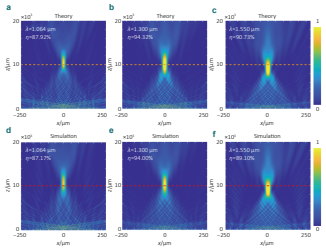
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Article

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基于改进 DBS 算法的三波长消色差透镜设计



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摘要：传统衍射透镜受限于材料的固有特性，存在聚焦效率低、工作波长单一和色差等问题，常通过多个透镜级联提高成像质量，限制了光学系统的小型化与集成化发展。多台阶微透镜为光学系统的微型化提供了新思路，然而仍受到色差等影响且设计较为复杂。为此，本文提出一种基于改进直接二进制搜索算法的三波长消色差透镜设计方法，在 1.064 μm、1.300 μm 和 1.550 μm 三波长下实现了高效率消色差。理论结果表明，优化后的八台阶、十六台阶透镜的平均聚焦效率分别达到 90.99% 和 92.46%，相较于优化前分别提升了 13.95% 和 13.64%。该方法可用于三波长成像系统、光计算与光信息处理和生物医学成像等领域。

关键词：三波长；直接二进制搜索算法；消色差；高效率；衍射透镜

The English title and abstract appear at the end of the paper.

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1　引　言

传统折射透镜系统 (如显微镜和望远镜) 长期受限于光学材料色散和光学器件结构缺陷引起的色差问题，限制了其成像质量的提高[1]。为降低色差影响，常基于互补色散特性[2-3]，通过传统折射透镜与衍射透镜混合实现色差补偿[4-6]，然而，此类折衍混合透镜系统所需要透镜的数量与消色差的波数成正比[7]，在一定程度上制约了光学系统集成化发展。单片式折衍混合透镜[8-10] 采用一侧为折射面，另外一侧为衍射面的设计，可在消色差的同时有效减少该功能学元件的数量，但是整体结构较复杂，限制了其广泛应用。超构表面[11-13] 可在亚波长尺度实现对光波相位、偏振、振幅和频率等参量的灵活调控，已实现宽带消色差能力[14-15]，广泛用于偏振成像[16-18]、聚焦透镜[19]、电磁隐身[20-22] 和负折射材料[23-24] 等领域，但是，其加工精度要求较高，工艺复杂度远超传统衍射元件[25-26]。目前，主要采用结构较简单且加工难度较低的衍射透镜消除色差。

计算机技术的快速发展为消色差透镜设计提供了新途径。2021 年，中国科学院光电技术研究所巩畅畅等[27] 设计了一种分区式消色差衍射透镜，通过 RGB 三色波长对应各自的同心环带，实现了衍射透镜结构的简化，平均效率低于 40%。次年，苏州大学马顾等[28] 设计了一种大孔径、高效率消色差衍射透镜 (phase-coded diffractive

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lens, PCDL)，在 50 nm 的带宽和 16°视场的范围内实现了衍射极限成像。2025 年，李奥玲等[29]设计了两种多波长混合折射透镜，聚焦效率分别为 74.64% 和 86.03%。2021 年，郑高等[30]利用材料低色散特性和四重对称结构在可见光波段设计了一种聚焦效率接近 71% 宽带消色差超透镜。综合而言，最近设计的消色差透镜仍存在效率提升有限或结构设计较复杂的问题。为此，本文提出了基于改进直接二进制搜索算法的多台阶衍射透镜设计方法，在 1.064 μm、1.300 μm 与 1.550 μm三波长实现了平均超过 90% 的聚焦效率，在光学效率、器件集成化与加工工艺实现较好平衡。

本文采用改进直接二进制搜索算法，对微结构高度进行迭代优化，设计了一种近红外三波长消色差多台阶衍射透镜。该透镜在 1.064 μm、1.300 μm 和 1.550 μm 三波长下实现了高效率消色差，优化后的八台阶和十六台阶一维透镜的仿真聚焦效率分别达到 90.09% 和 91.62%，均表现出高效消色差性能，且分辨率接近衍射极限，各波长归一化强度响应得到有效优化，抑制了色差的影响。该设计方法可降低成像系统的结构复杂度，为光学领域的创新提供新的思路和方向。

2 基本原理

2.1 传统衍射微透镜

目前，多数介电材料的折射率随波长增大而减小，传统折射透镜的焦距随波长的增加而增大，从而产生色差，如图 1 (a) 所示。传统衍射透镜通常被认为是衍射光学元件[31-33] (diffractive optical element, DOE)，其典型结构通常一侧为平面，另外一侧为不同高度的同心圆环浮雕结构，如图 1 (b) 所示。衍射透镜的色差通常由透镜表面微结构高度的差异所致，使不同波长的光在空间上分离，常通过优化其结构高度抑制色差。DOE 通常采用抛物线的相位模型进行相位调制，其数学表达式为

$$\varphi_1(r)=\frac{2\pi}{\lambda}\left(f-\sqrt{r^2+f^2}\right), \tag{1}$$

式中：λ 是入射光波长；r 表示衍射透镜半径；f 为衍射透镜的焦距。传统衍射透镜通常会将上述相位限制在 0~2π 区间，并进行离散相位梯度处理。由式 (1) 可知，相位分布与 λ 相关，这导致传统衍射透镜的工作带宽有限，并受色差影响。图 1(c) 所示的一维多台阶衍射透镜在一定程度上可提高聚焦效率，为消色差透镜设计提供了新方案。

2.2 DBS 算法相位优化

目前常用于消色差衍射透镜优化算法常采用 Gerchberg-Saxton (GS) 算法[34]、遗传算法[35-36]、深度学习算法[37-39] 和直接二进制 (direct binary search, DBS) 算法[40-41]。GS 算法通常需要填零减少采样间隔，导致计算量增大，且输出平面的非信号区有明显的斑纹[34]；遗传算法需大量预设参数，尤其针对多变量问题，在全局范围内搜索速度较慢，收敛效率较低[42]；深度学习算法需大量的训练数据集，且实现起来具有一定的挑战性[37, 43]。因此，本文基于式 (1) 结合 DBS 算法，将多台阶衍射透镜的相位量化过程体现为离散的台阶高度变化，并通过迭代扰动局部区域的相位状态优化多台阶衍射透镜，此相位延迟模型可表述为

$$\varphi_i=k_0\left(n(\lambda)-1\right)\cdot h_i, \tag{2}$$

式中：$k_0=2\pi/\lambda$ 为自由空间的波矢；$n(\lambda)$ 是波长为 λ 对应的折射率；h_i 表示第 i 级台阶的高度。基于高度与相

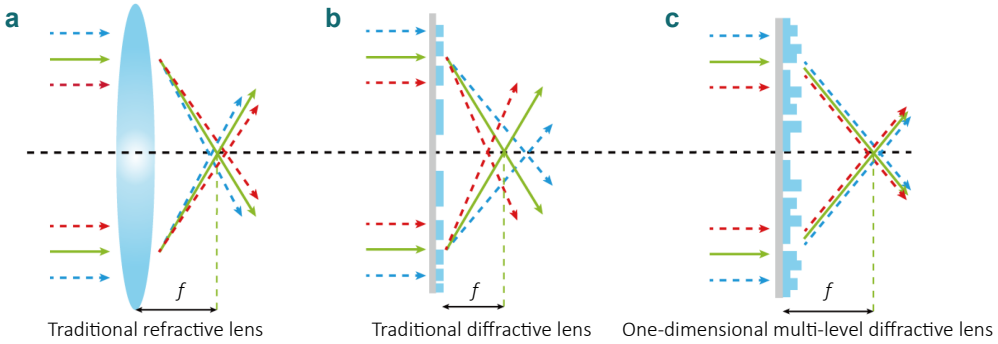


图 1 不同透镜的成像示意图。(a) 传统折射透镜; (b) 传统衍射透镜; (c) 一维多台阶衍射透镜

Fig. 1 A schematic representation of the imaging of the different lenses. (a) Traditional Refractive Lens; (b) Traditional Diffractive Lens; (c) One-Dimensional Multi-Level Diffractive Lens

位的定量关系，DBS 算法能筛选出最优台阶高度分布 h_i，抑制色差。此时，衍射透镜的台阶高度为

$$h(\lambda)=\frac{\lambda}{2\pi(n(\lambda)-1)}\varphi_i. \tag{3}$$

传统 DBS 算法常需多次生成随机初始结构实现高度优化，降低了计算效率，并且台阶高度不具备旋转对称性，难以推广至二维多台阶衍射元件。针对传统 DBS 算法受随机结构影响、效率低、耗时严重等问题[44]，本文提出了一种采用径向对称初始结构的改进 DBS 算法，其计算方法公式为

$$h_{\text{chushi}}=\begin{cases}\text{Mod}\left[\dfrac{(m\cdot d)^2}{3f(n(\lambda_1)-1)},h_{\max}(\lambda_1)\right], & m \quad \text{is} \quad 0\\ \text{Mod}\left[\dfrac{(m\cdot d)^2}{3f(n(\lambda_2)-1)},h_{\max}(\lambda_2)\right], & m \quad \text{is} \quad 1\\ \text{Mod}\left[\dfrac{(m\cdot d)^2}{3f(n(\lambda_3)-1)},h_{\max}(\lambda_3)\right], & m \quad \text{is} \quad 2\end{cases}, \tag{4}$$

式中：Mod (a,b) 为取余函数；f 为衍射透镜的焦距；$n(\lambda_1)$、$n(\lambda_2)$ 和 $n(\lambda_3)$ 是不同波长下材料的折射率；m 是台阶的序号；d 是台阶的宽度；$h_{\max}(\lambda)$ 是不同波长下相移为 2π 时的台阶高度。取余函数将不同波长的台阶高度交替分布在不同位置，每个波长在相应位置上可获得有效相位调制。同时，所设计的衍射透镜具有径向对称的台阶高度分布，有助于提高 DBS 算法的计算效率。

$$h_{\max}(\lambda)=\frac{2\pi}{k_0(n(\lambda)-1)}. \tag{5}$$

为评价所设计衍射透镜的性能，采用式 (6) 所示的评价函数 (figure-of-merit，FOM) 进行量化评估：

$$FOM=\left(\sum_{i=1}^{M}\omega_i\mu_i\right)/M-\alpha\left(\sum_{i=1}^{M}\omega_i\varepsilon_i\right)/M, \tag{6}$$

式中：第一项表示 M 个波长的平均加权效率；第二项为 M 个波长的模拟函数和目标函数的加权归一化绝对差值。为平衡两项的权重，引入调节系数 α (α =10)。同时，通过加权系数 ω_i 调控不同波长的权重占比。为进一步评估效率，引入效率 μ 和归一化 (normalized) 绝对差值 ε[39]：

$$\mu_j=\frac{\int_{x_{\min}}^{x_{\max}}I_j(x)\cdot T_j(x)\mathrm{d}x}{\int_{x_{\min}}^{x_{\max}}I_j(x)\mathrm{d}x}, \tag{7}$$

$$\varepsilon_j=\frac{\int_{x_{\min}}^{x_{\max}}\left|normalize(I_j(x))-T_j(x)\right|\mathrm{d}x}{\int_{x_{\min}}^{x_{\max}}\mathrm{d}x}, \tag{8}$$

$$T_j(x)=\exp\left\{-\frac{[x-(x_{\max}+x_{\min})/2]^2}{(\lambda_j/(4\cdot NA))^2}\right\}, \tag{9}$$

式中：$I_j(x)=|U_j(x,y)|^2$ 为第 j 个波长在像面的模拟光强分布；$T_j(x)$ 是第 j 个波长的观测平面上聚焦点扩散函数 (PSF) 的一阶近似值，以 $(x_{\min}+x_{\max})/2$ 为中心的高斯函数，是评估衍射透镜消色差能力的关键指标。基于上述原理，本文改进的 DBS 算法流程如图 2 所示。

3 衍射透镜设计

在近红外波段，1.064 μm、1.300 μm 和 1.550 μm 波

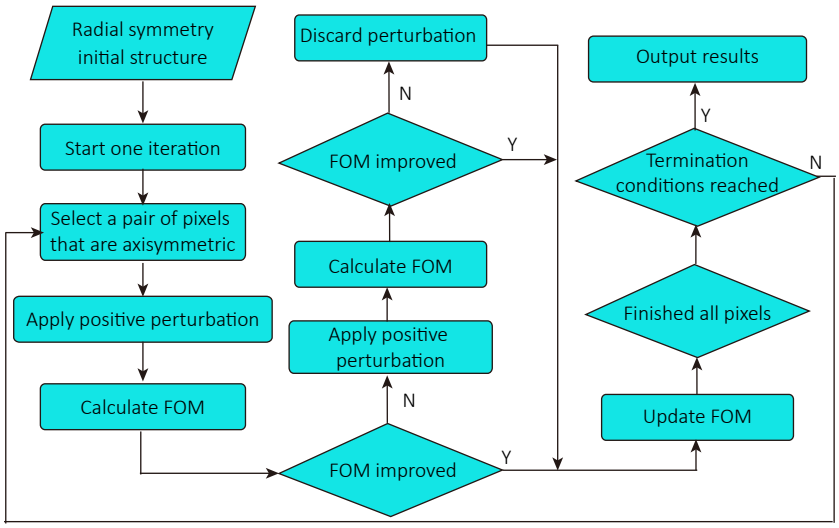


图 2 改进 DBS 算法流程图

Fig. 2 Flow chart of the improved DBS algorithm

长的激光广泛应用于生物医学和光纤通信领域。本文设计的近红外三波长消色差衍射透镜的直径为 560 μm，由宽度为 2 μm 的同心台阶构成，每个台阶的高度在 0~3 μm 范围内以 0.1 μm 为特征尺寸变化，共 31 级，NA = 0.028，焦距 f =10 mm。在近红外范围，PMMA 在入射光波长<2.8 μm 时，保持高透过率，且熔点为 150 ℃，便于制造。凭借 PMMA 具有低熔点、透光率高，线性膨胀系数低等优势，且可兼容光刻技术快速加工掩模板，实现低成本和大规模生产，常用作玻璃的替代材料。PMMA 材料色散系数及折射率公式如表 1 和式 (10) 所示：

$$n^2(\lambda) = B_0 + B_1\lambda^2 + B_2\lambda^{-2} + B_3\lambda^{-4} + B_4\lambda^{-6} + B_5\lambda^{-8}, \quad (10)$$

式中：n (λ) 为 PMMA 在波长 λ 处的折射率；λ 为入射光波长。依据表 1 和式 (10)，PMMA 在波长 1.064 μm、1.300 μm 和 1.550 μm 时的折射率分别为 1.4827、1.4813 和 1.4804。

表 1　PMMA 的色散系数[45]
Table 1　Sellmeier coefficients for PMMA

Coefficient	PMMA
B_0	2.18645820
B_1	-2.44753480×10^{-4}
B_2	1.41557870×10^{-2}
B_3	-4.43297810×10^{-4}
B_4	7.76642590×10^{-5}
B_5	-2.99363820×10^{-6}

为验证改进 DBS 算法的可行性，基于矢量衍射理论计算焦深方向上的理论强度分布[46]。此外，利用商用电磁仿真软件 CST Microwave Studio 中通过有限积分技术模拟消色差衍射透镜的光学特性，在 x 和 z 方向均采用开放边界条件，y 轴方向上采用周期边界条件，平面波激励源为沿 z 传播的 x 线偏振光。为提高工作效率缩短计算时间，在距离衍射透镜出口 1 μm 出提取电场分布，并基于矢量角谱理论计算后续光场。

3.1 理想相位分布与量化阶数对比分析

改进的 DBS 算法通过优化衍射透镜的台阶高度，并生成对应的相位轮廓。图 3(a-c) 和图 3(d-f) 分别为 16 台阶衍射透镜，波长为 1.064 μm、1.300 μm 和 1.550 μm 的理想相位分布与优化后的相位分布，且在中心位置截取的相位调制曲线如图 3(g-i) 所示。

为进一步分析改进 DBS 算法的优化结果，优化高度对比与相位误差分析结果如图 4 所示。其中，图 4(a,b) 为优化后 8 台阶和 16 台阶衍射透镜高度图。在 1.064 μm、1.300 μm 和 1.550 μm 波长处，L=8 (L=16) 优化后的相位曲线与理想相位曲线之间的最大允许误差 (maximum permissible errors, MPE) 分别为 10.85° (8.61°)、11.25° (11.14°) 和 10.24° (10.21°)，平均值为 10.78° (9.98°)，如图 4(c) 所示。改进 DBS 算法优化后的相位分布曲线与理论结果基本一致，误差较小，基本满足设计要求。

优化前八台阶 (L=8) 和十六台阶 (L=16) 的衍射透镜焦深强度分布如图 5 所示。L=8 时，波长为 1.064 μm、1.30 μm 和 1.55 μm 时 (图 5(a-c))，衍射透镜的聚焦效率分别为 61.50%、82.55% 和 87.08%，平均聚焦效率为 77.04%。聚焦效率定义为焦斑 3 倍半高全宽 (full width at half maximum, FWHM) 范围内的光功率与器件的传输光功率之比[47]。当 L=16 时 (图 5(d-f))，波长为 1.064 μm、1.30 μm 和 1.55 μm 时，聚焦效率分别为 66.85%、82.94% 和 86.68%，平均值为 78.82%。受色差等影响，两个衍射透镜的平均聚焦效率均小于 79%。

为提高衍射透镜的聚焦效率并抑制色差，以上述透镜为基础，采用改进 DBS 算法优化其结构高度。在不同波长下，随迭代次数变化的聚焦效率分布如图 6 所示。当 L=8 (图 6(a))，迭代次数为 4000 次，波长为 1.064 μm、1.300 μm 和 1.550 μm 时，相应的优化后的衍射透镜聚焦效率分别为 87.92%、94.32% 和 90.73%，其平均值达到 90.99%，相较优化前提高了 13.95%。同样条件下，L=16 时 (图 6(b))，优化后的衍射透镜在不同波长的光入射时，对应的聚焦效率分别达到 90.01%、96.63% 和 90.73% (平均值为 92.46%，相较于优化前提高了 13.64%)。由于一维衍射透镜结构间的相互作用相较于二维透镜更小，聚焦效率相对偏高。此外，近期研究人员设计了相关高效率消色差衍射透镜，例如 Banerji 科研团队设计的短波红外波段多级衍射透镜 (multi-level diffractive lens, MDL) 通过直接二进制搜索 (DBS) 算法，可将点扩散函数 (point spread function, PSF) 能量集中于主瓣，能有效抑制高阶衍射能量[48-50]，模拟聚焦效率可达到 91%。此外，迭代次数接近 4000 时，两个衍射透镜的平均聚焦效率趋于稳定 (L=8，接近 91%；L=16，接近 92%)，因此，后续优化过程中，迭代次数均设为 4000 次。

为分析加工误差对消色差衍射透镜的影响，将消色差衍射透镜引入加工误差 (每个台阶以 0.2 μm 的高度

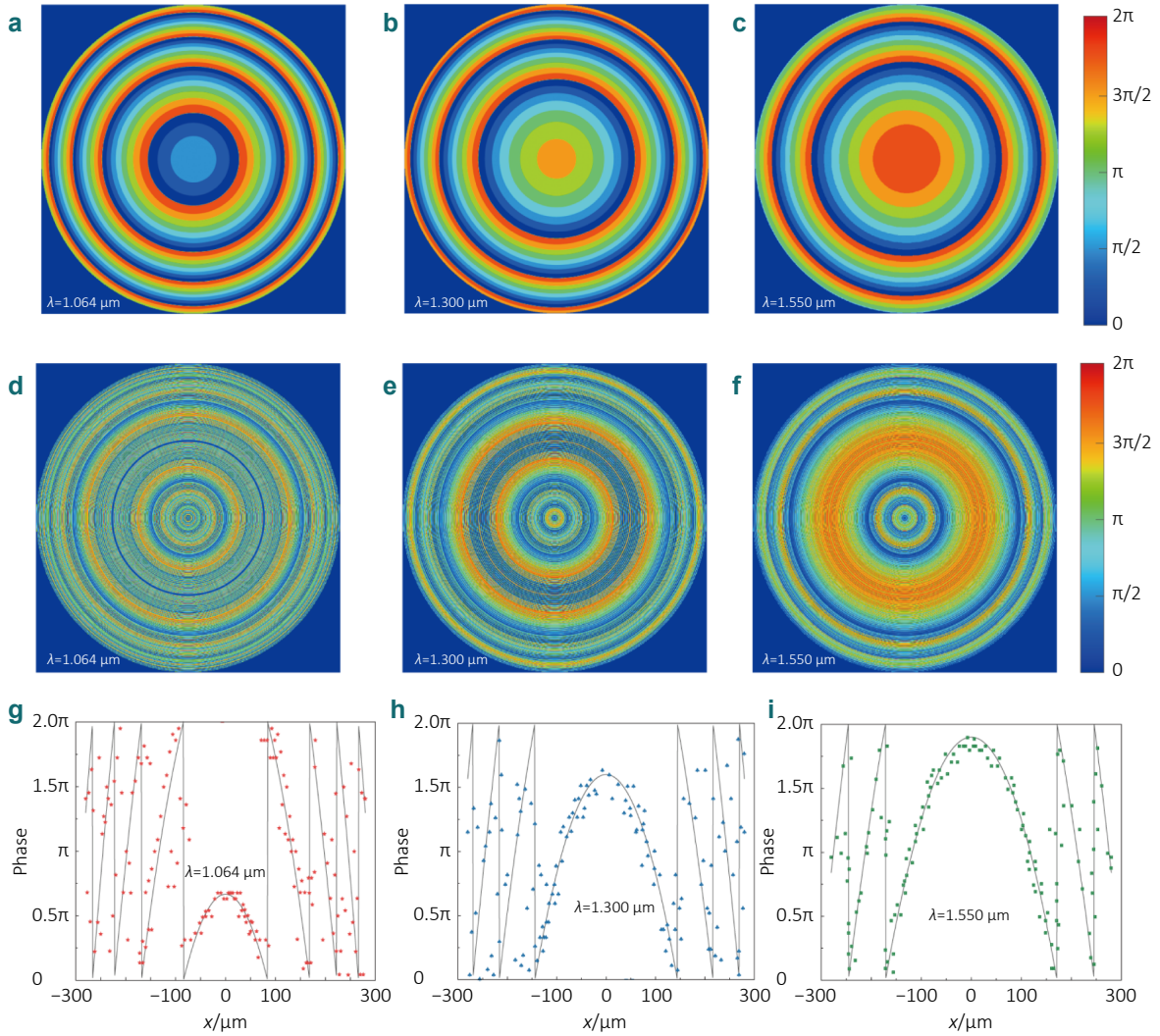


图 3 多台阶消色差衍射透镜相位示意图。(a-c) λ=1.064 μm、1.300 μm 和 1.550 μm 下的理论连续相位分布；(d-f) 相同波长下经 DBS 算法优化后的 16 台阶量化相位分布；(g-i) 对应波长下理论相位与量化相位的中心截线对比

Fig. 3 Phase schematic diagram of multi-level achromatic diffractive lens. (a-c) Theoretical continuous phase distributions at λ=1.064 μm, 1.300 μm, and 1.550 μm, respectively; (d-f) DBS-optimized 16-level quantized phase distributions at the corresponding wavelengths; (g-i) central phase profile comparisons between the theoretical and quantized phases

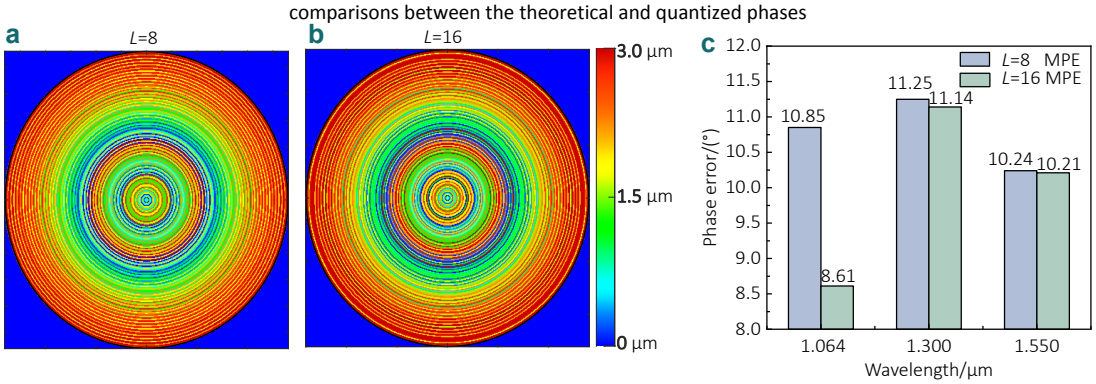


图 4 优化高度对比与相位误差分析。(a) 8 台阶衍射透镜的优化高度分布；(b) 16 台阶衍射透镜的优化高度分布；(c) λ= 1.064 μm、1.300 μm 和 1.550 μm 下 L = 8 与 L = 16 的最大允许相位误差对比

Fig. 4 Comparison of optimized height profiles with phase error analysis. (a) Optimized height distribution of the diffractive lens with L = 8; (b) Optimized height distribution of the diffractive lens with L = 16; (c) Comparison of the maximum permissible phase error between L = 8 and L = 16 at λ = 1.064 μm, 1.300 μm, and 1.550 μm

间隔变化至 0.8 μm)，如图 7 所示。当波长为 1.064 μm，误差高度在 0~0.8 μm 时，8 台阶和 16 台阶的聚焦效率下降幅度较大，聚焦效率分别为 67.1% 和 65.31%，与理想无误差的聚焦效率 87.92% (L=8) 和 90.0% (L=16) 分别下降了 20.82% 和 24.69%。相比之下，波长为 1.300 μm 和 1.550 μm 时，加工误差的引入对衍射透镜聚焦效率影响较小，8 台阶和 16 台阶的平均聚焦效率约为 85%，衍射透镜的聚焦效率下降低于 10%。8 台阶和 16 台阶三波长平均聚焦效率~80%，相较于理想无误差降低~12%。本文设计的消色差衍射透镜引入加工误差下仍保持较好的性能，具有一定实际应用的可行性。

3.2 理论与仿真对比分析

优化后的一维 8 台阶消色差衍射透镜的理论和仿真归一化强度分布如图 8 所示。衍射透镜的聚焦效率在

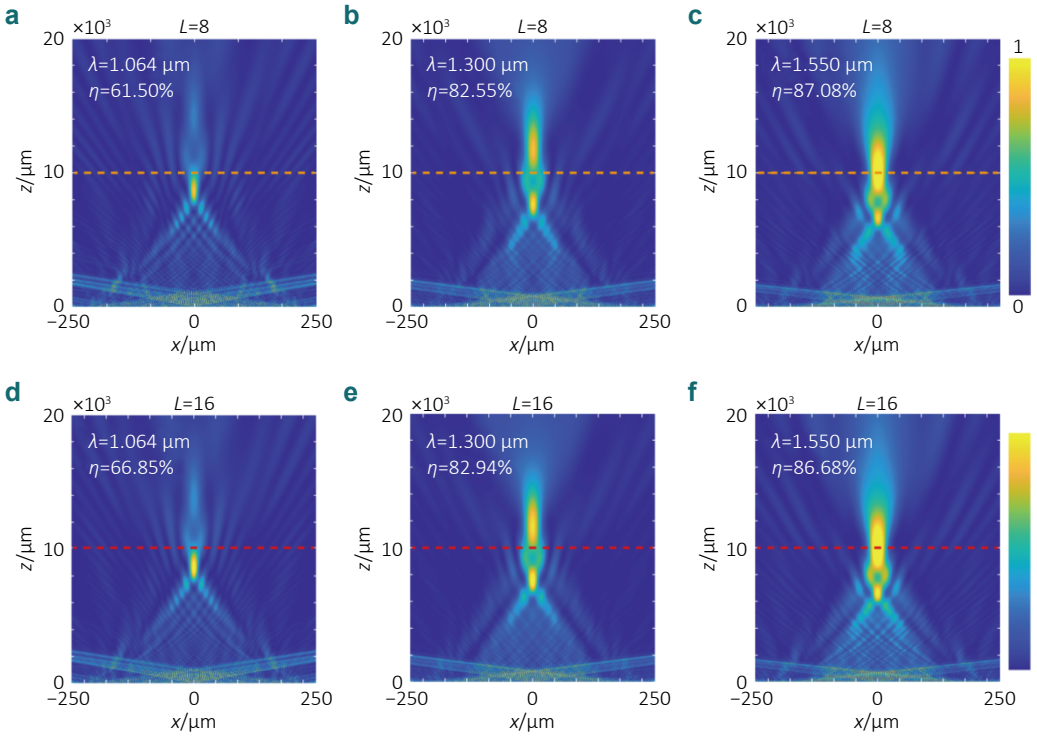


图 5 优化前多台阶消色差衍射透镜的模拟结果。(a-c) 分别为 L=8 时在 λ=1.064 μm、1.300 μm 和 1.550 μm 下的轴向光强分布；(d-f) L=16 时在相同波长下的轴向光强分布

Fig. 5 Simulation results of pre-optimization multi-level achromatic diffractive lens. (a-c) Axial intensity distributions of the diffractive lens with L = 8 at λ=1.064 μm, 1.300 μm, and 1.550 μm, respectively; (d-f) Axial intensity distributions of the diffractive lens with L=16 at the corresponding wavelength

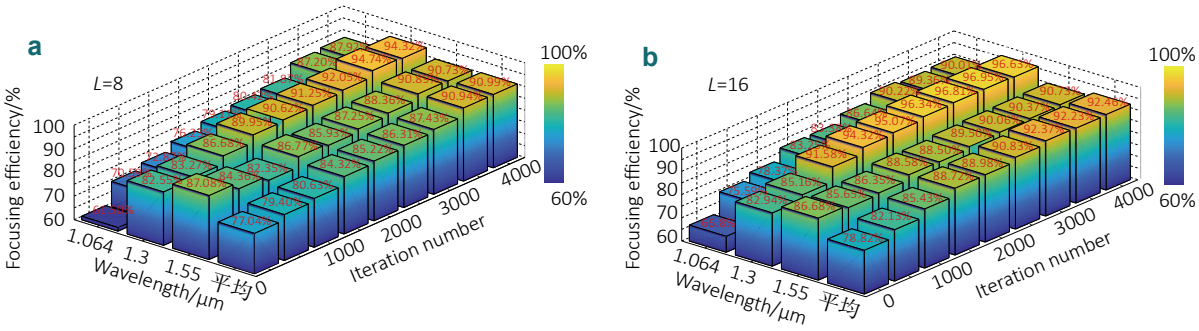


图 6 多台阶消色差衍射透镜的聚焦效率。(a) L=8 时聚焦效率随迭代次数的变化；(b) L=16 时聚焦效率随迭代次数的变化

Fig. 6 Focusing efficiency schematic diagram of multi-level achromatic diffractive lens. (a) Focusing efficiency versus iteration number for L=8; (b) Focusing efficiency versus iteration number for L=16

1.064 μm、1.300 μm 和 1.550 μm 波长处，理论结果分别达到 87.92%、94.32%、90.73% (平均值为 90.99%)，如图 8(a-c) 所示。图 8(d-f) 的仿真结果表明，聚焦效率分别为 87.17% (1.064 μm)、94.00% (1.300 μm) 和 89.10% (1.550 μm)，平均值为 90.09%。仿真与理论结果基本一致，且均在焦平面位置 (f=10 mm) 聚焦，表明基于改进 DBS 算法设计的一维衍射透镜具备高效消色差性能，两者之间的差异可能由于理论计算基于完美条件，未考虑结构间的相互作用影响[51]。

为进一步验证其高效消色差特性，设计了图 9 所示

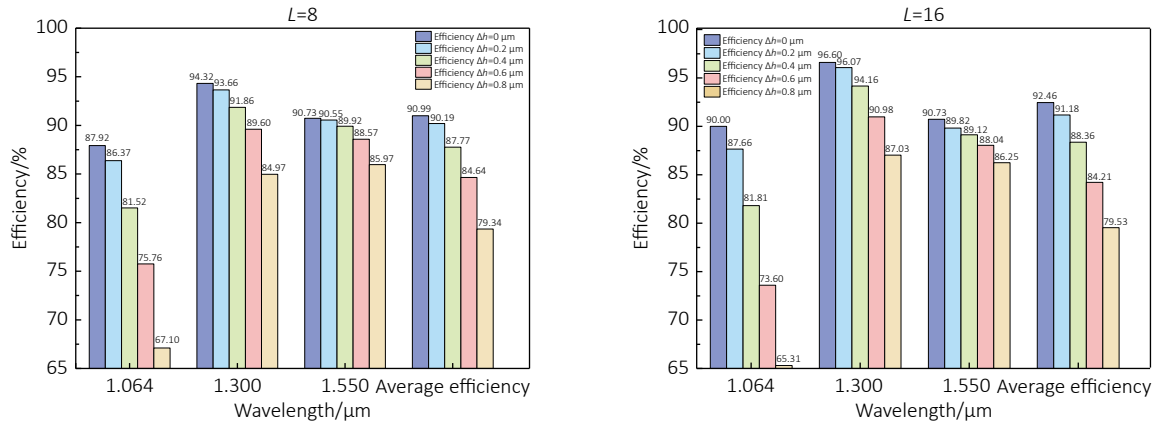


图 7 8 台阶和 16 台阶加工误差效率对比。(a) L=8 时不同加工高度误差下的聚焦效率对比；(b) L=16 时不同加工高度误差下的聚焦效率对比

Fig. 7 Comparison of efficiency vs. fabrication error for 8-level and 16-level structures. (a) Focusing efficiency under different fabrication height errors for L=8; (b) Focusing efficiency under different fabrication height errors for L=16

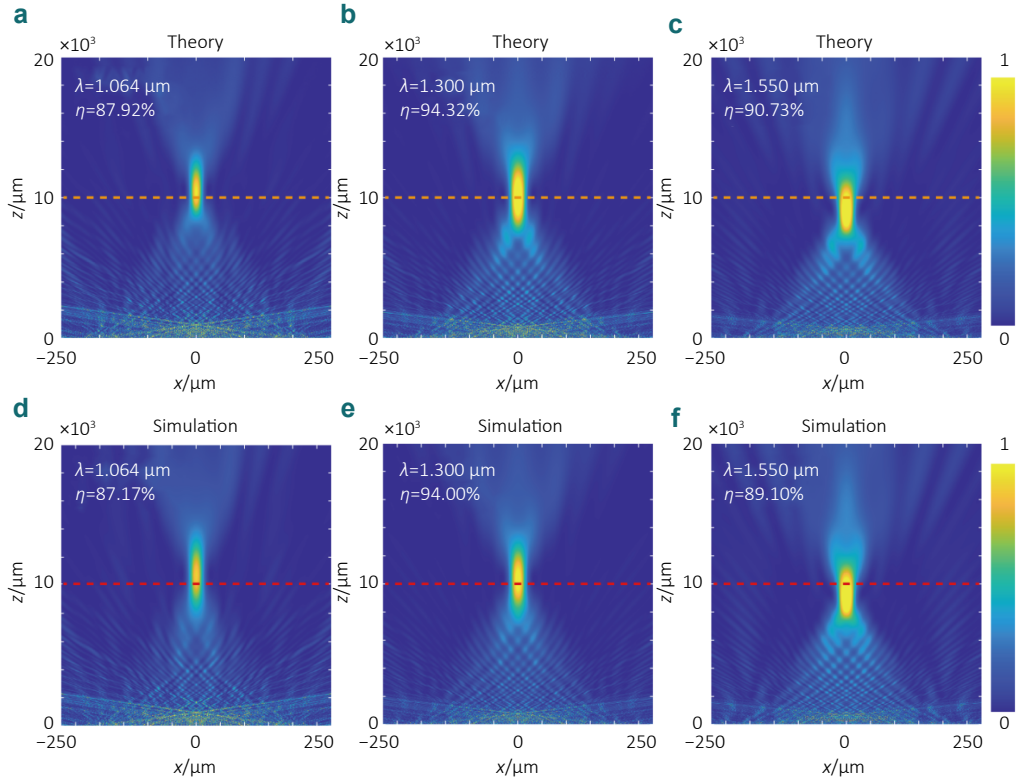


图 8 (d-f) 分别为相同波长下的仿真轴向光强分布 (L=8)。(a-c) 分别在 λ=1.064 μm、1.300 μm 和 1.550 μm 波长下的理论轴向强度分布；(d-f) 相同波长下的模拟轴向强度分布

Fig. 8 Simulation results of multi-level achromatic diffractive lens (L=8). (a-c) Theoretical axial intensity distributions at λ=1.064 μm, 1.300 μm, and 1.550 μm, respectively; (d-f) Simulated axial intensity distributions at the corresponding wavelengths

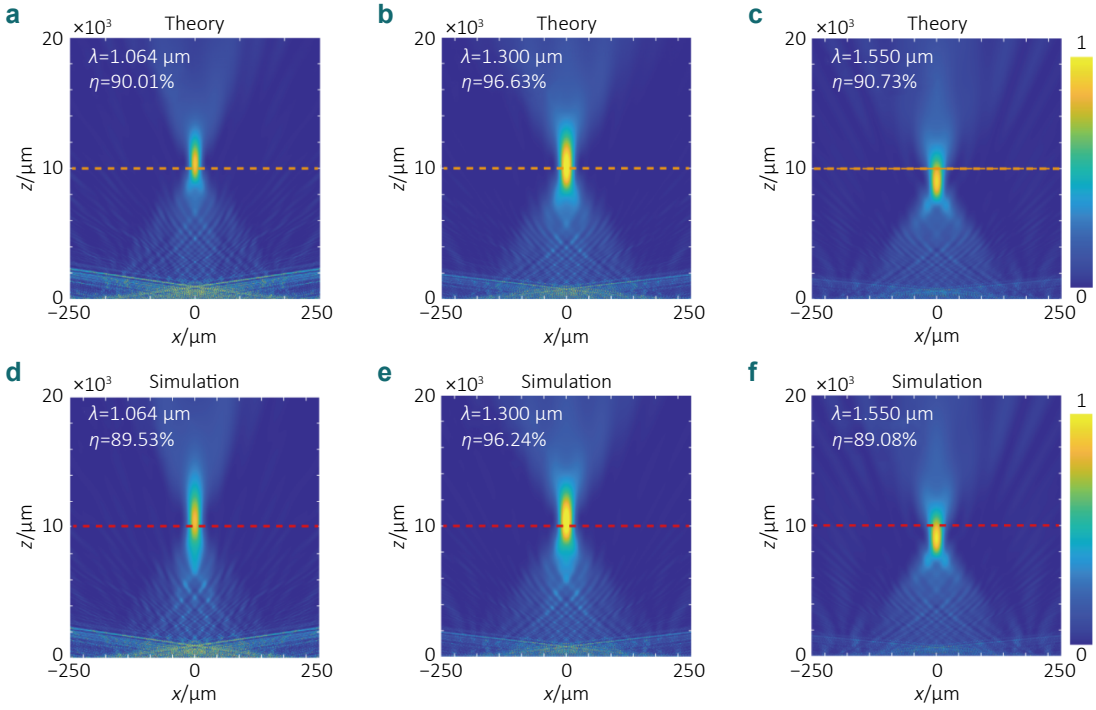


图 9 16 台阶消色差衍射透镜的理论和仿真结果。(a-c) 分别为 λ=1.064 μm、1.300 μm 和 1.550 μm 下的理论轴向光强分布；(d-f) 分别为相同波长下的仿真轴向光强分布

Fig. 9 Simulation results of multi-level achromatic diffractive lens (L=16). (a-c) Theoretical axial intensity distributions at λ=1.064 μm, 1.300 μm, and 1.550 μm, respectively; (d-f) Simulated axial intensity distributions at the corresponding wavelengths

的一维 16 台阶消色差衍射透镜。当 1.064 μm 波长的光入射时，聚焦效率的理论和仿真分别为 90.01% 和 89.53%，如图 9(a,d) 所示。当入射光波长变为 1.30 μm 时，聚焦效率分别为 96.63% (理论) 和 96.24% (仿真) (图 9(b,c))。波长为 λ=1.55 μm 时，图 9(c,f) 所示的理论和仿真效率分别为 90.73% 和 89.08%。不同波长光入射时，该透镜的理论和仿真平均聚焦效率为 92.46% 和 91.62%。相较于图 8 所示的 8 台阶透镜，16 台阶透镜的平均效率提高 ~ 1.5%，同样具备高效消色差性能，但制造难度相对更大。

图 10 为 8 台阶 (L=8) 和 16 台阶 (L=16) 消色差衍射透镜的焦平面处的理论 (蓝色虚线) 和仿真 (红色虚线) 归一化强度曲线。如图 10(a-c) 所示，波长为 1.064 μm、1.300 μm 和 1.550 μm 时，理论 FWHM 分别为 21.8 μm、26.6 μm 和 32.2 μm，仿真为 25.8 μm、26.9 μm 和 33.4 μm。当 L=16 时，三波长对应的仿真 FWHM 为 26.9 μm、26.9 μm 和 33.4 μm，而理论结果不变，如图 10(d-f) 所示。上述理论和仿真结果在不同波长处，均接近其衍射极限 19.00 μm、23.22 μm 和 27.69 μm ($\lambda/(2NA)$，NA=0.028)[52]，在消色差的同时，具备较好的成像性能。

4 结　论

本文设计了一种基于改进 DBS 算法的一维多台阶消色差衍射透镜。在 1.064 μm、1.300 μm 和 1.550 μm 入射波长下，本文设计的八台阶和十六台阶消色差衍射透镜理论平均聚焦效率分别为 90.99% 和 92.46%，仿真平均聚焦效率分别为 90.09% 和 91.62%，具备高效消色差性能，且成像分辨率接近衍射极限。本文设计的多台阶消色差衍射透镜为三波长消色差问题提供了新的思路与方向，有望应用于三波长成像系统、光信息处理、轻量化准直器、光通信等领域。

作者贡献

蔡吉祥：研究资料的收集、分析，指导论文选题，论文审核与编辑写作；胡成宇，李玮：论文初稿写作与论文修改；张婷婷：论文审核与编辑写作。

利益冲突

所有作者声明无利益冲突

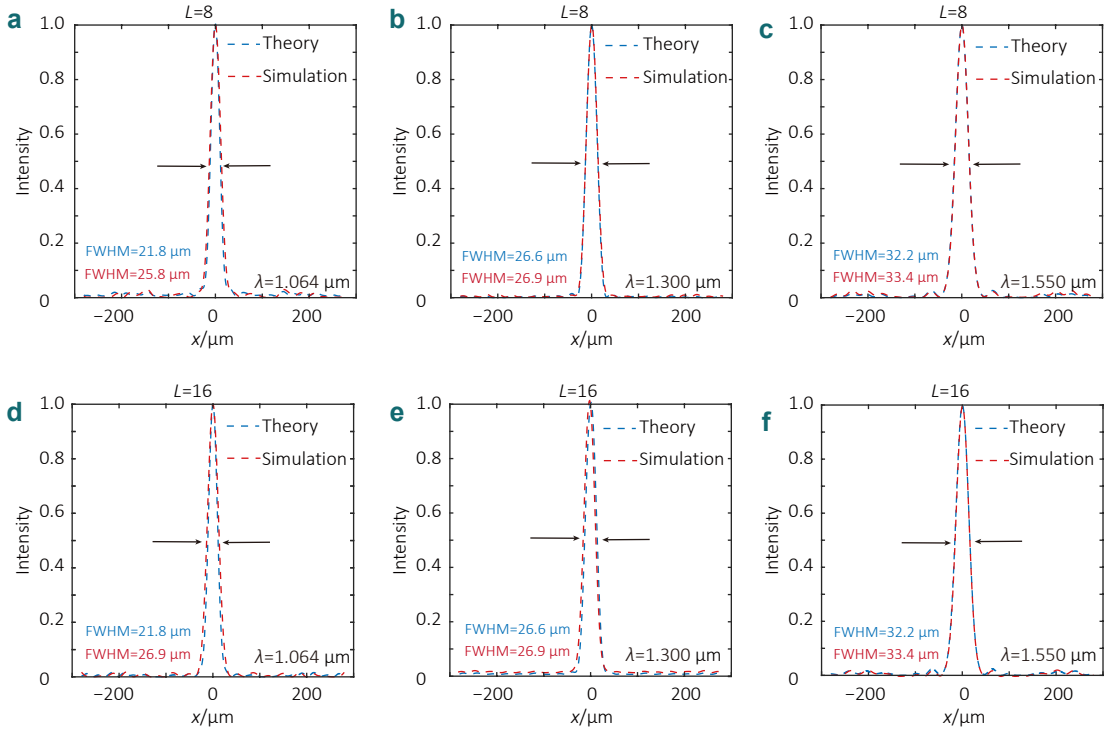


图 10 多台阶消色差衍射透镜归一化强度曲线对比。(a-c) 分别为 L=8 时在 λ=1.064 μm、1.300 μm 和 1.550 μm 下的理论与仿真归一化强度曲线；(d-f) 分别为 L=16 时在相同波长下的理论与仿真归一化强度曲线

Fig. 10 Normalized intensity curve comparison of multi-level achromatic diffractive lens. (a-c) Theoretical and simulated normalized intensity profiles for L=8 at λ=1.064 μm, 1.300 μm, and 1.550 μm, respectively;(d-f) Corresponding results for L=16 at the corresponding wavelengths

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Design of three-wavelength achromatic lens with modified DBS algorithm

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Abstract

Objective Traditional diffraction lenses can manipulate wavefronts by adjusting the refractive index of materials and surface profiles of devices, which are widely applied in optical imaging. However, such imaging capabilities are usually constrained by limitations of low focusing efficiency, a single operating wavelength, and chromatic aberration. To suppress chromatic aberration and improve image quality, it is commonly used by combining positive and negative refractive index lenses. Nevertheless, this scheme hinders the miniaturization and integration of optical systems. Although monolithic refractive-diffractive hybrid lenses provide an alternative method to enhance system integration for achromatic performance, complex structural design restricts their further applications. Recently, metasurfaces offer another methodology for realization of broadband achromatic, but the high processing precision in micro-nanofabrication is always required. Consequently, there is still a great challenge for designing diffractive lenses with simple structure, low processing difficulty, and achromatism.

Methods For conventional direct binary search (DBS) algorithm to optimize diffraction lenses, the random initial structures are commonly used, whereas it commonly leads to slow convergence, sensitivity to the starting state. Here, a modified DBS algorithm is proposed for designing three-wavelength multi-order achromatic diffraction microlenses by directly tuning the discrete surface-relief heights. Utilizing the radially symmetric initial height distribution, such approach can reduce the randomness and improve computational stability and corresponding main procedures are as follows: First, the ideal continuous phase distribution of achromatic focusing lens with a parabolic phase profile can be generated; Second, such continuous phase is quantized into discrete phase corresponding to different step-heights for optimizing multilevel diffractive lens by iterative perturbations of local phase; Third, a radially symmetric initial structure determined by modulo function is introduced to replace the conventional random initialization, and then the step heights corresponding to different wavelengths are alternately distributed at distinct positions. Finally, a figure-of-merit (FOM) is adopted to evaluate the performance of the designed lens and guides the iterative updates of the step-height distributions. As a proof of concept, the 8-step and 16-step diffraction lenses (with a diameter, focal length, and numerical aperture of 560 μm, 10 mm, and 0.028, respectively) are designed and analyzed both theoretically and through simulation.

Results and Discussions For pre-optimization, the average focusing efficiencies of the diffractive lenses with 8 phase levels (L=8) and 16 phase levels (L=16) are 77.04% and 78.82% at the wavelengths of 1.064 μm, 1.300 μm, and 1.550 μm, respectively. Therefore, the average focusing efficiencies of both lenses are less than 79% affected by chromatic aberration in theory. To improve the focusing

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efficiency and suppress chromatic aberration, a modified DBS algorithm is employed to optimize the step-height distribution. For post-optimization, the focusing efficiencies of diffraction lens (L=8) can reach 87.92%, 94.32%, and 90.73% (the efficiency is 90.99%) at 1.064 μm, 1.30 μm, and 1.55 μm after 4000 iterations, respectively, which is improved 13.95% compared to pre-optimization in theory. When L is changed to 16, the efficiencies exceed 90.01%, 96.63%, and 90.73% (at 1.064 μm, 1.300 μm, and 1.550 μm) respectively, and corresponding average value surpasses 92.46% (the improvement is 13.64% compared to pre-optimization) under the same conditions. These results indicate that the proposed achromatic diffraction lens maintains higher performance with the proposed modified DBS algorithm in theory. To further validate the achromatic performance, numerical simulations are conducted using CST microwave studio. For the diffraction lens with L=8 and 16, the focusing efficiencies at 1.064 μm are 87.17% and 89.53% in simulation, respectively. Moreover, it can be increased to 89.10% and 96.24% at 1.30 μm, while the efficiencies are 89.10% and 89.08% at 1.55 μm, respectively. Therefore, corresponding average efficiencies can reach 90.09% (L=8) and 91.62% (L=16), respectively. Note that the slight difference between theoretical prediction and numerical simulation may be attributed to the ideal assumptions (neglected the interactions between structures) in the theory. Furthermore, the point spread functions (PSFs) at the focal plane for different wavelengths are employed to characterize the achromatic performance of the designed diffraction lens. The simulated full width at half maximums (FWHM) are 25.8 μm, 26.9 μm, and 33.4 μm (L=8) and 26.9 μm, 26.9 μm, and 33.4 μm (L=16) at 1.064 μm, 1.300 μm, and 1.550 μm, respectively, which are agree well with the theoretical results of 21.8 μm, 26.6 μm, and 32.2 μm and close to their diffraction limits of 19.00 μm, 23.22 μm, and 27.69 μm at different wavelengths. Totally, both the 8-step and 16-step diffraction lenses possess an average focusing efficiency of ~79% (at 1.064 μm, 1.30 μm, and 1.55 μm) before optimization. However, the average efficiencies can exceed 90.99% and 92.46%, (improvements of 13.95% and 13.64%), respectively, based on the improved DBS algorithm (after 4000 iterations) in theory. Moreover, it has also demonstrated that the FWHM of the 8-step and 16-step diffraction lenses can reach the diffraction limit at three wavelengths, exhibiting high imaging performance.

Conclusions Here, a new methodology is proposed for achieving three-wavelength achromatism, and may offer advantages in reduction of device complexity, requirements of machining accuracy, and the manufacturing costs. These results may be further extended to diverse applications, such as three-wavelength imaging systems, optical computing, lightweight collimators, optical communications, biomedical imaging, and laser processing.

Keywords: three-wavelength; direct binary search algorithm; achromatism; high focusing efficiency; diffraction lens

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