

具有渐变折射率、可变截面三维光波导的激光直写技术

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摘 要: 飞秒激光具有超短脉冲宽度与超高峰值功率的特点, 可实现基于高度非线性效应的透明材料内部的高精度三维微纳加工, 已成为集成光电子器件制备的重要工具。近年来, 基于多次扫描策略的飞秒激光直写技术可以实现波导截面几何形貌、模场及折射率分布的精细调控, 已成为微结构光波导制备方向的研究热点。本文系统阐述了飞秒激光多次扫描在透明材料内部直写光波导的最新研究进展, 重点分析该技术通过三维可变截面波导结构设计在有源/无源光波导器件、集成化量子光学芯片及天文光子学系统等领域的创新应用。进一步从波导截面形貌的精确调控、低损耗弯曲波导结构优化、跨尺度纵深直写技术等维度探讨了三维集成光子回路面临的关键技术挑战, 展望实现全玻璃基三维光子芯片的未来发展趋势。

关键词: 三维光波导; 飞秒激光直写; 可变截面; 光波导器件

中图分类号: TN249 文献标志码: A 文章编号: 0454-5648(2025)10-2899-13

网络出版时间: 2025-09-08



随着现代高性能光计算与高速光通信技术的飞速发展, 对三维集成光子光路(3D PICs)提出了更为严苛的性能要求^[1-2]。与二维光波导器件相比, 三维光波导器件具有更高的制备自由度, 能够实现更高质量的集成、更复杂的截面形状控制以及对更复杂的物理现象进行模拟和预测^[3]。目前的三维集成光波导制备技术主要分为 2 类: 三维堆叠技术以及飞秒激光直写光波导技术。三维堆叠技术不仅可以实现结合硅、氮化硅、氧化硅波导等硅基材料的集成, 也可通过化学气相沉积和掩膜转印等方式将薄膜铌酸锂等异质材料与硅基材料相组合以提升 3D PICs 的性能^[4-6]。但是, 多材料体系的三维堆叠集成光波导器件随着集成度提升, 其制备复杂度与成本也显著提升, 所以研究具备超越光衍射极限以及真三维加工能力等诸多优势的飞秒激光直写技术具有重要意义。

1996 年, Davis^[7]等首次利用飞秒激光在玻璃内部直写光波导, 从此开启了在玻璃及晶体等透明介质内部制备光波导的研究热潮。目前, 飞秒激光直写光波导的传输损耗已低至 0.1 dB/cm^[8]、波导纵深

高达 1.1 mm^[9]、折射率对比度达 $10^{-4} \sim 10^{-2}$ ^[10]。飞秒激光直写技术将具有高峰值功率和短脉冲宽度的激光脉冲聚焦在透明材料内部局域诱导折射率改变, 具有无须复杂掩膜操作、高效灵活的三维加工能力, 在三维光波导、集成光波导器件、集成光量子计算、光学模拟以及拓扑光子学等领域具有广泛的应用前景^[11-21]。

飞秒激光诱导透明介质材料的改性主要可分为 2 大类: 其一为利用低于材料自聚焦阈值的飞秒激光脉冲能量在聚焦位置产生均匀折射率升高区域的 I 型折射率改性; 其二为在激光聚焦区域引起负折射率变化而邻近区域具有相对较高折射率的 II 型折射率改性, 通过 2 条并行排列或一系列环形排布的基于 II 型折射率改性可分别构成应力挤压双线型波导与凹陷包层型波导。当然, 由于在聚焦飞秒激光照射过程中不同非线性效应均产生作用, 并且诱导结构随着时间会不断产生演变, 其现象和机理层出不穷, 在此我们聚焦 I 型和 II 型折射率改性结构。基于 II 型折射率改性的波导, 其优势在于具有良好

收稿日期: 2025-04-15。 修订日期: 2025-05-21。

基金项目: 国家自然科学基金(52432001)。

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Received date: 2025-04-15. Revised date: 2025-05-21.

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的热稳定性,退火后波导损耗较低且能有效保持导光区域原本的光学性质^[22]。由于强烈的非线性吸收效应,飞秒激光改性区域仅限于激光焦斑内的小部分区域,飞秒激光单次扫描轨迹能够超越光的衍射极限^[23]。但受限于较低的折射率对比度和较小的直径,单根轨迹导光性能较弱。增加扫描次数可有效提升折射率对比度,但同时热效应积累也会导致飞秒激光改性区域逐渐大于激光聚焦区域,进而增加波导模场直径。

飞秒激光聚焦在透明材料内部时,空气与介质之间存在折射率失配会导致球差产生。另外,聚焦区域也存在自聚焦效应以及非线性吸收效应,这些因素均会使聚焦区域的能量分布畸变,导致波导截面呈现椭圆形,从而增大波导的模场不对称性、耦合损耗以及传输损耗^[24]。因此,实现截面形状可控对于制备低损耗的复杂光波导集成器件具有重要意义。飞秒激光光束整形技术作为一类时空域光场调控的工艺方法,被证实具有显著的技术优势,可以实现对波导横截面几何形貌的有效调控与传输损耗抑制。飞秒激光光束整形技术中,狭缝整形因其操作简便,现已成为改善波导横截面几何对称性的主流方案,但其存在能量利用效率低的缺陷^[25–27];基于柱透镜对的光束整形虽然可以实现聚焦光场能量分布的空间优化,但受制于像散光场构建过程中复杂的调节需求,面临着系统集成度与操作可控性显著降低的技术瓶颈^[28–30];为克服以上2种方案存在的能量损失大以及操作复杂的问题,研究人员提出了涡旋光场整形^[31–32]、可变形镜光束整形^[33]和空间光调制整形技术^[34–37],但仍然存在对波导截面形貌和折射率分布可控性差的问题。

另一类制备高对称性波导截面的方法是多次扫描技术^[38–39]。飞秒激光多次扫描过程中可以结合光束整形技术,实现对于波导截面形状、尺寸和折射率分布更加精确可控的调节,并且不局限于高对称性圆形波导,实现任意截面形状控制。通过在三维空间内排布全正折射率的轨迹实现对光波导折射率分布和截面形状的精确控制,现已被广泛用于制备近红外^[40]以及中红外^[38]的低损耗光波导。本文主要针对利用多次扫描飞秒激光直写实现三维波导的制备技术和应用进行阐述和分析。

1 飞秒激光直写技术的最新进展

1.1 玻璃波导

玻璃基上直写三维低损耗光波导不仅可以提供

比二维的硅基波导更高的自由度,还有望为基于波导的集成光路现存的问题提供新的解决思路,例如实现绝热、高效、高精度的波导模式转换,实现高精度的片上偏振控制,实现在高分辨率下任意变换波导的横截面积和形状等,寻求能够解决这些问题的普适方法将会推动光子芯片的制备、光量子计算以及拓扑光子学等领域的发展^[24, 41]。

为了在硼磷掺杂玻璃中实现低传输损耗和低耦合损耗的光波导,Nasu等^[40]首次提出了经典的多次扫描方案,利用低数值孔径的透镜降低焦点附近功率密度从而防止光学损伤,调控激光多次扫描的偏移距离与扫描时间的变化有助于精确控制波导芯部的形状和大小,制备了传输损耗为0.35 dB/cm、模场失配损耗低于0.1 dB/point的单模矩形芯部波导。多次扫描飞秒激光直写波导技术的优势主要在于可以通过灵活精确改变波导的截面形状实现对波导的色散特性、传输损耗以及模场分布等光学特性的控制。近年来,基于多次扫描策略的飞秒激光直写玻璃波导已成为波导制备的重要方案^[42]。2022年,Wang等^[23]首次提出了正折射率变化的类光子晶格波导,该波导也被扩展到聚合物体系^[43],如图1a所示。其中修改后的线条排列从正六边形慢慢变为环状,实现从高斯光束到空心光束的模式转换。同年,Sun等提出一种通过引入液晶空间光调制器以校正系统像差的玻璃波导制备方案,即球形相位诱导多芯波导(SPIM-WG),并且利用该方案经过9×2多次扫描制备了如图1b所示沿长度方向横截面形状大小发生变化的扭曲波导。SPIM-WG具有高折射率对比度(0.017)、低传输损耗(0.14 dB/cm)以及低耦合损耗(0.19 dB)。该方案的突破在于实现了波导芯间距小于2 μm,这在传统多次扫描技术中是难以实现的,从而获得了更理想的波导截面、高制备效率制备时间降低1个数量级、更精细的折射率控制以及更优良的模式转换^[41]。2023年,Sun等^[44]在Er³⁺掺杂磷硅酸盐玻璃中设计不同截面形状的LP₀₁模式与LP₀₂模式的类光子晶格包层波导,实现波导插入损耗低至1.88 dB以及高达3.52 dB的波导光放大。同年,Yang等^[45]也利用多次扫描飞秒激光直写技术设计波导截面,在玻璃中制备出具有高空间分辨率、低插入损耗(1 dB)、低模式泄露且易于与光纤耦合的类光子晶格趋肤波导。

然而,波导截面形状和折射率分布的精细调控依然是一种挑战。为了解决这一问题,Wang等首次提出一种重叠控制多次扫描技术(OCMS),通过精确

控制激光聚焦区域的热积累, 实现三维波导截面折射率分布控制精度达 10^{-5} 量级^[46]。其脉冲能量 (20~30 nJ) 远低于自聚焦阈值, 同时比结构改性阈值高 1.0~1.5 倍以避免焦点位置偏移。使用高数值孔径 (1.3) 的油镜以最小化扫描线尺寸, 同时改变写入相邻扫描线的重叠比率以精确控制空间内不同点处的折射率变化量。图 1c 与图 1d 展示了基于 OCMS

方案设计的 4 种具有不同扫描线重叠率分布的 $10\text{ }\mu\text{m}$ 直径圆形波导。另外, 利用 OCMS 也可以实现对模式耦合的精确控制, 在玻璃芯片上直写具有可控折射率分布和可变横截面面积的波导空间模式转换器件, 波导模场截面的横式选择性保证了高纯度的模式转换, 可以用于在多组分玻璃上集成具有高鲁棒性和高相位匹配精度要求的模式耦合器件。

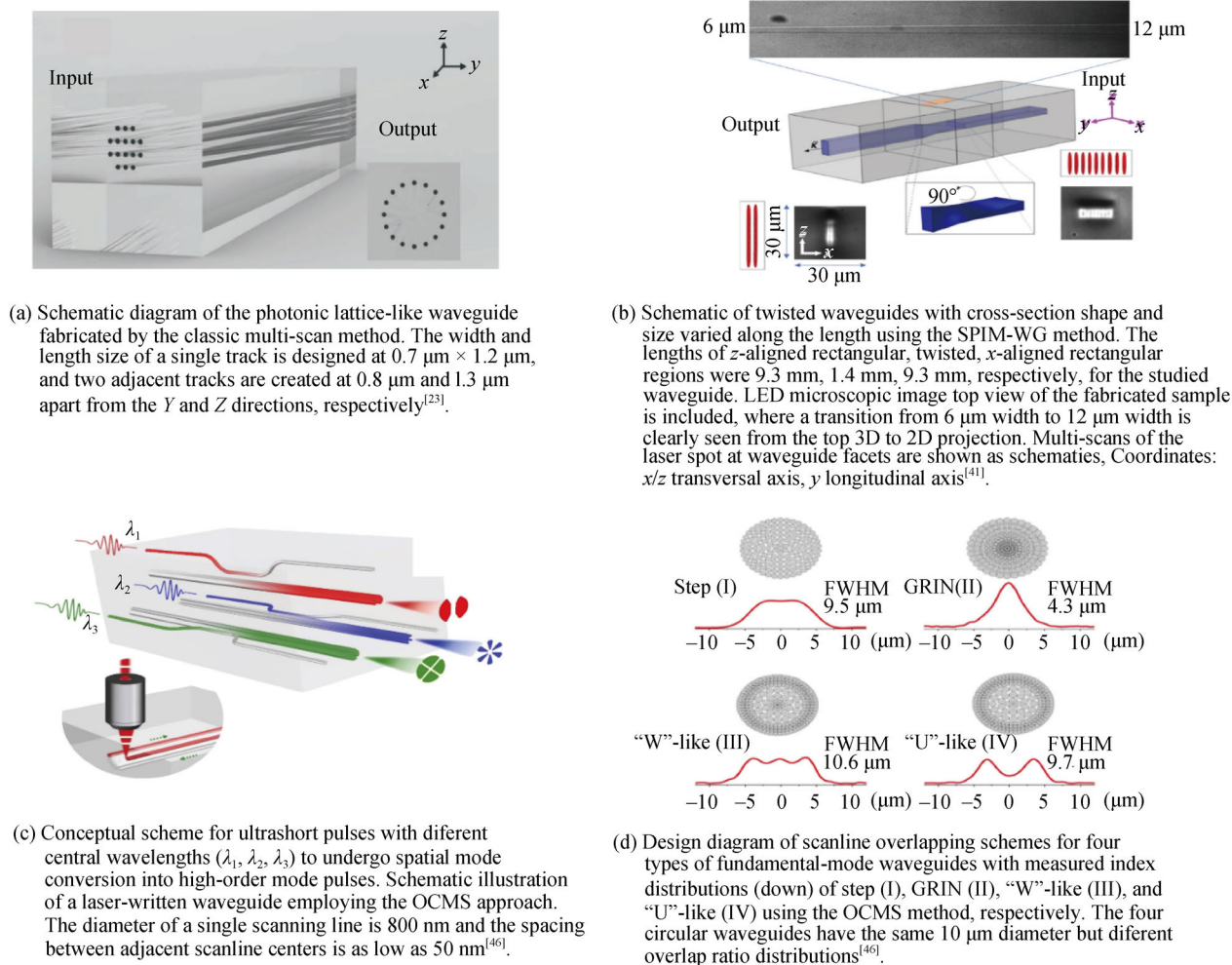


图 1 经典多次扫描方法, SPIM-WG 方法以及 OCMS 方法的示意图

Fig. 1 Schematic illustration of the classic multi-scan method, the SPIM-WG method, and the OCMS method

1.2 晶体波导

传统的在晶体中制造光波导的方法包括离子交换^[47]、金属离子扩散^[48]以及光刻^[49]等, 但是这些方法存在制备复杂度高、高成本、低效率、环境要求苛刻等限制, 所以飞秒激光直写技术也被用于晶体波导的制备。2004 年, Apostolopoulos 等^[50]首次在钛蓝宝石晶体内部制备出 II 型改性双线型波导, 此后有不少利用飞秒激光直写 II 型改性晶体光波导以及实现高性能波导激光输出的研究探讨^[51-54]。为了实现更优异的光束限制能力, Liu 等^[55]在 Nd:YAG 晶

体中通过刻蚀 2 个直径不同的同心圆形管状结构, 实现了良好的导光性能且易于与光纤系统耦合。2019 年, Kifle 等^[56]在 $\text{Ho}^{3+}:\text{KDG}(\text{WO}_4)_2$ 晶体中直写圆形包层波导, 并泵浦该 $\text{Ho}^{3+}:\text{KDG}(\text{WO}_4)_2$ 晶体波导, 在 2055 nm 处实现了 67.2% 的斜率效率、输出功率为 212 mW 的激光输出。类光子晶格包层波导一般采用 II 型改性光波导结构, 其在宽频谱范围内具有良好的光约束性能, 并且能有效弥补包层波导存在的难以实现单模输出的缺陷^[57], 2014 年 Jia^[58]等在 Yb:YAG 晶体中直写六边形类光子晶格波导并通

过灵活改变横截面形状制备出 1×2 的光分束器。2017 年, Ren 等^[59]在 Ti:Sapphire 晶体中直写六边形和双六边形的类光子晶格波导并以此制备出 1×2 和 1×4 的分束器。2020 年, 山东大学陈峰教授课题组^[54]在 Nd:YAG 晶体中写入具有包层和六边形类光子晶格形状截面的 S 形弯曲波导与直波导, 并将其作为激光腔体, 制备出 1064 nm 与 1079 nm 的双波长下, 信噪比高达 49 dB 的波导激光。

另一方面, 在晶体中制备的 II 型改性波导仍然存在轨迹形状具有粗糙裂纹, 应力场的包层损伤轨迹引入大量散射损耗, 且改性区域与导波区域不重合的问题, 所以为了实现复杂三维光波导集成器件的快速制备, 研究在晶体内直写低损耗 I 型折射率改性波导同样具有重要意义。但是由于飞秒激光诱导改性区域折射率升高往往存在于玻璃等非晶材料中, 且晶体中单线波导存在热稳定差等问题, 所以目前在晶体内部实现高质量的 I 型折射率改性波导仍存在较大的研究空间。Macdonald 等首次利用多

次扫描飞秒激光直写技术在 ZnSe 多晶中写入纳米波长下, 传播损耗为 1.07 dB/cm 的 I 型近红外传输波导。图 2a 展示了该波导截面的光学显微镜图像以及模场分布^[38]。次年, Rodenas 等报道了在激光晶体写入高折射率对比度的阶跃型波导(如图 2b 所示)。在 1550 nm 波段的传输损耗约为 1.1 dB/cm^[60]。为了获得更高波导性能以及更具普适性的 I 型改性晶体波导制备方案, 2024 年 Chen 等在掺杂 Yb³⁺ 的 YAG 晶体、掺杂 Er³⁺ 的 LuAG 晶体以及未掺杂的钕酸锂晶体中结合狭缝整形和浸油物镜实现了亚微米级精确控制波导的截面形状、尺寸、模场以及折射率分布, 并且通过多次扫描技术制备出了任意截面形状、高空间分辨率(700 nm)、高折射率对比度(10^{-2})、低传播损耗(0.23 dB/cm)且偏振不敏感的 I 型折射率改性波导^[61]。图 2c 中展示了利用该通用的亚微米级精度的多次扫描和密集堆叠技术直写在 123 nJ 的脉冲能量下, 以 1.9 μm 的相邻单线间距扫描 32 次后得到的波导光学显微图像和近场模式分布。

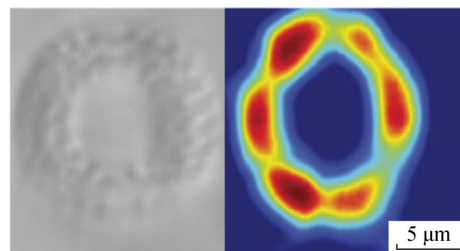
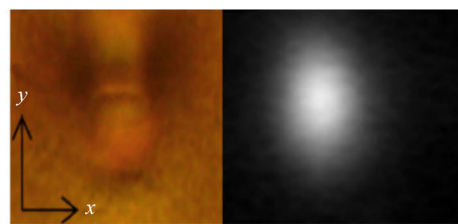
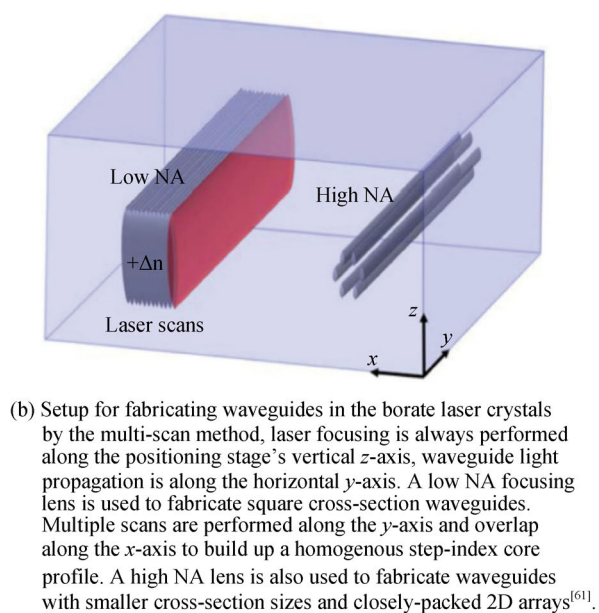


图 2 通过飞秒激光多次扫描技术对晶体波导的横截面形状、尺寸和模场分布进行精细控制

Fig. 2 Fine control for the cross-sectional shape, size, and mode-field distribution of crystal waveguides by the multi-scanning technique

2 可变截面光波导的应用

2.1 有源光波导器件

利用光波导结构可以实现有效的光信号放大与

激光输出, 应用于长距离光纤通信、光纤传感、光存储等领域^[62–66]。表 1 总结了不同材料体系中飞秒激光直写有源波导的配置以及其损耗特性。根据波导的类型, 光波导放大器一般可以分为基于 I 型改性的

波导放大器^[67]、基于 II 型改性的波导放大器^[68]、基于脊形的波导放大器^[69-70]以及可变截面波导放大器。

表 1 有源波导的配置与损耗特性

Table 1 Summary of reported results for waveguide configuration and loss properties of active waveguides

Sample	Waveguide configuration	Working wavelength/nm	Propagation loss/(dB·cm ⁻¹)	Reference
Pr : SrAl ₁₂ O ₁₉	Dual line	634.5	0.16@633 nm	[71]
Pr,Mg : SA1 ₁₂ O ₁₉	Dual line	525.3	0.12@632.8 nm	[72]
Pr : LiYF ₄	Rhombic cladding	604	2.3@632.8 nm	[51]
Ti : sapphire	Dual line	700 – 870	0.65@532 nm	[73]
Ti : sapphire	Dual line	798.5	0.65@798.5 nm	[74]
Yb : YAG	S-curved dual line	1030	-(Guiding loss 0.8dB)@1064 nm-	[75]
Yb : YAG	Y-branch dual line	1030	-(Guiding loss 3.1dB)@969 nm-	[76]
Yb : YAG	Dual line	1030	0.5@633 nm	[77]
Yb : YAG	Dual line	1030	1@969 nm	[78]
Nd : YAG	Double cladding	1030	1.7@633 nm	[55]
Yb : KLuW	Surface cladding	1040	0.61@981.6 nm	[79]
Nd : YAG	Cladding	1064	1.3@808 nm	[80]
Nd : YAG	Ear-like cladding	1064	0.99@1064 nm	[81]
Nd : YAG	Y-branch cladding	1064	1.1@632.8 nm	[82]
Nd : YAG	Optical-lattice like	1064	-(Guiding loss 0.5dB)@1064 nm-	[83]
Nd : YAG	Optical-lattice like	1064	0.7@1064 nm	[58]
Nd : YVO ₄	Buried depressed-cladding	1064	1.1@632.8 nm	[84]
Nd : YVO ₄	Cladding	1064	0.46@1064 nm	[85]
Nd : YAP	Cladding	1064 and 1079	0.15@1064 nm	[86]
Nd : YAP	Optical-lattice like	1072 and 1079	-(Guiding loss 0.52dB)@1064 nm-	[57]
Nd : GdVO ₄	Dual line	1063.6	0.5@780 nm	[87]
Nd : GdVO ₄	Cladding	1064	0.7@632.8 nm	[88]
Nd : GGG	Dual line	1061	2@632.8 nm	[89]
Nd : LuVO ₄	Dual line	1066.4	2@633 nm	[90]
Nd : KWG	Dual line	1065	2@796 nm	[91]
Nd : KWG	Cladding	1067	-(Guiding loss 1.8dB)@1067 nm-	[92]
Er:Yb-doped phosphate glas	Single line	1530 – 1565	0.3@1600 nm	[67]
LiNbO ₃	Single line	1550	2.22@1064 nm	[93]
Tm : YLF	Cladding	1877	0.84@1550 nm	[68]
Tm ³⁺ : KLu(WO ₄) ₂	Surface cladding	1846.8	0.7@830 nm	[94]
Tm ³⁺ : KLu(WO ₄) ₂	Cladding	1841 – 1848	1.6@1840 nm	[95]
Tm : YAG	Cladding	1940	0.77@1047 nm	[96]
Ho : KGd(WO ₄) ₂	Cladding	2055	0.94@2055 nm	[56]
Tm : MgWO ₄	Surface cladding	2080	0.1@1890 nm	[97]
Fe : ZnSe	Cladding	4122	0.16@4122 nm	[98]

Osellame 等首次实现了在 Er³⁺-Yb³⁺共掺杂的磷硅酸盐玻璃中直写基于 Type-I 型改性的光波导放大器^[67]。图 3a 展示了 980 nm 与 976 nm 双端泵浦下, 测量出该波导能实现 1550 nm 处 1.4 dB 的峰值增益。虽然 Er³⁺-Yb³⁺共掺杂磷硅酸盐玻璃具有掺杂浓度高, 发射截面大, 荧光寿命长, 能实现 C 波段

(1530 ~ 1565 nm)的光放大等优势^[99-100], 但是这类稀土离子掺杂磷硅酸盐玻璃存在强烈的吸水性, 导致在玻璃中实现高增益和低材料吸收损耗的基于 I 型改性的光波导仍存在挑战^[101-103]。在磷硅酸盐玻璃中写入基于 II 型改性的光波导放大器也存在波导截面形状不规则, 模场分布不可控等问题。因此,

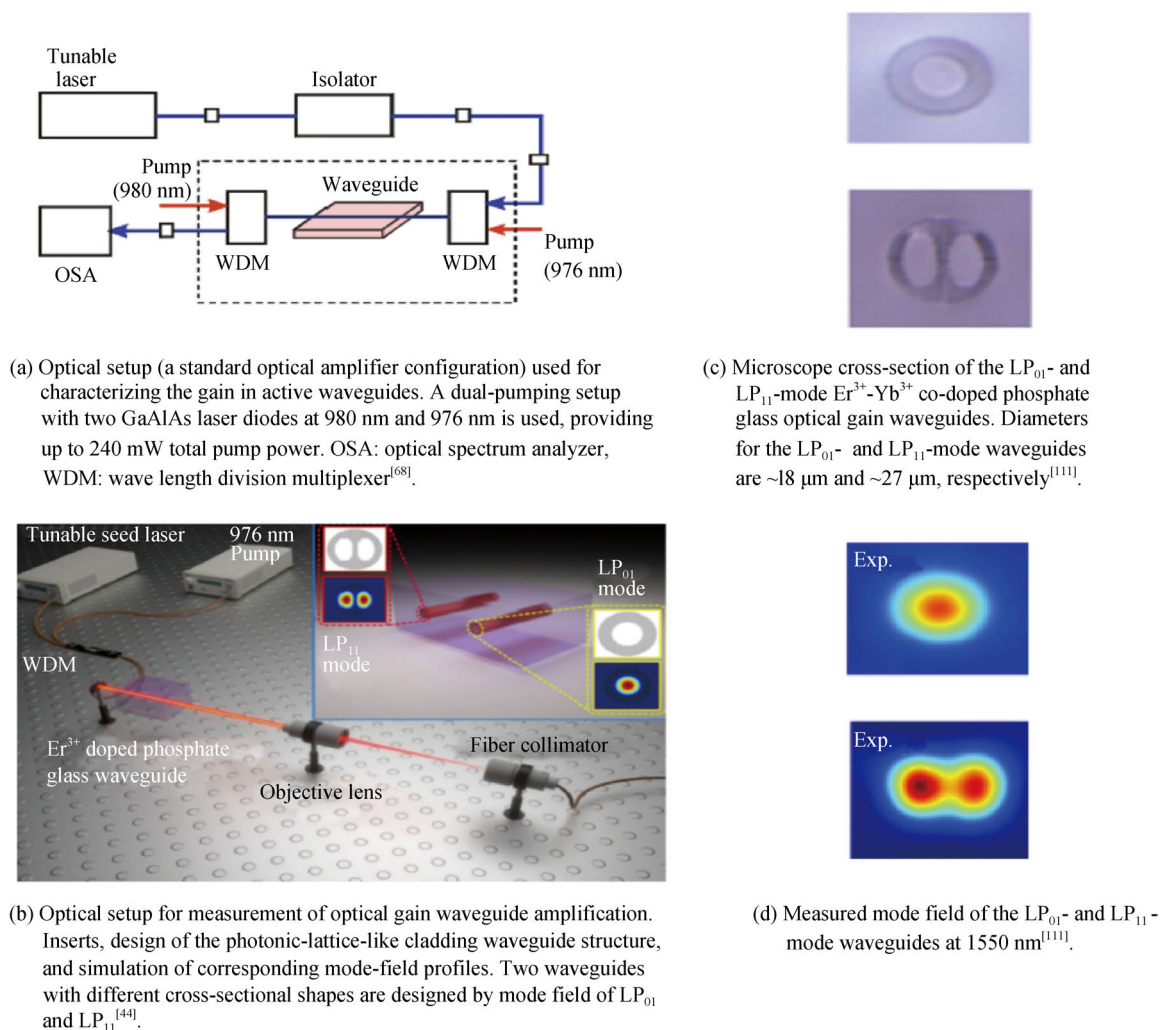


图3 光学增益波导

Fig. 3 Optical gain waveguides

为了在光通信系统中实现更大带宽和更高增益, Sun 等^[44]提出利用改良的飞秒激光多次扫描技术实现可变截面的高阶模式光波导放大器。如图 3b 所示, 以 $0.8 \mu m$ 相邻轨迹间距写入光子晶格包层波导, 成功制备了 LP_{01} 模式与 LP_{11} 模式波导, 并且在 1550 nm 波段插入损耗为 1.88 dB, 开关增益高达 3.52 dB。次年, Sun 等利用二次熔融和脱水技术制备了能抑制水吸收的高质量 Er^{3+} - Yb^{3+} 共掺磷酸盐玻璃, 优化获得插入损耗低至 0.9 dB 的 LP_{01} 模式和 LP_{11} 模式光波导, 其截面显微图像与模场分别如图 3c、图 3d 所示。并获得了迄今为止在 Er^{3+} - Yb^{3+} 共掺玻璃中最高的净增益(7 dB)^[104]。

2.2 无源光波导器件

飞秒激光多次扫描法被广泛应用于在玻璃和晶体等材料中制备光学分束器^[105–107], 实现二维平面上 1 分为 N 和三维空间内 1 分为 N 的分束。2017 年, Ren 等在 Ti:Sapphire 晶体薄片上利用飞秒激光

多次扫描技术, 以 $30 \mu m$ 的相邻单线间距直写基于六边形/双六边形的类光子晶格波导, 并在此基础上设计了 1064 nm 波段分束比为 0.96:1 的 1×2 分束器与分束比为 0.98:0.95:1:0.89 的 1×4 的分束器^[59]。这种方案具有模式转换平滑, 能有效抑制分束损耗等优势。Ajates 等在 $LiNbO_3$ 中多次扫描写入包层波导, 设计了如图 4a 所示的 2 种分束方式, 3D-Y1 为在水平平面(XY)内进行分束且每个 Y 分支在垂直平面(XZ)内发生三维角度变化, 3D-Y2 为首先在分支处发生深度变化, 然后在垂直平面内变换方向, 最后在水平平面内进行分束, 实现了良好的可见光与红外光传输, 但 TE 与 TM 偏振光仍具有较高损耗^[108]。He 等在 BGO 晶体内多次扫描制备 Type-I 型波导以及具有图 4b 所示截面的偏振无关的三维光学分束器^[109], 之后又设计出 $LiNbO_3$ 晶体中基于 II 型改性的 1×2 与 1×3 光子晶格波导光学分束器。图 4c 与图 4d 给出了 1×2 光学分束器的横截面光学

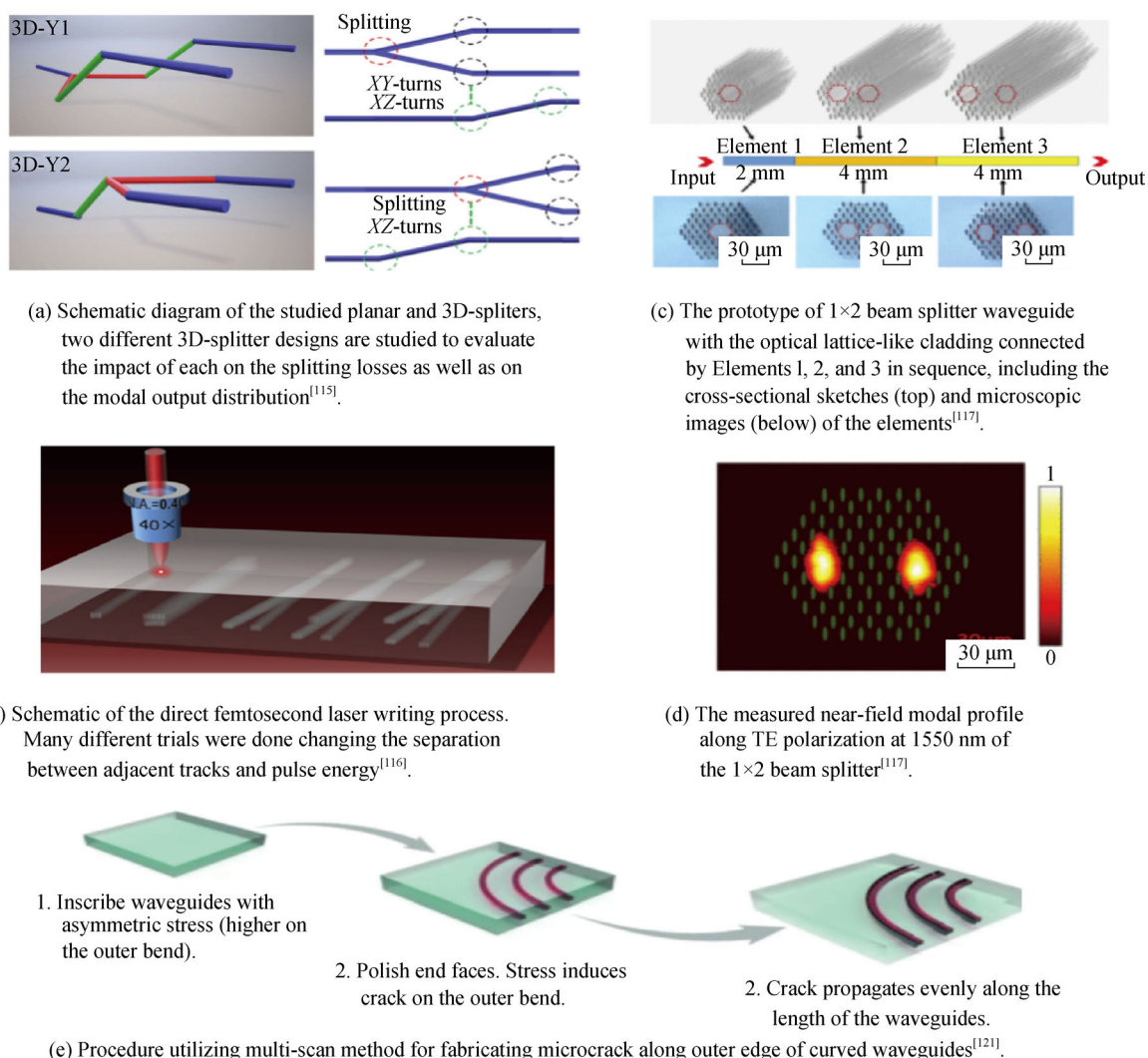


图 4 飞秒激光多次扫描技术制备 $1 \times N$ 分束器
Fig. 4 $1 \times N$ splitters fabricated by the multi-scan method

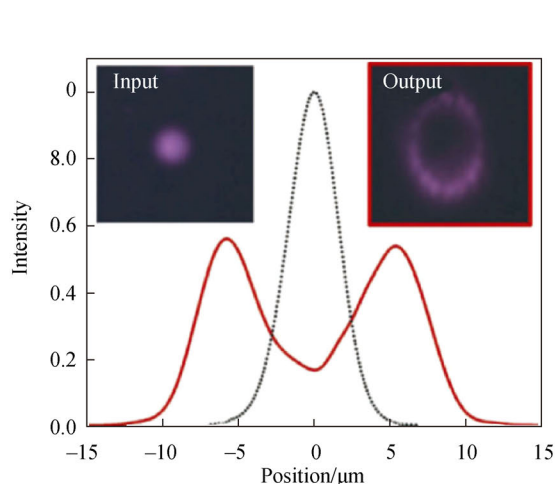
显微图像以及 1550 nm 处 TE 偏振时的模式近场分布^[110]。Li 等归纳了基于不同材料无源光波导的飞秒激光加工参数、波导类型、波导损耗,以及光学分束器等无源器件的性能参数^[111]。此外,在制备光学分束器等具有弯曲波导的器件时,通常存在曲率半径与弯曲损耗呈现负相关,限制了器件的集成度^[112]。由于大曲率弯曲波导的损耗主要源于弯曲半径过大导致波导对光的束缚能力下降,因此飞秒激光多次扫描技术可以通过多次激光修饰增强波导芯层与包层的折射率对比度,同时优化波导截面折射率分布,有助于增强波导对光的束缚能力,进而降低波导的弯曲损耗。基于此, Lee 等在熔融石英中利用多次扫描技术诱导非对称的应力分布,从内侧弯曲边缘直写(如图 4e 所示),制造出具有平滑性、鲁棒性以及非散射截面的裂纹,实现 10 mm 弯曲半径下 1 dB/cm 的损耗^[113]。证明该方案可以有效通过增加

折射率对比度来增强模式约束,从而降低弯曲损耗。这种方案具有制造过程简单有效,结构长期稳定等优点。Li 等则利用飞秒激光多次扫描技术在弯曲波导内部写入紧密排布的修饰线,并且通过改变修饰线的数量、修饰线与波导的中心间隔、写入功率等参数获得 S 型弯曲波导的最优弯曲波导损耗(0.64 dB/cm),为弯曲波导集成提供了一种普遍适用的方法^[114]。

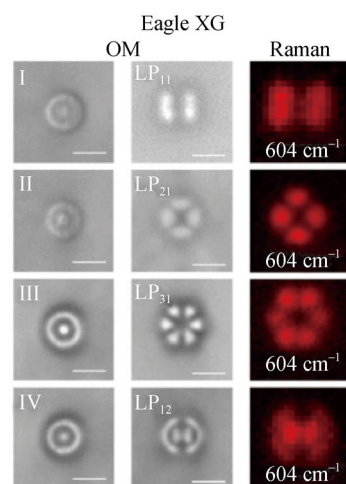
飞秒激光多次扫描技术通过多次扫描精准调控波导截面形状与模式分布,现已成为制备三维模式转换器件的关键技术。相较于二维模式转换器件,其优势在于更易实现与光纤的低耦合损耗连接,以及更便于生成对称的高阶模式^[35, 115]。2022 年, Wang 等^[23]在玻璃中直写类光子晶格波导,波导具有 4 μm 宽度的六边形输入和 8 μm 半径的环形输出,其输入、输出端的模场图像以及近场分布如图 5a

所示, 可以实现从高斯模式到空心光束模式的稳定转换。2024 年, Wang 等继续利用提出的 OCMS 方法实现了在极高空间分辨率下的模式操控, 如图 5b 所示, 利用 OCMS 方法在玻璃芯片上直写截面形状和折射率分布分别与 LP_{11} 、 LP_{21} 、 LP_{31} 、 LP_{12} 模式的强度分布匹配的截面中心对称波导, 可有效将基模 LP_{01} 转换为高阶模, 提升模式纯度^[46]。此外, 飞秒激光多次扫描技术也被用于制备具有超大工作带

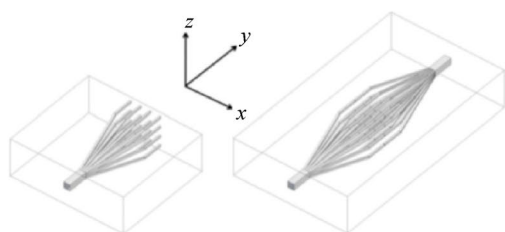
宽、高鲁棒性和低插入损耗的光子灯笼^[116–119]。Thomson^[120]首次实现 16 个单模波导汇聚至 1 根多模波导的光子灯笼, 图 5c 展示了多模到单模波导以及多模到多模的光子灯笼的设计方案。图 5d 是单模波导阵列和多模波导端面的显微图像。通过空间组合多个单模波导构建大横截面积的多模波导, 1539 nm 波段的耦合损耗约为 0.7 dB, 在光子光谱仪与天文望远镜图像的光谱分析等领域具有应用潜力^[121]。



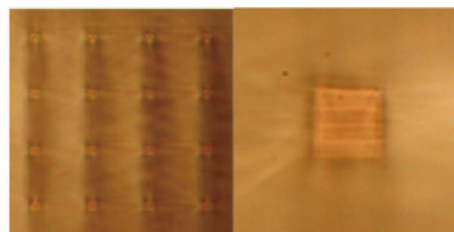
(a) The near-field distributions of photonic lattice-like waveguides. Inserts: mode images of input and output sides. The PLLW is written with scanning speed of 40 $\mu\text{m/s}$ and pulse energy of 175 nJ^[23].



(b) Optical micrographs of four fundamental-mode waveguides(left), four higher-order mode waveguides for LP_{11} , LP_{21} , LP_{31} , and LP_{12} modes (middle) in Eagle XG, as well as Raman mappings of four higher-order mode waveguides (right). Scale bars are 10 μm ^[46].



(c) Schematics of a Multi-mode (MM)-to-Single-mode (SM) integrated photonic lantern (PL) transition (left) and a MM-to-SM-to-MM transition created by inscribing two of the PLs shown in back-to-back(right)^[128].



(d) White light transmission micrographs of the 4 × 4 SM array end of PL (left) and one end of MM (right) are shown to study the characterization of photonic lantern^[128].

图 5 多次扫描技术制备模式控制器件

Fig. 5 Mode controlling devices fabricated by the multi-scan method

3 结论与展望

3.1 结论

基于多次扫描激光直写技术在透明材料中制备光波导已得到广泛应用。该技术通过激光诱导折射率变化的空间叠加效应, 不仅能实现对波导横截面几何对称性的精密调控, 还可同步达成耦合效率优化、传输损耗抑制以及折射率分布的亚微米级空间

调制, 从而为片上模式转换器件等有源和无源光子器件的设计提供了新范式。当前三维集成光子回路产业化进程仍面临 3 大核心挑战:

- 1) 如何减少亚毫米尺度弯曲结构的损耗;
- 2) 如何保持跨毫米级纵深直写的效果;
- 3) 如何制备动态可重构的光子器件。

3.2 展望

未来研究需着重发展自适应波前补偿与多参量

协同调控的新型飞秒激光加工体系, 以突破全玻璃化三维单片集成光子芯片的工程化制备壁垒。

(第二十七届中国科协年会学术论文)

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Direct-Writing Technique of Three-Dimensional Optical Waveguides with Gradient Refractive Index and Arbitrarily Variable Cross-Sections

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Extended Abstract

With the rapid advancement of high-performance optical computing and high-speed optical communication, a demand for more efficient and compact photonic systems has driven the development of three-dimensional photonic integrated circuits (3D PICs). The existing approaches for the fabrication of 3D integrated waveguides primarily involve two methods, *i.e.*, 3D stacking technique and femtosecond laser direct-writing technique. 3D stacked integrated waveguides suffer from limitations such as high cost and fabrication complexity. In contrast, femtosecond laser direct writing (FLDW) technique, which offers advantages in surpassing diffraction limit and providing flexible 3D processing capability, has emerged as a promising technique for high-precision 3D micro-nano fabrication of integrated 3D photonic optical circuits.

Femtosecond laser, characterized by ultrashort pulse width and extremely high peak power, can result in material modifications in focal regions of transparent materials. These modifications are typically categorized into two types, *i.e.*, Type-I and Type-II, corresponding to positive and negative refractive index changes within the material, respectively. 3D optical waveguides can be fabricated in transparent materials by using the two types of modifications. However, despite these impressive capabilities, femtosecond laser direct-writing still faces some challenges like the difficulty of fabricating waveguides with controllable cross-sectional geometries and low propagation losses. These issues are due to spherical aberrations caused by refractive index mismatches between the waveguide and the surrounding air, as well as nonlinear effects that degrade the performance of waveguides. A conventional solution to these problems is beam shaping technologies, *i.e.*, slit beam shaping, astigmatic beam shaping, astigmatic beam shaping and spatial light modulator beam shaping. However, these strategies have drawbacks of large energy loss, complex operation, high transmission loss, and low quality of generated light field, respectively. There is an ongoing need for innovative methods that can overcome these issues.

To address the challenges above, multi-scan laser direct-writing technology gradually becomes a research hotspot in the field of microstructure optical waveguide fabrication. In this approach, the laser trajectory with full positive refractive index is carefully controlled in three-dimensional space, allowing for a more refined modification of the refractive index. The multi-scan method facilitates a precise control over the cross-sectional geometry, refractive index profile, and mode field distribution of waveguides *via* adjusting parameters such as the offset distance between laser scans and the scanning time.

This review first systematically describes the latest research progress on direct-written optical waveguides inside transparent materials by femtosecond laser multiple scanning. General methods for fabricating waveguides with precisely controlled refractive index profiles and well-defined cross-sectional geometries in glass and crystal substrates using the multi-scan strategy are described in

details. This review also focuses on the innovative applications of this technique. The multi-scan technique can be used to fabricate active optical waveguide devices, such as variable cross-section waveguide amplifiers with high gain. It is also utilized to prepare passive optical waveguide devices, including optical beam splitters, 3D mode conversion devices, and photonic lanterns, which can pave a way for applications in the field of integrated quantum optics and astronomical photonics. In addition, this review discusses the key technical challenges currently faced by the 3D integrated photonic circuits from the dimensions of precise control of waveguide cross-sectional morphology, optimization of low-loss curved waveguide structures, and cross-large-depth direct-writing technology, and looks forward to the development trend of realizing all-glass-based three-dimensional photonic chips.

Summary and Prospects Optical waveguides in transparent materials based on the multi-scan laser direct-writing technique are widely employed in the fabrication of three-dimensional integrated devices. The multi-scan laser direct-writing technique enables a precise control over the geometric symmetry of the waveguide cross-sections through the spatial superposition effect of laser-induced refractive index changes. Also, it simultaneously allows for submicron spatial modulation of the refractive index distributions and suppression of transmission losses, thus providing a novel approach for the design of on-chip mode conversion devices. Although the multi-scan laser direct-writing technique has significant advancements in recent years, several core challenges still remain in its practical application and ongoing industrialization. These challenges include a) minimizing losses in submillimeter-scale curved structures, b) maintaining consistent direct writing effects across millimeter-scale depths, and c) enabling the fabrication of dynamically reconfigurable photonic devices. To address these issues, a future research should focus on the development of a next-generation femtosecond laser processing system with adaptive compensation and multi-parameter coordinated control. Such innovations will be critical in overcoming the engineering barriers currently restricting the production of fully glassed, three-dimensional, monolithic integrated photonic chips.

Keywords three-dimensional optical waveguide; femtosecond laser direct-writing; variable cross-section; optical waveguide device