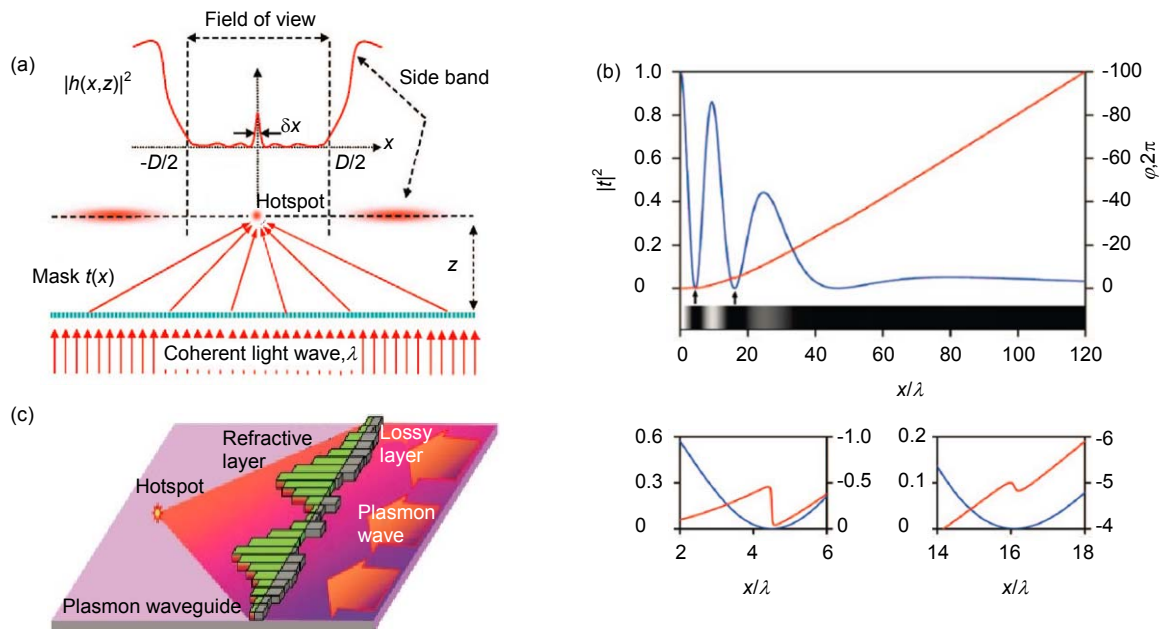


图 5 (a) 超振荡光场调制示意图. (b) 产生亚波长焦斑的掩模的强度和相位分布曲线. (c) 等离子体超振荡透镜的可行结构<sup>[79]</sup>.

Fig. 5 (a) Schematic of the optical super-oscillation effect. (b) The intensity and phase profile of a transmission mask which could generate a subwavelength hotspot. (c) A possible configuration of a plasmonic focusing device for creating super-oscillation hotspot<sup>[79]</sup>.



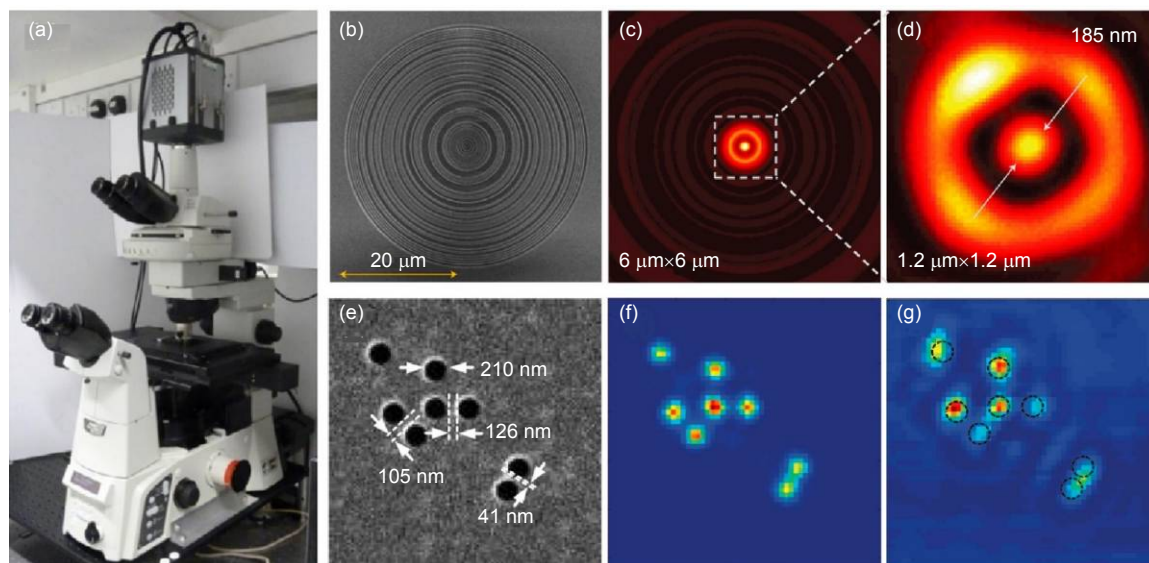


图 6 (a) 超振荡显微成像系统照片. (b) 超振荡透镜 SEM 图像. (c) 工作波长在 640 nm 的超振荡透镜在 10.3  $\mu\text{m}$  工作距离上的聚焦能量分布模拟结果. (d) 实验测得到半高全宽为 185 nm 的超衍射极限焦斑. (e) 用于测试成像能力的孔阵样品 SEM 图. (f) 利用超振荡透镜显微成像系统对孔阵结构成像效果模拟图. (g) 超振荡透镜显微系统成像实验结果<sup>[74, 80]</sup>.

Fig. 6 (a) Photograph of the super-oscillatory microscope. (b) SEM image of the fabricated SOL. (c) The simulated energy distribution for the 640 nm wavelength SOL at the distance of 10.3  $\mu\text{m}$  away from the lens plane. (d) Experimental focal spot with a FWHM of 185 nm. (e) SEM image of a hole array sample. (f) Simulated imaging result of the hole array sample by the SOL microscopy. (g) Experimental imaging result by the SOL microscopy<sup>[74, 80]</sup>.

可见光和近红外的消色差超振荡透镜<sup>[75-77, 81-84]</sup>。

## 4 超临界透镜

2015 年,新加坡国立大学的研究小组通过构建二元振幅型平面超临界透镜,实现了对矢量偏振光束的超衍射极限调制。研究小组加工制备了工作在 633 nm 波长的平面超临界透镜,在拓扑荷为 1 的涡旋位相叠加的角向偏振光 (azimuthally polarized beam with vortical phase, APV beam) 激发下,在空气中得到了横向尺寸约 265 nm ( $0.42\lambda$ ) 的超衍射极限焦斑,工作距离长达  $240\lambda$ ,比前述超振荡透镜的焦距提高了近一个数量级<sup>[91]</sup>。

从图 7(a)~7(c)中可以看到,在其焦平面上的场分布中,主焦斑占支配地位。同时其焦斑可以沿传播方向约  $12\lambda$  的范围内保持  $0.42\lambda\sim 0.49\lambda$  的横向尺寸,形成亚波长光针的聚焦效果,如图 7(d)~7(f)所示。亚波长光针的聚焦特性为超临界透镜在激光高精加工和高密度光存储等方面的应用提供了极大的便利。同时,他们通过测量焦斑图样的斯托克斯参数 (Stokes parameters) 分析了焦斑区域的偏振特性,从实验上验证了聚焦的 APV 光束的偏振特性。由电磁波理论可

知,电场的纵向分量在两种介质的界面处是不连续的,尤其是光从低折射率的介质进入到高折射率的介质时,其纵向场透过率很低。聚焦角向偏振光束的独特之处在于其超衍射极限的聚焦焦斑主要以横向电场分量为主,几乎不存在纵向分量。使得其聚焦光斑在传输过程中不会因为界面折射率的变化而产生明显的变化,非常有利于在光学高密度数据存储以及基于固体浸没透镜的光学成像系统中的应用<sup>[66]</sup>。

亚波长的光学空洞 (optical hollow) 在荧光显微成像,光学捕获与微操控以及纳米尺度曝光等领域有重要的应用价值,角向偏振光是用来产生光学空洞的较好方式之一。国际上已报道了多种通过聚焦角向偏振光产生光学空洞的方法,但空洞的尺度一般受限于衍射极限。新加坡国立大学的研究组利用工作在 633 nm 波长的超临界平面透镜聚焦角向偏振光,在远场成功得到了亚波长的光学空洞<sup>[91]</sup>。工作距离与生成超衍射极限焦斑时基本一致,其数值孔径可达 0.95 以上,光学空洞的半高全宽约为  $0.31\lambda$ ,如图 8(a)~8(c)所示。同时,他们在实验中分析了光学空洞的偏振特性,由图 8(d)可以看出,角向偏振光经平面超临界透镜聚焦所形成的光学空洞其偏振态仍然为角向偏振,与其他研究者在理论上的预测相符合<sup>[104]</sup>。

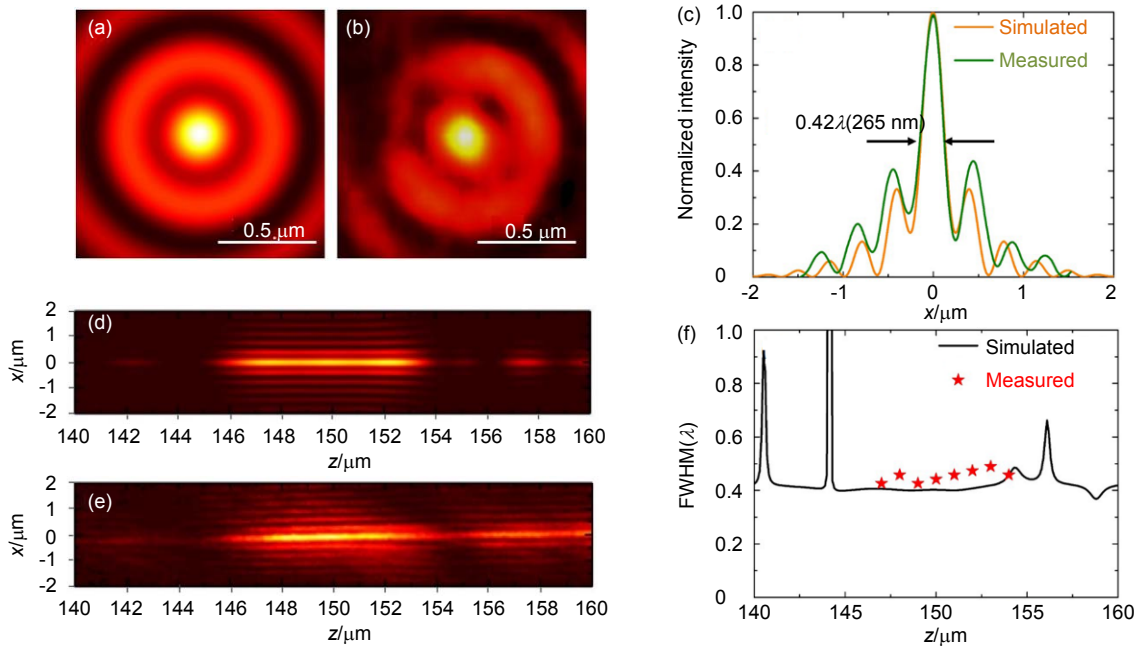


图 7 工作波长在 633 nm 的超临界透镜对涡旋相位叠加的角向偏振光的聚焦效应. (a) 在 150 μm 工作距离上的聚焦能力模拟图. (b) 实验记录的焦斑强度分布. (c) 模拟和实验结果的一维强度对比图. (d) 聚焦光针的模拟结果. (e) 光针强度分布的实验结果. (f) 在传播距离为 140 μm~160 μm 的区域内的焦斑半高全宽变化趋势的理论和实验对比<sup>[91]</sup>.

Fig. 7 Focusing effect of the 633 nm super-critical lens induced by the azimuthally polarized beam with vortice phase. (a) Simulated energy distribution at the focal plane of  $z=150 \mu\text{m}$ . (b) Experimental recorded focal spot pattern. (c) Line profile of the intensity distribution for the simulated and measured focal spot. (d), (e) Simulated and experimental recorded optical needle formed in the range from  $z=140 \mu\text{m}$ ~ $160 \mu\text{m}$ . (f) FWHM of the optical needle along the propagation direction<sup>[91]</sup>.

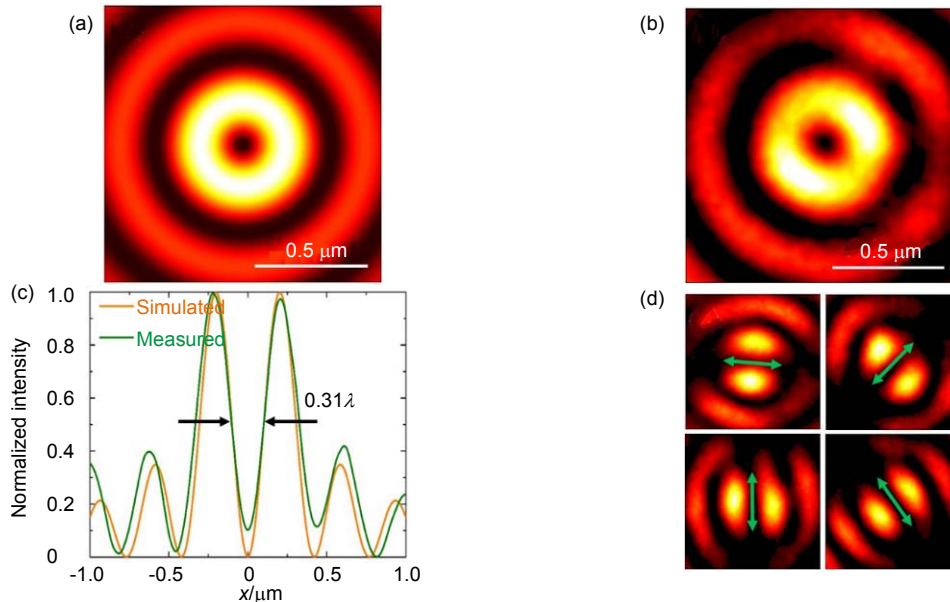


图 8 (a),(b) 平面超临界透镜在角向偏振光激发下远场产生光学空洞的理论和实验结果. (c) 光学空洞模拟和实验结果的一维强度对比图. (d) 光学空洞的偏振特性表征<sup>[91]</sup>.

Fig. 8 (a), (b) The simulated and measured optical hollows created by the 633 nm SCL induced by azimuthally polarized beam. (c) Line profile of the intensity across the focal spot for the simulated and measured results. (d) Characterization of the polarized property of the optical hollow<sup>[91]</sup>.



光学远场超分辨成像是平面超临界透镜的重要应用方向。在利用 633 nm 的超临界透镜实现了超衍射极限聚焦的基础之上, 2016 年新加坡国立大学的研究小组进一步把工作波长推向短波长区域, 利用 405 nm 圆偏振入射光激发, 在远场得到了半高全宽为 165 nm 的低旁瓣超衍射极限聚焦焦斑, 同时该焦斑可沿着光轴方向稳定保持亚波长特性达  $5\ \mu\text{m}$ , 形成光针的聚焦效

果, 如图 9 所示。结合共焦成像原理, 搭建了基于 405 nm 振幅型平面超临界透镜的远场超分辨显微成像系统。通过样品扫描的方式, 在空气中获得纯光学的 65 nm 分辨率的远场超分辨成像效果<sup>[87]</sup>。工作距离达到  $135\lambda$ , 基本与传统显微镜相近。同时, 由于超临界透镜低旁瓣的优势, 使得成像结果受背景光的影响很小, 具有很高的信噪比, 如图 10 所示。

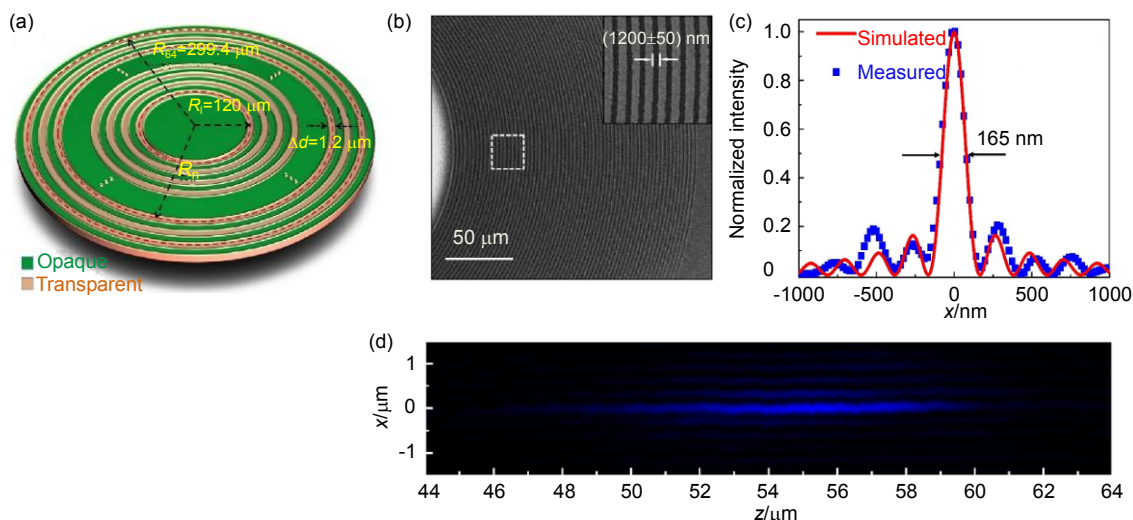


图 9 (a) 405 nm 超临界透镜的结构示意图. (b) 加工得到的超临界透镜 SEM 图. (c) 超衍射极限聚焦特性的理论和实验对比. (d) 实验测得的亚波长聚焦光针<sup>[87]</sup>.

Fig. 9 (a) Schematic configuration of the 405 nm supercritical lens. (b) SEM image of the fabricated 405 nm SCL. Inset is the zoom-in view of the dashed box region. (c) Line profile of the sub-diffractive focal spot under illumination of 405 nm circular polarized beam. (d) Experimental recorded intensity distribution of the sub-wavelength optical needle<sup>[87]</sup>.

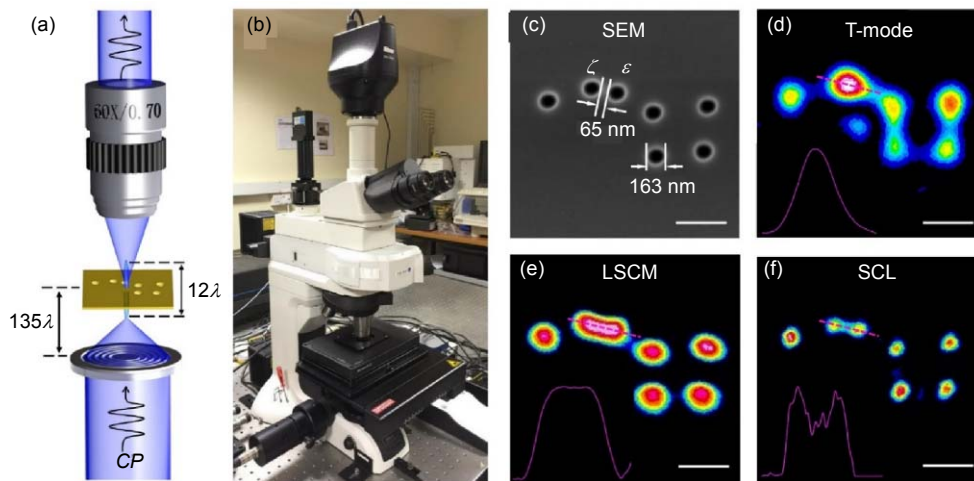


图 10 (a) 超临界透镜成像原理示意图. (b) 超临界透镜显微成像系统实物照片. (c) 纳米尺度北斗七星孔阵待成像样品 SEM 图. (d) 常规透射式显微镜成像结果. (e) 激光共聚焦显微镜的成像结果. (f) 超临界透镜显微成像系统对样品的成像结果<sup>[87]</sup>.

Fig. 10 (a) Schematic of the SCL microscopy. (b) The photograph of the SCL microscope system. (c) SEM of the nanoscale big dipper as the imaging specimen. (d) Imaging result by the normal transmission-mode microscopy. (e) Imaging results by the laser scanning confocal microscopy. (f) Imaging result by the 405 nm SCL microscopy<sup>[87]</sup>.

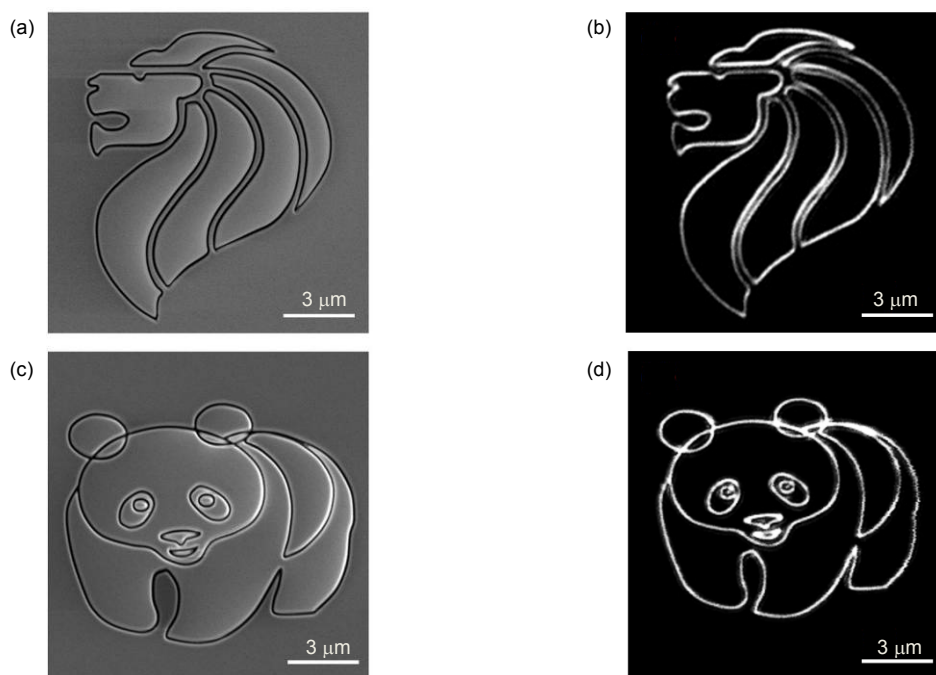


图 11 超临界显微成像系统对大尺寸非周期结构的成像能力, (a),(c) 样品 SEM 图样. (b),(d) 利用超临界显微成像系统扫描所成的超分辨图像<sup>[87]</sup>.

Fig. 11 Large-scale non-periodic patterns imaged by the supercritical lens microscopy. (a),(c) The SEM images of fabricated samples with a size of  $13.5 \mu\text{m} \times 13.5 \mu\text{m}$ . (b), (d) The imaging results by the supercritical lens microscope<sup>[87]</sup>.

作为比较, 他们同时给出了同等条件下普通透射式显微镜和激光共聚焦显微系统的成像图 (图 10(d), 10(e)), 结果显示基于超临界透镜的成像系统的成像能力与现有显微镜相比具有明显优势<sup>[87]</sup>.

对大尺度样品成像一直都是各种光学超分辨技术所面临的障碍之一, 大尺寸样品所带来的像差和样品离焦等因素的影响会对成像效果造成显著的影响。而基于超临界透镜的显微成像系统为解决这个问题提供了一种途径。由于超临界透镜光针聚焦特性所带来的超长成像焦深, 使得该成像技术对样品的水平倾斜具有很大的容忍度。同时基于样品扫描式的共焦成像方式, 也避免了传统光束扫描成像所必然存在的离轴像差的影响。新加坡国立大学的研究小组利用超临界透镜显微成像技术成功地实现了对复杂结构非周期大尺寸样品的( $13.5 \mu\text{m} \times 13.5 \mu\text{m}$ )超分辨成像, 如图 11 所示。此外, 大焦深特性还为超临界透镜显微成像技术带来一个独特的能力, 即可以通过一次扫描实现对三维立体结构的水平投影成像<sup>[87]</sup>。

与振幅型的设计相比, 位相型的平面超透镜可以得到明显更高的能量利用效率。新加坡科技局数据存储研究所, 新加坡国立大学, 以及南安普顿大学等多

个研究小组在利用位相型平面透镜实现超衍射极限的聚焦方面做了大量的工作<sup>[68, 81, 85]</sup>。2016 年, 中国科学院光电技术研究所和重庆大学的研究团队利用电子束曝光结合标准的镀膜刻蚀加工工艺在  $\text{Si}_3\text{N}_4$  薄膜上制备出了二元相位型平面超透镜, 分别对径向偏振光和角向偏振光进行调制时, 同样在远场得到了超衍射极限的聚焦焦斑和光学空洞, 如图 12 所示<sup>[105, 106]</sup>。

## 5 对比与讨论

从前文对超振荡透镜和超临界透镜的介绍中可知, 应用平面超透镜对光场调控的影响是多方面的。

首先, 平面超透镜对光场调控的主要效果体现在对聚焦艾里斑主瓣的压缩。一般以调制后焦斑的宽度(零点位置)与艾里斑主瓣的宽度之比来表征, 比例越大表明其对焦斑的压缩能力越强, 其分辨率提升的程度也就越高。由于平面超透镜对艾里斑的光强分布的调制是在三维空间上的, 艾里斑主瓣会在径向和轴向两个方向上受到压缩或者拉伸。所以, 根据平面超透镜的不同设计又可以分为横向超分辨和三维超分辨。

其次, 应用平面超透镜来压缩焦斑尺寸的过程本质上是一种调制光场在焦平面上能量分布的过程。当

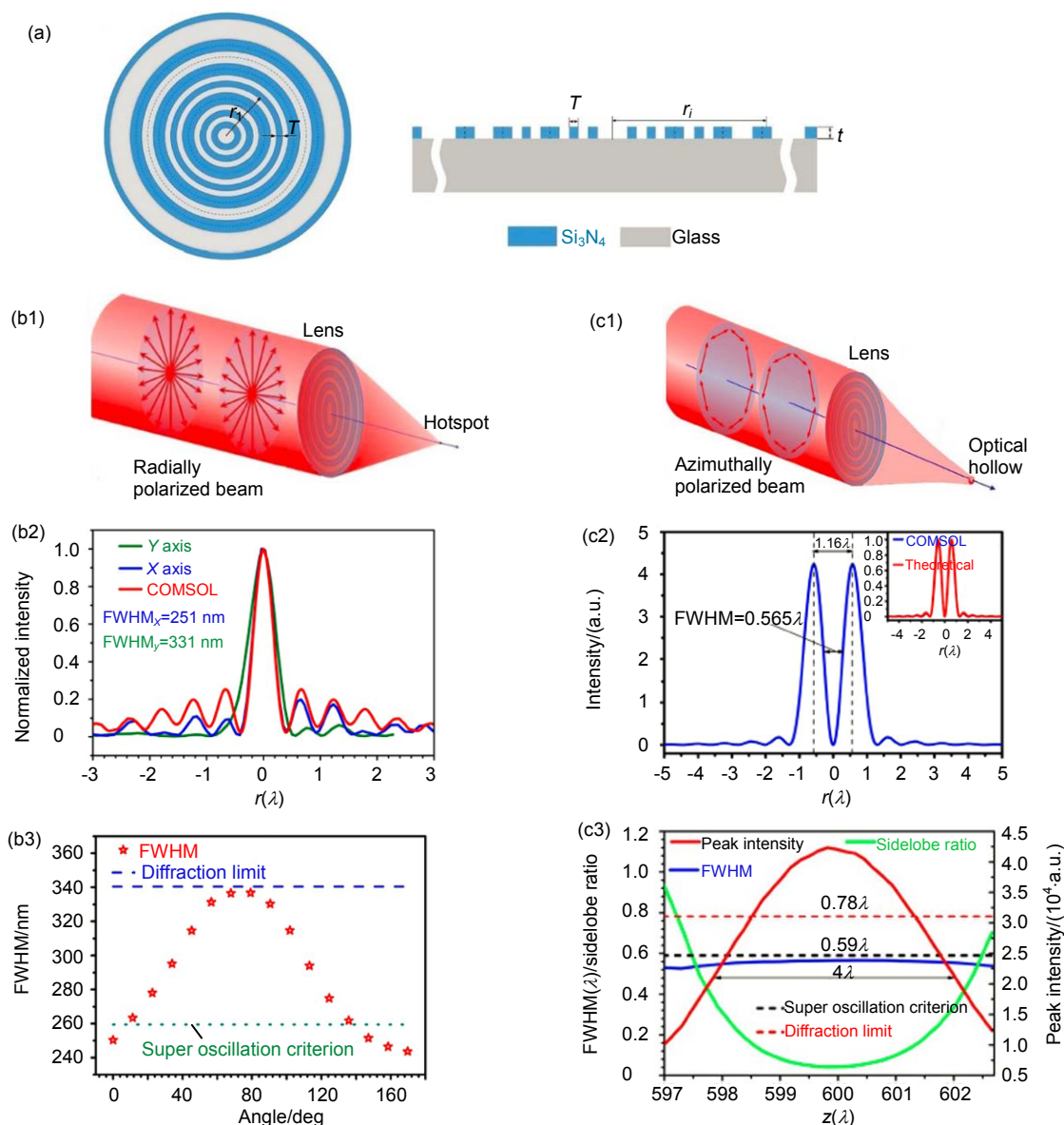


图 12 (a) 二元相位型平面超透镜结构示意图. (b1)~(b3) 在径向偏振光激发下产生超衍射极限焦斑. (c1)~(c3) 在角向偏振光激发下产生亚波长光学空洞<sup>[105,106]</sup>.

Fig. 12 (a) Schematic of the binary phase planar metalens. (b1)~(b3) Sub-diffractive focusing by the binary phase planar metalens under illumination of radial polarized beam. (c1)~(c3) Shaping subwavelength optical hollow with the binary phase planar metalens induced by azimuthally polarized beam<sup>[105,106]</sup>.

聚焦焦斑的主瓣受到压缩时, 光场能量会被转移到旁瓣当中, 因此旁瓣的强度会有所提升。而旁瓣强度的提升主要体现在第一旁瓣的改变上, 其它旁瓣强度的改变较小。菲涅耳波带片(FZP)等传统透镜聚焦所得的艾里斑其第一旁瓣强度与主焦斑强度之比仅为 1.75% 左右, 超临界透镜的强度对比也可以控制在 <20% 的程度。而超振荡透镜为追求尽量小的主瓣尺寸, 其旁瓣强度会显著增强, 甚至可以远大于主瓣的强度。旁瓣强度占比越大, 对其后在成像等应用中所带来的影响也越大。控制旁瓣强度在较低的范围内对于实际应用

具有重要的意义。共焦显微成像系统的有效点扩散函数是照明系统和探测系统各自点扩散函数的卷积, 通过光瞳滤波技术对照明系统或者探测系统的点扩散函数进行有效调制, 能在一定程度上解决旁瓣抑制的问题, 从而利用主焦斑实现超分辨的显微成像, 这也是超振荡显微技术和超临界显微系统都采用共焦扫描成像原理的主要原因。此外, 也可采用在主焦斑和第一旁瓣之间叠加多个零强度点的方式来扩大视场区域, 对于减小成像过程中的串扰作用也有积极意义<sup>[85, 92]</sup>。

同时, 主焦斑的能量强度在实际应用中也非常重



要。在利用平面超透镜压缩主焦斑的同时, 由于能量在焦平面上的再分配效应, 主瓣的一部分能量转移到了旁瓣中去, 使得主瓣的能量降低, 在实际应用中的信噪比将受到一定程度的降低。在保证超分辨效果的前提下, 尽可能大地提高能量利用效率对平面超透镜的实际应用非常必要。焦斑大小、旁瓣强度以及能量利用效率三个方面相互影响, 相互制约。在超分辨平面透镜的设计和应用中, 应根据实际需要做好这三方面的性能平衡, 这样才能最大限度地发挥平面超透镜的效用。

就目前所报道的超振荡透镜和超临界透镜比较而言, 超临界透镜的所有透光环带具有固定的宽度, 最小特征尺寸为  $1.2\ \mu\text{m}$ , 整个设计中不存在亚波长的特征尺寸, 使得透镜的加工完全不必像超振荡透镜一样需要用到聚焦离子束刻蚀或电子束曝光等复杂技术。微米级别的特征尺寸使得该透镜可以采用成熟的激光直写光刻工艺高效低成本加工, 为把平面超衍射极限透镜推向实际应用提供了切实的可行性。同时, 用微米量级特征尺寸的透镜实现了纳米量级的成像效果, 打破了成像领域所一直认为的“纳米尺寸的成像所使用的透镜一定具有纳米尺度特征尺寸”的传统认知。图 13 为菲涅耳波带片(FZP)、超振荡透镜(SOL)、超临界透镜(SCL)等三种典型的平面透镜性能对比图。该图从聚焦能力、旁瓣影响、焦深、焦距以及加工的容易程度五个方面进行了定性的比较。在聚焦能力方面, SOL 具有一定的优势, 但是与 FZP 相比其代价是损失

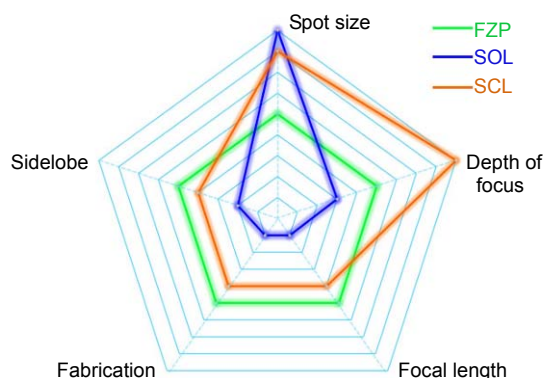


图 13 三种典型的平面衍射透镜性能对比图。其中 FZP, SOL 和 SCL 分别指菲涅耳波带片, 超振荡透镜和超临界透镜。

Fig. 13 Quality indices of three types of planar metalens. FZP, SOL and SCL refer to the fresnel zone plate, superoscillatory lens and supercritical lens, respectively.

了其他几个方面的性能, 尤其是高旁瓣的焦斑模式对超振荡透镜的实际应用带来了极大的影响。而超临界透镜虽然在焦斑尺寸方面比超振荡透镜做出了一定的妥协, 但却在其他几个方面得到了极大的释放, 为把平面超透镜推向实际应用提供了便利。

## 6 总结和展望

以超振荡透镜和超临界透镜为代表的平面超透镜技术是当前衍射光学和纳米光子学等领域研究的热点之一。本文简要概述了平面超衍射极限透镜的原理和基本设计思想, 对超振荡透镜和超临界透镜的主要研究进展及其在远场超分辨成像能力进行了介绍和总结, 并对其性能特性进行了对比和讨论。基于超振荡透镜和超临界透镜的超分辨成像是一种纯光学的远场成像技术, 不需要消逝场的参与, 也无需借助材料的非线性荧光响应, 具有广泛的应用前景。

纵观其发展历程, 平面超透镜的研究一直都是向着更有利于实际应用的角度来推进的。展望未来, 拓展平面超透镜在精密光学加工, 高密度光学存储, 光学微操纵以及半导体检测等领域的应用必将成为平面超透镜的发展方向。为此, 我们认为该研究方向仍然需要在以下几个方面进行深入探索: 首先在能量利用效率方面, 目前平面超透镜主要是基于二元强度或者相位构型, 其能量利用效率较低。通过与超构表面等最新的科学概念相结合<sup>[107-116]</sup>, 实现高效的超衍射极限的光场调控是其发展方向之一。其次在消色散和像差方面<sup>[76, 111, 117]</sup>, 已报道的平面超透镜的研究主要集中在对单色光在光轴上的超衍射极限聚焦。研究和探索对多色光的调制特性, 以及离轴响应特性, 对其实际应用具有重要意义。最后在可调节和可重构方面<sup>[81]</sup>, 随着理论研究的深入和微纳加工工艺的进步, 探索平面超透镜的多用途特性, 实现其在焦距, 工作波长以及光场调控特性的可调节, 将为推进平面超透镜在多领域的应用以及全光集成系统的实现提供重要支撑和保障。

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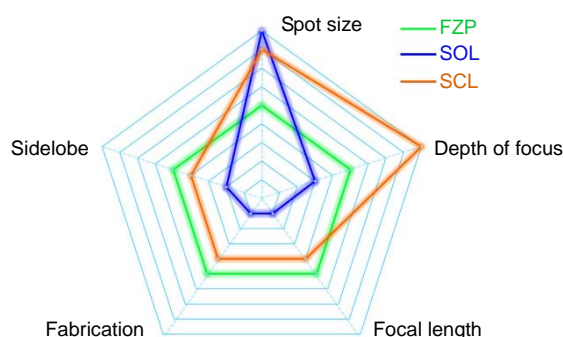
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# From super-oscillatory lens to super-critical lens: surpassing the diffraction limit via light field modulation

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Win or loss: comparison between three typical diffractive lenses.

**Abstract:** Improving the imaging resolution has always been one of the most important topics since the invention of optical microscope. Due to the fundamental laws of wave optics, the focusing and imaging resolution of traditional refraction and diffraction lenses are subject to the Rayleigh Criterion ( $0.61\lambda/NA$ ), and the spatial resolution of optical microscopy is restricted to  $\sim 200$  nm at visible light. Tremendous efforts have been made to fight against the diffraction limit in the past decades, and several novel approaches have been invented which could be categorized as near-field and far-field modes. For the near-field techniques, such as NSOM, superlens, hyperlens, microsphere lens, they always suffer from the challenges of near-field operation and small field of view, which make them not meet some requirements of practical applications. Although very high imaging resolution in far-field could be achieved by the fluorescence-based approaches, all these techniques have a common feature that is quite limited to biological domain because of the requirement to put dyes and fluorescence into objects. Therefore, the label-free technique for super-resolution imaging in far field is very important for general applications. Recent advance in this field is the development of planar metalens which could achieve sub-diffractive focusing and imaging in far field by means of light field modulation. Super-oscillatory lens (SOL) and super-critical lens (SCL) are the typical representatives of planar metalens. Through precisely modulating the interference effect of each diffractive unit, the focal spot size in a certain region of the target plane is controllable in lateral and longitudinal directions. Combined with the confocal technique, the label-free superresolution imaging could be realized in far field with purely non-invasive manners. Compared with the traditional optical lens, the planar metalens is much more attractive due to its distinct advantages of powerful focusing capabilities, compact configuration, higher design freedom and the integratable properties, etc. In this review, we briefly introduce the field modulation mechanism and design principle of the planar metalens. The research progress of the super-oscillatory lens and super-critical lens, as well as their applications in far-field label-free super-resolution imaging, is presented in detail. The advantages and limitations of that planar lens are compared and briefly discussed. A perspective about the future outlook of planar metalens is summarized. Since the planar metalens has a powerful capability in manipulating the light field, the rapid development in various applications would be gradually realized in the near future.

**Keywords:** super-oscillatory lens; super-critical lens; super-resolution imaging; diffractive optics

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