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基于光场调控的飞秒激光直写光波导研究进展（特邀）

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摘　要：飞秒激光直写是一种无掩模、高效、灵活的三维加工技术，可以对材料实现微纳米级加工，已经成为应用最广泛的材料精密加工技术之一。基于光波导的微纳光子器件（如分束器、频率转换器和电光调制器等），不但可以保持块体材料本身的优异特性，还能极大提高器件的性能和集成度，具有块体材料器件所不具备的特点和优势。因此，对集成光波导和光波导器件的研究，一直是集成光学和现代光通信领域的研究热点。利用光场调控技术，对传统的飞秒激光高斯光束进行整形，能够大幅度提升波导加工效率和质量。本文从光束整形出发，综述了整形飞秒激光直写光波导的最新研究进展，并对潜在的几个研究方向进行了展望。

关键词：光场调控；飞秒激光直写；透明材料；光波导；光学器件
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0　引言

飞秒激光直写是材料精密加工领域最重要的技术之一，可以在透明光学材料内部快速高效地制备三维微纳光子结构[1-32]。利用透镜或显微物镜将飞秒激光聚焦到透明材料内部，由于飞秒激光具有超高的峰值功率和超短的脉冲宽度，在焦点附近可以产生多光子吸收、隧穿电离和雪崩击穿等一系列强烈的非线性相互作用，还能够抑制热影响区的形成[1,33]。光波导对光束具有良好的限制和引导作用，激光在光波导中经过一段较长的相互作用距离后，仍然可以保持较高的光强度，这对制备高质量、微型化、多功能的集成光子器件具有十分重要的意义[1,34-37]。1996年，DAVIS K M等利用飞秒激光在玻璃内部成功制备了光波导，这是有关飞秒激光直写光波导的最早报道[38]。从此以后，飞秒激光直写技术被广泛用于玻璃、晶体和光学陶瓷等透明材料中制备三维光波导和光波导器件（如分束器、频率转换器和电光调制器等）[1,39-57]。利用光波导构建的频率转换器等微纳光子器件，性能较好、集成度较高、块体材料自身的优异特性也可以得到很好的保留，具有块体材料器件所不具备的一些特点和优势。因此，对光波导和集成光波导器件的研究，一直是集成光学和现代光通信领域的研究热点。

通过多光子吸收、隧穿电离和雪崩击穿等非线性相互作用过程，飞秒激光在透明材料中可以诱导产生两种改性（折射率改变）：I类改性（激光焦点处折射率升高）和II类改性（激光焦点处折射率降低）[1,58]。在I类改性区域和II类改性区域，材料原有结构均会受到一定程度的破坏，只是I类改性区域的破坏程度相对较小；此外，I类改性区域和II类改性区域的折射率发生相反变化，可能与飞秒激光诱导的材料缺陷类型不同有关，更准确的物理机制有待进一步研究。飞秒激光加工参数（脉冲宽度、脉冲能量和重复频率等）和材料

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固有特性(带隙、硬度和折射率等),都会影响激光焦点处发生的材料改性的类型。一般来说,当飞秒激光单脉冲能量较低时,更容易在材料中诱导产生I类改性;随着单脉冲能量的升高,飞秒激光对材料的损伤逐渐增强,最终导致II类改性出现。因为I类改性区域的材料折射率升高,所以飞秒激光辐照区域即为导波区域。利用I类改性,可以在材料中构建单线波导(仅由一条I类改性区域构成)[43],再结合多重扫描技术(将多条I类改性区域横向紧密排列),可以制备横截面积可控的多线波导结构(调控导波区域的有效折射率大小和分布)[59],对近红外和中红外波段低损耗光波导器件的研制具有重要意义。利用飞秒激光诱导的I类改性,虽然可以在透明材料中方便灵活地构建三维光波导器件,但是,器件的热稳定性相对较差,不适合高温和高功率应用。此外,单线波导横截面呈椭圆形,不利于实现单模传输。II类改性区域的材料折射率降低,在改性区域不能直接形成光波导结构,但可以利用II类改性围成双线波导或包层波导(导波区域位于双线或包层中间)[60-62]。利用双线波导或包层波导构成的光波导器件,具有较好的热稳定性。由于飞秒激光没有直接辐照导波区域,因此块体材料的性质在导波区域可以得到很好的保留,另外,通过调节双线之间的间隔或包层横截面积的大小,不但可以灵活定制特定波长下的低损耗光波导,还可以实现特定波长下的模式调控[63]。利用双线波导和包层波导构建集成光波导器件具有上述诸多优势,但该类波导结构相对复杂,所需加工时间更长。为了提高波导制备的质量和效率,科研工作者将更多的目光聚焦在飞秒激光光束整形技术上[64-66]。

通常利用显微物镜将飞秒激光高斯光束聚焦到透明材料内部,以单点扫描的方式制备光波导结构。传统飞秒激光高斯光束的空间和时间能量分布,不能满足低损耗光波导快速高效制备的加工需求,通过调控飞秒激光光场在空域或时域的能量分布,可以改变飞秒激光直写光波导的横截面形貌以及波导中的模场分布,从而降低波导的耦合损耗和传输损耗,另外,利用整形飞秒激光直写光波导,还可以实现单条波导以及波导阵列的快速制备,从而大幅度提升波导制备的效率[64-66]。因此,利用光场调控技术对飞秒激光高斯光束进行整形,并用于快速高效地制备低损耗的光波导结构,成为近些年来集成光子学领域的一个研究热点。

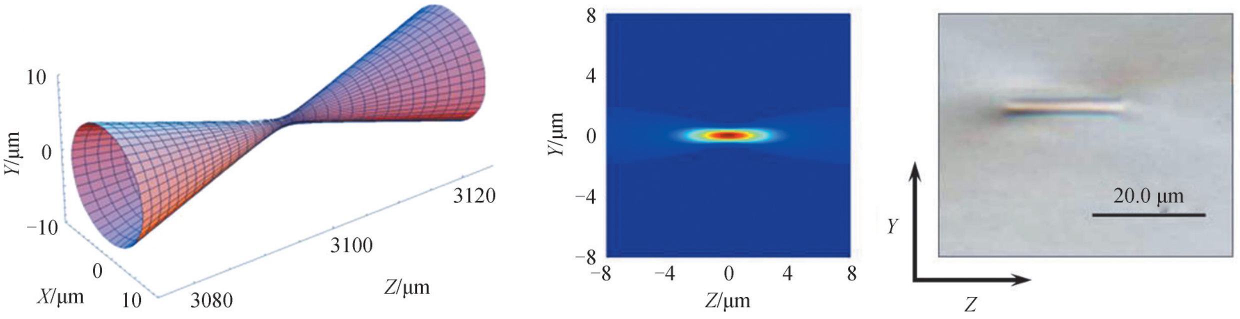
截至目前,国内外已有多篇综述文章总结过飞秒激光直写光波导的研究进展[1,67-69]、飞秒激光光束整形的原理和方法[64]、以及整形飞秒激光在微纳结构制造中的应用[65]。但是,重点介绍整形飞秒激光直写光波导的述评文章相对较少。本文将从飞秒激光光束整形技术出发,简明扼要地介绍整形飞秒激光直写光波导的最新研究进展,并对该领域潜在的几个研究方向进行展望。

1 狭缝光束整形

在传统的飞秒激光直写光波导过程中,通常利用显微物镜将飞秒激光高斯光束聚焦到透明材料内部。然而,在界面处会因为空气折射率和材料折射率的不匹配而产生球差效应(材料折射率越大、物镜数值孔径越大、聚焦深度越深,球差效应越明显),从而引起焦点处飞秒激光光场能量在纵向(激光入射方向)和横向(垂直激光入射方向)分布不均[66],另外,飞秒激光在材料内部产生的自聚焦、自散焦和成丝等非线性光学效应,会使焦点处飞秒激光光场能量在纵向和横向的分布更加不平衡,最终导致材料改性区域的纵向尺寸远大于横向尺寸[65]。为了在最大程度上提高加工灵活性,通常采用横向直写方式(飞秒激光扫描方向与入射方向垂直)制备光波导。然而,改性区域的这种纵向拉长对制备横截面为圆形的光波导结构十分不利。

为了提升光波导横截面和模场分布的圆形对称性,降低光波导的耦合损耗、弯曲损耗和传输损耗,科学家们致力于研究飞秒激光光束整形技术,以便快速高效地制备高性能的光波导和光波导器件。2003年,CHENG Y等[70]提出在物镜前端放置一个衍射狭缝,使狭缝方向平行于飞秒激光横向直写方向,可以制备横截面为近圆形的光波导,这就是后来在飞秒激光微纳加工领域中得到广泛应用的狭缝光束整形技术。

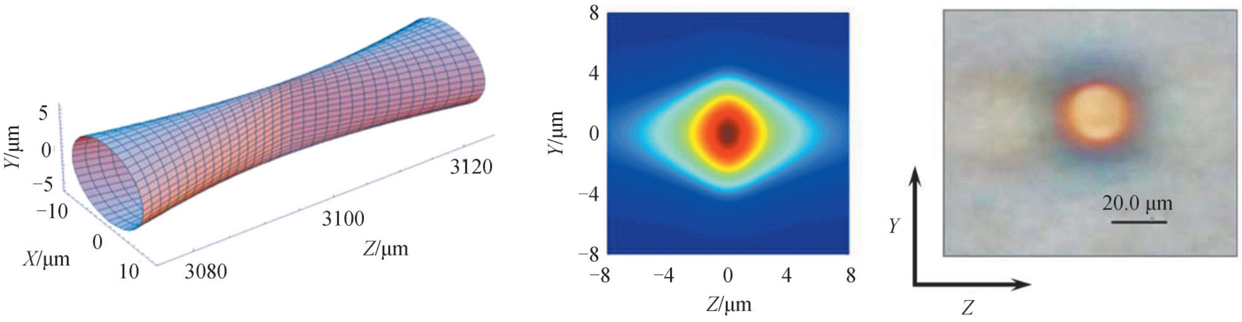
2005年,AMS M等[71]将缝宽为500 μm的狭缝插入显微物镜前端,利用整形后的飞秒激光在磷酸盐玻璃中成功制备了具有圆形横截面的单线波导。该波导能够支持635 nm波长下的单模传输,在1 550 nm波长下的传输损耗低至0.39 dB/cm。图1(a)~(b)分别是未加狭缝时,飞秒激光焦点附近的光束演化情况和能量分布情况;图1(d)~(e)分别是加入狭缝后,飞秒激光焦点附近的光束演化情况和能量分布情况;图1(c)~(d)分别是狭缝整形前后,飞秒激光直写光波导的端面显微镜图像,从图中可以看出:利用狭缝整形技术,能够将飞秒激光直写光波导的横截面由椭圆形变成近圆形,为圆形横截面光波导的制备提供了理论和实验基础。



(a) The beam evolution near the focus of femtosecond laser without slit

(b) The energy distribution of focus without slit

(c) The end-face microscopic image of waveguide without slit



(d) The beam evolution near the focus of femtosecond laser with slit

(e) The energy distribution of focus with slit

(f) The end-face microscopic image of waveguide with slit

图 1　狭缝光束整形与波导制备[71]

Fig. 1　Slit beam shaping and waveguide fabrication[71]

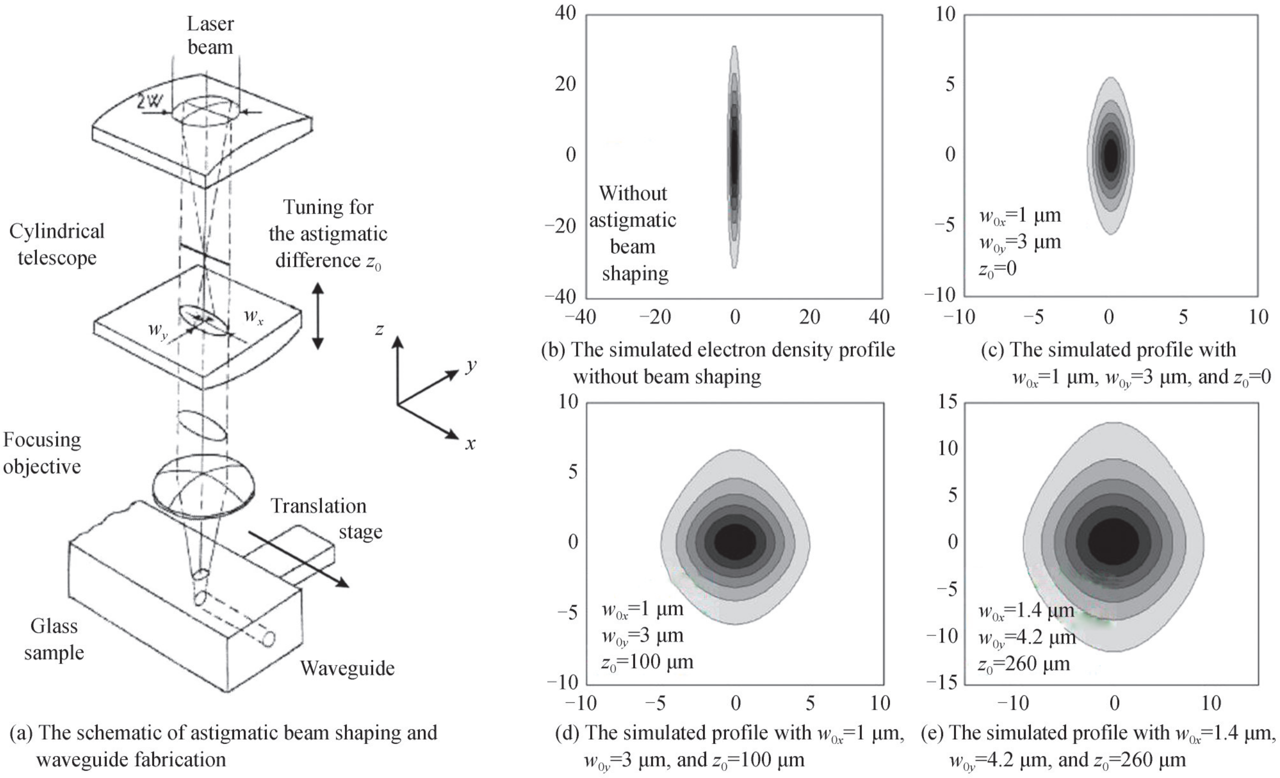
2006年，SOWA S等[72]利用缝宽为400 μm的狭缝对飞秒激光进行整形，在有机玻璃中成功制备了横截面为圆形的单线波导（支持632.8 nm波长下的单模传输）和高性能的定向耦合器（在632.8 nm波长下分光比为1∶1），这对在有机玻璃中制备高性能的集成光波导器件具有重要的指导意义。2009年，ZHANG Y等[73]将缝宽为400 μm的狭缝固定在一个360°电动旋转台上，利用动态狭缝整形技术在石英玻璃中成功制备了横截面为圆形的90°圆弧波导（在波导制备过程中，旋转狭缝使狭缝方向与波导弧的切线保持平行），为利用飞秒激光直写技术在石英玻璃中制备低损耗的三维光波导结构提供了技术支撑。2009年，MARSHALL G D等[74]利用缝宽为520 μm的狭缝对飞秒激光进行整形，在石英玻璃中制备了圆形横截面单线波导，并用于构建定向耦合器，首次成功实现了基于该波导平台的三光子量子干涉，为狭缝整形飞秒激光直写技术在集成量子光子学领域的广泛应用奠定了基础。2011年，DHARMADHIKARI J A等[75]利用缝宽为500 μm的狭缝对飞秒激光整形，并用于制备硼硅酸盐玻璃中的单线波导，该波导在635 nm波长下的传输损耗约为0.5 dB/cm。2021年，ROLDÁN-VARONA P等[76]利用缝宽为500 μm的狭缝对飞秒激光进行整形，首次在光纤内部成功制备了具有圆形横截面的包层光波导（在633 nm波长下的传输损耗约为0.21 dB/cm），为微型光学传感器的制造提供了可能。

狭缝光束整形简单易操作，为飞秒激光直写具有圆形横截面的光波导提供了一个切实可行的解决方案，对优化波导模场分布和降低波导传输损耗都十分有效。狭缝光束整形已相对成熟，利用该技术已经在多种玻璃材料中成功制备了低损耗的光波导结构（传输损耗<0.5 dB/cm），但是，此项技术在晶体波导制备方面应用较少。狭缝不可避免地会造成大部分飞秒激光能量损失，这是狭缝整形技术的一个缺点。

2　像散光束整形

在显微物镜前放置一个像散柱面望远镜，利用像散光束整形技术对飞秒激光进行整形，也可以在透明材料中制备横截面为圆形的光波导[77-78]。图2（a）为像散光束整形和波导制备的示意图，图2（b）为模拟的没有经过像散光束整形的飞秒激光焦点处的电子密度分布图，图2（c）~（e）分别是在不同像散光束整形参数下模拟的飞秒激光焦点处的电子密度分布图。从图2（b）~（e）中可以看出：利用像散光束整形技术，可以实现

飞秒激光焦点处能量的近圆形分布，另外，通过操控像散差 z_0，不但可以提升飞秒激光焦点处能量分布的圆形对称性，还可以改变该能量分布区域的面积大小。



(a) The schematic of astigmatic beam shaping and waveguide fabrication

(b) The simulated electron density profile without beam shaping

(c) The simulated profile with w_{0x}=1 μm, w_{0y}=3 μm, and z_0=0

(d) The simulated profile with w_{0x}=1 μm, w_{0y}=3 μm, and z_0=100 μm

(e) The simulated profile with w_{0x}=1.4 μm, w_{0y}=4.2 μm, and z_0=260 μm

图 2　像散光束整形与波导制备[77-78]

Fig. 2　Astigmatic beam shaping and waveguide fabrication[77-78]

2002年，CERULLO G等[77]首次提出了像散光束整形技术，并用于飞秒激光整形，2003年，他们进一步发展了像散光束整形技术[78]，利用整形飞秒激光在铒镱共掺磷酸盐玻璃中制备了具有圆形横截面的单线波导（支持1.5 μm波长下的单模传输），该波导在1534 nm波长下的传输损耗约为0.25 dB/cm、内部增益约为1.4 dB。2016年，BÉRUBÉ J P等[79]利用像散光束整形后的飞秒激光，在几种硅酸盐玻璃的近表面制备了高折射率对比度的单线波导（波导横截面呈现近圆形分布），可以支持405 nm波长下的单模传输，该工作为利用飞秒激光直写技术在玻璃近表面制备新型的集成光子器件开辟了道路。2017年，他们又利用像散光束整形技术对飞秒激光进行整形[80]，在钡镓锗酸盐玻璃中制备了具有近圆形横截面的单线波导，该波导可以支持2.78 μm波长下的单模传输（传输损耗约为0.5 dB/cm），该工作对飞秒激光直写中红外波段的低损耗光波导器件具有重要意义。2019年，WANG C Y等[81]利用像散光束整形后的飞秒激光，在石英玻璃内部制备了旋转偏振定向耦合器，该波导器件在光通信和量子信息处理等方面具有重要的潜在应用价值。

经过近20年的发展，像散光束整形技术已趋于成熟，利用该技术也可以将玻璃波导的传输损耗降低到0.5 dB/cm以下，此项光束整形技术同样适用于低损耗晶体光波导的制备。当制备弯曲光波导及相关波导器件时，在飞秒激光直写过程中，狭缝光束整形和像散光束整形需要分别动态调整狭缝的方向和柱面透镜对的方向，加工过程将会变得非常复杂。正是由于这种较高的技术复杂性，限制了狭缝光束整形技术和像散光束整形技术在飞秒激光直写光波导方面的进一步应用。

3　可变形镜光束整形

利用一个二维可变形镜对飞秒激光整形，也可以在透明光学材料中制备横截面为圆形的光波导[82]。图3为可变形镜光束整形与波导制备的示意图。图3中，利用二维可变形镜对飞秒激光只在一个轴向进行聚焦，使飞秒激光在进入显微物镜之前的光强呈线状分布，从而能够在透明材料中制备横截面接近圆形的光

波导结构。2008年，THOMSON R R等[82]首次提出了可变形镜光束整形技术，他们通过调节可变形镜的曲率来调控飞秒激光焦点处的能量分布，成功在钠钙硅酸盐玻璃中制备了横截面接近圆形的单线波导，该波导支持1.55 μm波长下的单模传输，传输损耗约为1.5 dB/cm。

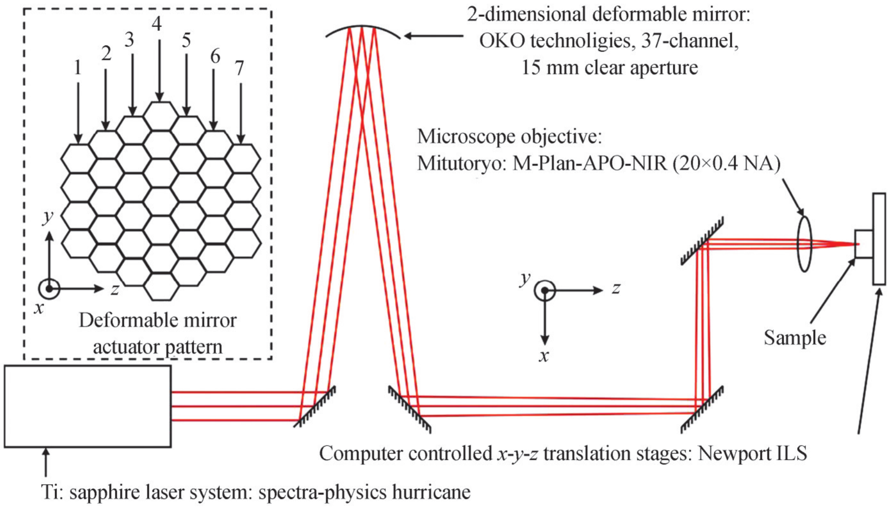


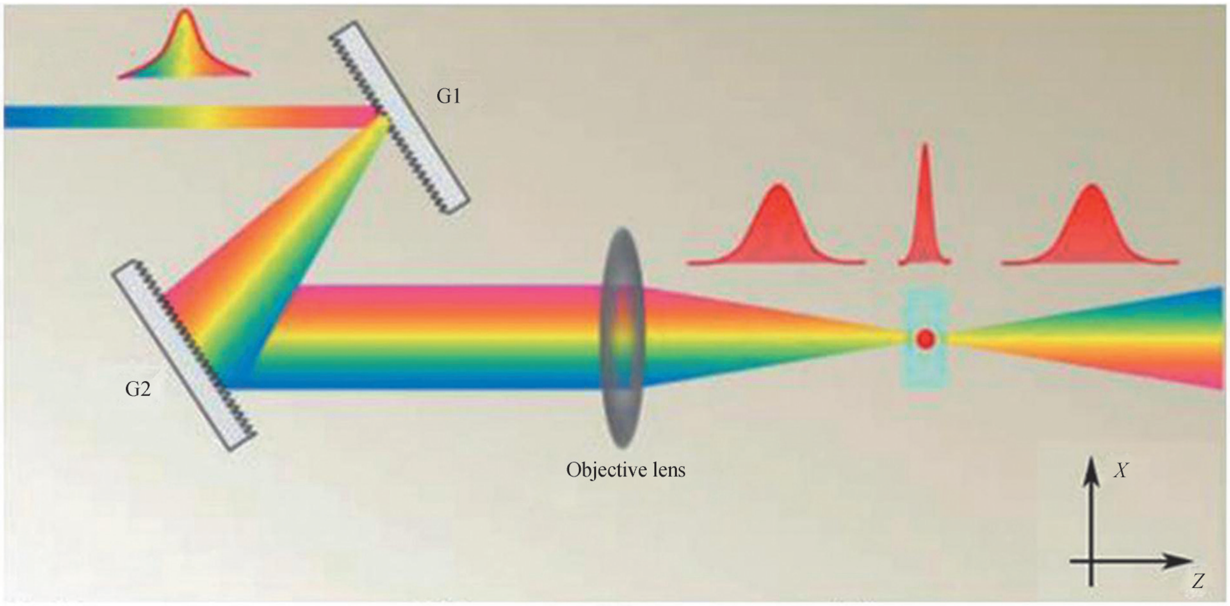
图3　可变形镜光束整形与波导制备[82]

Fig. 3　Deformable-mirror beam shaping and waveguide fabrication[82]

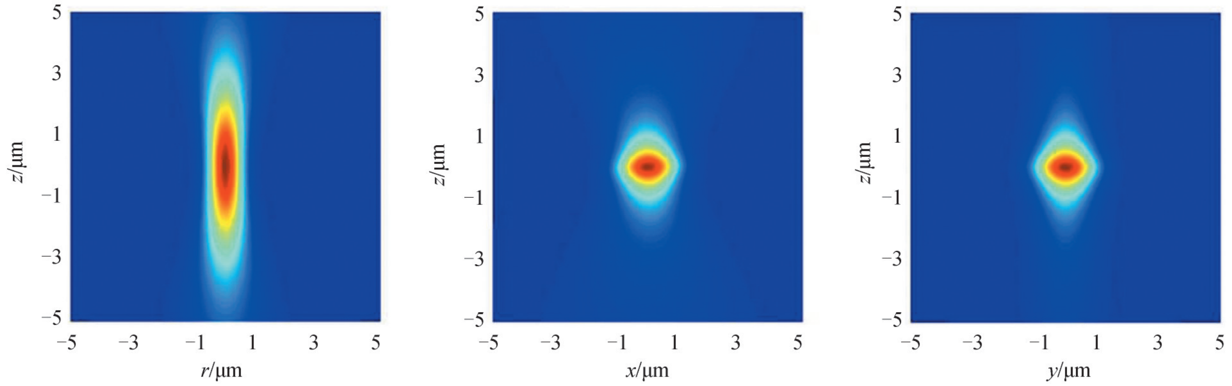
可变形镜光束整形技术可以实现与狭缝光束整形技术类似的功能。与狭缝光束整形技术相比，在飞秒激光直写过程中利用可变形镜光束整形技术，可以灵活地操控显微物镜之前线状焦点的宽度和方向，对圆形横截面光波导结构的快速制备具有重要意义。该技术可以用于降低玻璃波导和晶体波导的传输损耗，然而目前所能实现的最小传输损耗为1.5 dB/cm，距离实用化的目标（<0.5 dB/cm）还有一段距离。

4　时空域协同光束整形

在飞秒激光时空域协同光束整形技术中，只有焦点处飞秒激光的脉冲宽度最短，另外，通过定制沿激光传输方向的脉冲序列，可以在时域上调控焦点处飞秒激光的脉冲宽度，因而利用该技术能够在透明光学材料中实现三维各向同性加工[64，66]。图4（a）所示为飞秒激光时空域协同光束整形的示意图，图4（b）是模拟的没有经过时空域协同光束整形的飞秒激光焦点处的强度分布，图4（c）～（d）是模拟的经过时空域协同光束



(a) The schematic of simultaneous spatiotemporal focusing



(b) The simulated intensity distribution without beam shaping

(c) The simulated intensity distribution in the *ZX* plane

(d) The simulated intensity distribution in the *ZY* plane

图4　时空域协同光束整形技术[66,83]

Fig. 4　Simultaneous spatiotemporal focusing[66,83]

整形的飞秒激光焦点处的强度分布，分别对应 *XZ* 面和 *YZ* 面的情况。在飞秒激光进入显微物镜之前，利用一对平行光栅把飞秒激光光谱在空域上连续分开（光栅对会引入负啁啾，需要对飞秒激光进行正啁啾补偿），经过显微物镜汇聚之后，不同频率的脉冲又组合成新的飞秒激光脉冲。因为光束各频率分量的空间重叠只发生在飞秒激光焦点附近，所以会出现时域聚焦（实际就是在焦点重回锁模状态），这就导致此时飞秒激光脉冲宽度最短、峰值强度最高[64–66]。

2005年，ZHU G H 等[84]最先提出了飞秒激光时空域协同光束整形技术，2010年，HE F 等[83]进一步发展了该技术，利用整形飞秒激光（辅以湿法刻蚀）在石英玻璃中成功制备了横截面为圆形的中空微流体通道。2018年，WANG P 等[85]通过色散元件将初始飞秒激光的脉冲宽度展宽至大约几十皮秒，基于飞秒激光时空域协同光束整形技术，可以几乎不受球差影响地在石英玻璃表面以下250 μm～9 mm的区域内诱导横截面为圆形的改性区域，为制备大纵向尺寸的三维微纳光子结构提供了技术支撑，在集成光子学和微流控光学等领域将会有更广泛的应用。

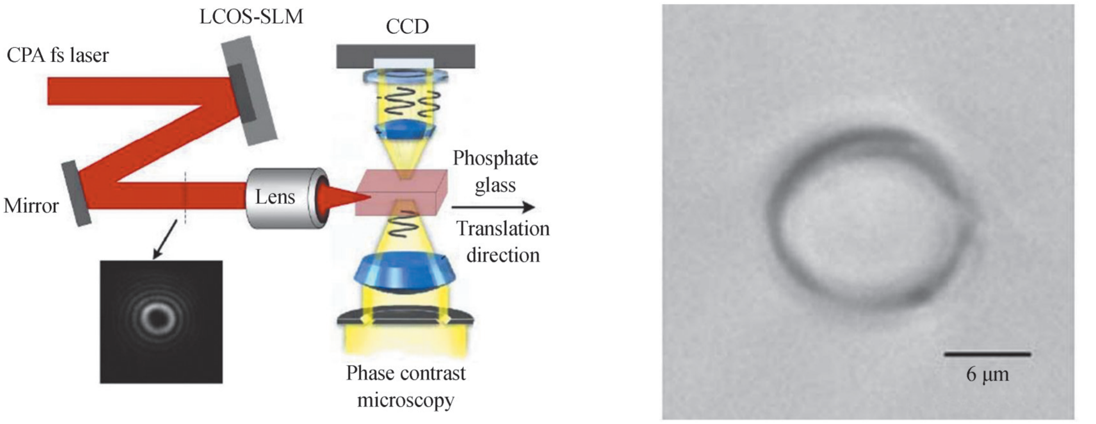
飞秒激光时空域协同光束整形技术的优点是：超短脉冲只在焦平面形成，能够大幅度削弱一些非线性副作用，对实现三维各向同性加工具有重要意义。但是，截至目前，飞秒激光时空域协同光束整形技术仍未被用于制备三维光波导结构。随着研究的进一步深入，飞秒激光时空域协同光束整形技术在制备低损耗玻璃波导和晶体波导方面有望得到广泛的应用。

5　空间光调制器光束整形

空间光调制器是一种在外部信号控制下，可以对入射激光的振幅、相位和偏振等参数进行动态调控的光学元件，空间光调制器光束整形具有效率高、质量好和易操作等特点[86]。将空间光调制器光束整形技术引入飞秒激光微纳加工领域，通过合理设计加工光路和调整加工参数，可以按需改变飞秒激光聚焦区域的光场强度分布，这对调控飞秒激光直写光波导的横截面形貌和提升光波导制备的效率都具有重要的实用价值。

2008年，MAUCLAIR C 等[87]利用空间光调制器对飞秒激光脉冲进行时空域自适应调控（动态波前矫正技术），当利用飞秒激光在硼硅酸盐玻璃中进行光波导直写时，球差补偿与飞秒激光直写同步（动态补偿球差），因此，该技术可以几乎不受球差影响地在材料不同深度处制备横截面为圆形的三维光波导结构。2012年，LONG X 等[88]利用空间光调制器将飞秒激光高斯光束整形为空心激光束，在磷酸盐玻璃中实现了包层光波导的单步制备，这是利用飞秒激光空心光束在磷酸盐玻璃中快速单步制备包层波导的最早报道，图5（a）为利用空间光调制器将飞秒激光高斯光束整形为空心激光束的示意图，图5（b）为包层波导端面的光学显微镜图像。2012年，SALTER P S 等[89]利用空间光调制器对飞秒激光进行自适应狭缝光束整形，在石英玻璃中制备了横截面接近圆形的单线波导，该波导可以支持825 nm波长下的单模传输（传输损耗小于

0.4 dB/cm），这项工作在制备弯曲光波导、布拉格光栅波导和模式转换器等方面具有重要的潜在应用价值。2016 年，HUANG L 等[90]把空间光调制器引入飞秒激光加工系统中，以实现动态的光束整形和球差矫正，该技术可以用于在玻璃表面以下＞1 mm 的深度范围内制备横截面呈圆形分布的单线波导（可以支持 630 nm 波长下的单模传输）。



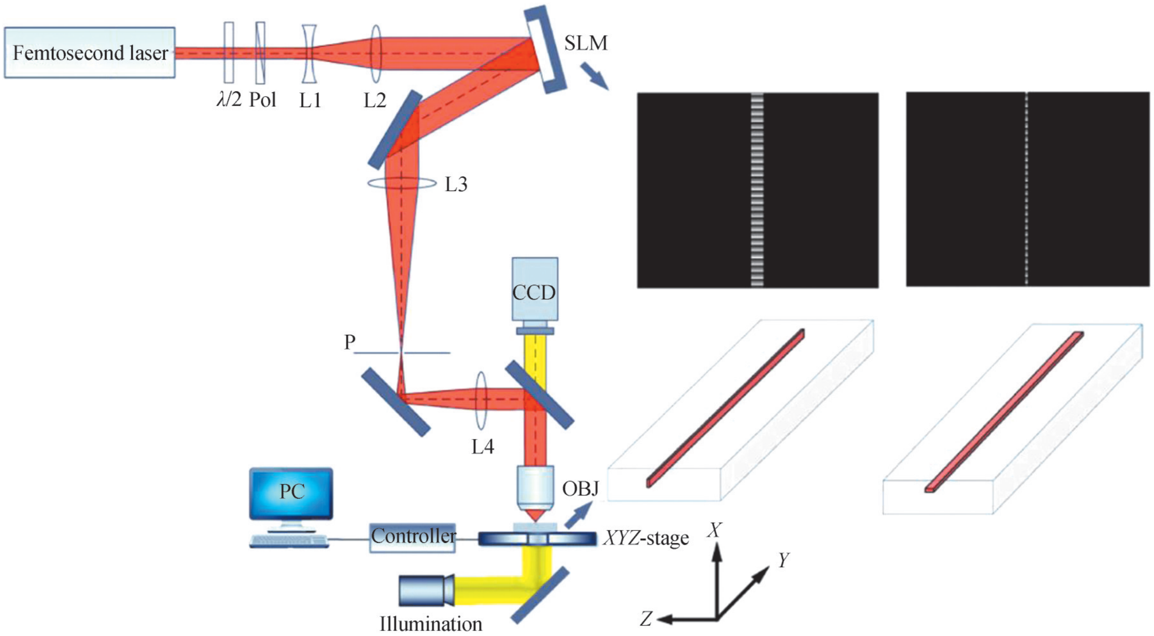
(a) The schematic of focused femtosecond hollow beam produced with a spatial light modulator

(b) The end-face microscopic image of depressed-cladding waveguide

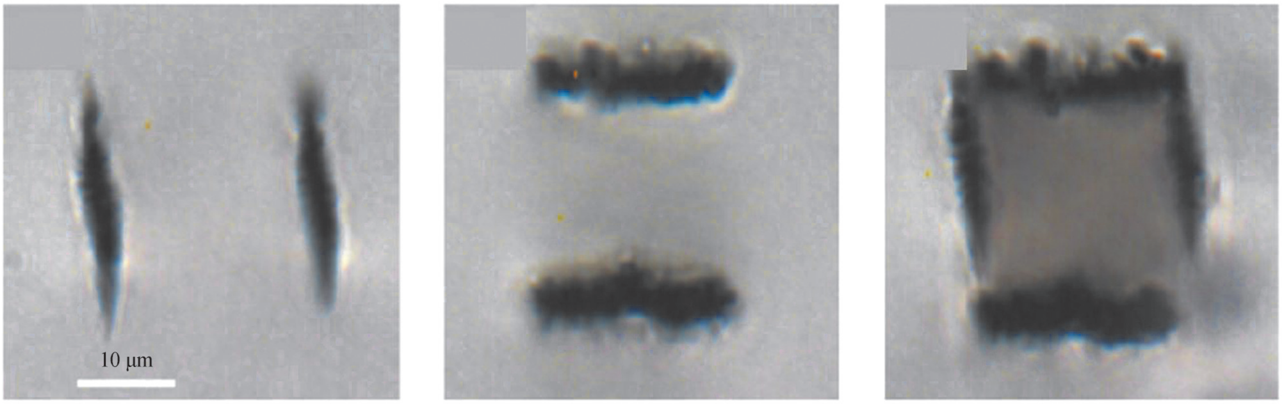
图 5　飞秒激光空心光束产生与波导制备[88]

Fig. 5　The generation of focused femtosecond hollow beam and waveguide fabrication[88]

2016 年，LIAO Y 等[91]利用空间光调制器对飞秒激光进行狭缝光束整形（通过设置空间光调制器上狭缝的宽度可以动态调控飞秒激光焦点处的能量分布），在精密电动位移台的配合下，只需将两种整形后的飞秒激光在氟化物玻璃中各扫描两次，便可以快速加工出“口字型”包层波导。同年，他们利用该技术在铌酸锂晶体中成功制备了双线波导、垂直双线波导和“口字型”包层波导[92]，图 6（a）所示为利用空间光调制器对飞秒激光进行狭缝光束整形的示意图。图 6（b）～（d）分别是铌酸锂双线波导、垂直双线波导和“口字型”包层波导的端面显微镜图像。2017 年，他们又基于该技术（辅以球差矫正）在铌酸锂晶体表面以下 1.4 mm 深度处制备了“口字型”包层波导（能够支持 1 550 nm 波长下的单模传输且与偏振方向无关）[93]，这项加工技术在制备大规模三维光波导结构方面具有广阔的应用前景。



(a) The schematic of slit beam shaping produced with a spatial light modulator

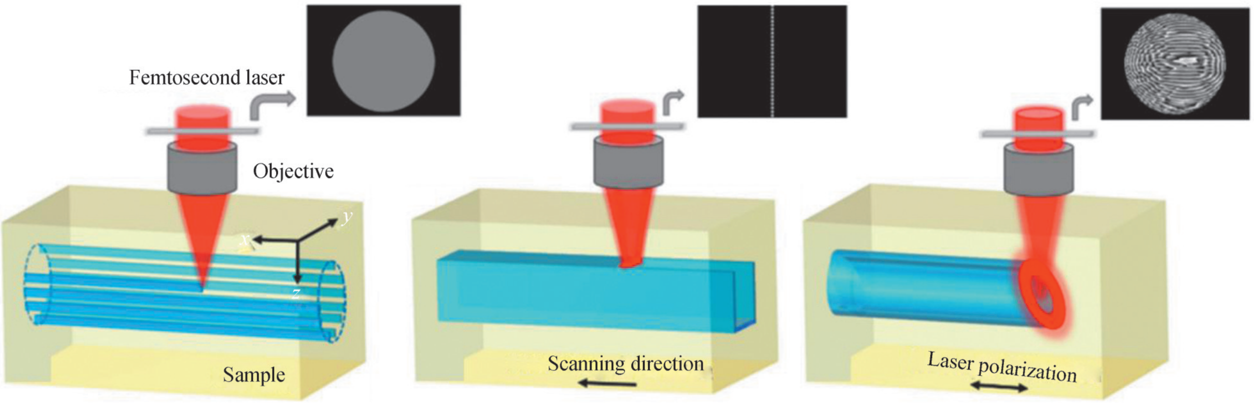


(b) The end-face image of dual-line waveguide
(c) The end-face image of vertical-dual-line waveguide
(d) The end-face image of depressed-cladding waveguide

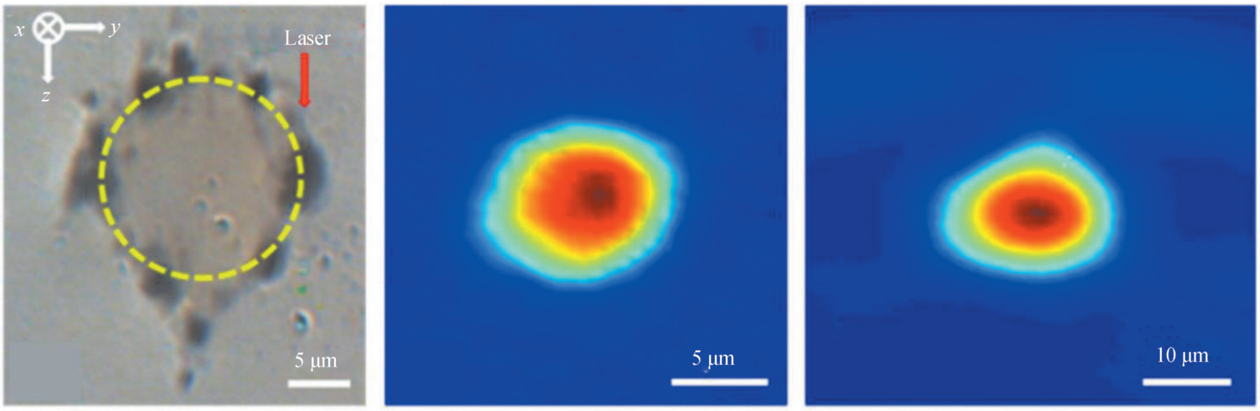
图 6 基于空间光调制器的狭缝光束整形和波导制备[92]

Fig. 6 The slit beam shaping based on spatial light modulator and waveguide fabrication[92]

2017年，ZHANG Q等[94]利用空间光调制器，将飞秒激光高斯光束整形为具有环形强度分布的激光束，在氟化物玻璃中实现了圆形包层光波导的单步快速制备。图7(c)所示为利用具有连续环形焦场的飞秒激光制备的圆形包层波导的示意图，与利用飞秒激光直写的多条平行线围成圆形包层波导(见图7(a))和利用狭缝光束整形后的飞秒激光制备“口字型”包层波导(见图7(b))两种技术相比，该技术能够在透明光学材料内部更加快速高效地制备包层光波导结构，另外，该技术是采用一种收敛性较好的加权Yang-Gu算法来设



(a) The waveguide composed of dozens of parallel lines
(b) The waveguide written with slit beam shaping
(c) The waveguide written with ring-shaped focal field



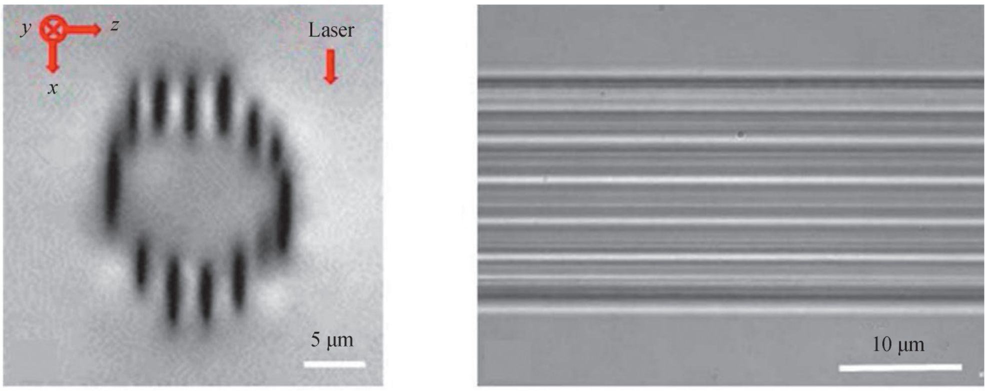
(d) The end-face microscopic image of waveguide written with ring-shaped focal field
(e) The near-field intensity distribution image of waveguide at 785 nm
(f) The near-field intensity distribution image of waveguide at 1550 nm

图 7 包层波导制备与表征[94]

Fig. 7 The fabrication and characterization of depressed-cladding waveguide[94]

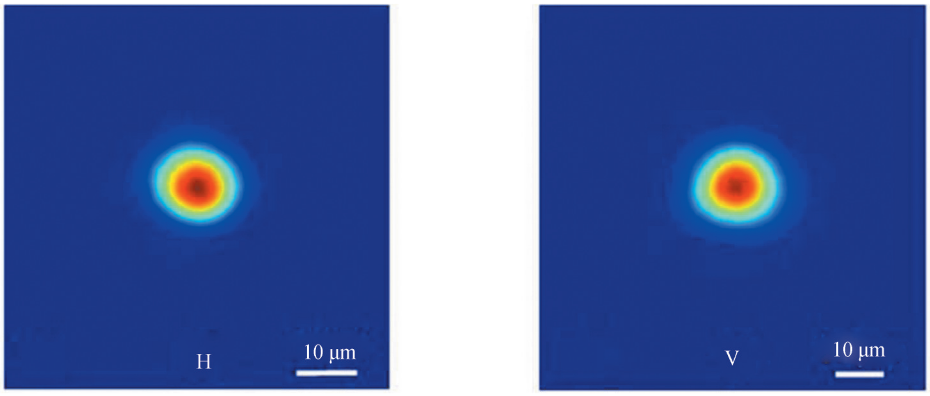
计相位掩模，从而得到具有连续环形焦场的飞秒激光，不同于2012年LONG X等[88]提出的利用飞秒激光空心激光束（高阶无衍射贝塞尔光束）单步制备包层波导的方法。图7(d)是利用图7(c)中环形焦场飞秒激光加工技术制备的包层波导的端面显微镜图像，图7(e)～(f)分别是包层波导在785 nm和1550 nm波长下的近场强度分布图（均为单模）。

2019年，他们又基于该技术，利用具有离散环形焦场的飞秒激光，在铌酸锂晶体内部制备了圆形包层波导[95]，图8(a)～(b)分别是该包层波导的端面显微镜图像和上表面显微镜图像，图8(c)～(d)分别是包层波导在1 550 nm波长下沿H偏振和V偏振的近场强度分布图（均为单模）。作为一项应用，他们利用该技术在铌酸锂晶体内部制备了基于圆形包层光波导的高性能定向耦合器。该工作为在晶体内部快速高效地制备基于包层光波导的复杂光子器件铺平了道路。



(a) The end-face microscopic image of waveguide

(b) The top view of waveguide



(c) The near-field intensity distribution image of waveguide at 1550 nm along H polarization

(d) The near-field intensity distribution image of waveguide at 1550 nm along V polarization

图8 利用具有离散环形焦场的飞秒激光制备的铌酸锂包层波导的显微镜图和近场强度分布图[95]

Fig. 8 The microscopic images and near-field intensity distribution images of depressed-cladding waveguide written by femtosecond laser with discrete ring-shaped focal field[95]

2021年，LI Z Z等[96]利用空间光调制器，将一个飞秒激光焦点调整为多焦点阵列，通过改变焦点阵列中子焦点彼此之间的距离和排列，可以方便灵活地调控飞秒激光直写光波导的横截面形貌，图9所示为利用多焦点飞秒激光进行光波导直写的示意图。该技术无需任何复杂的球差补偿算法，只需使用一个空间光相位调制器，就可以在透明光学材料中快速高效地制备横截面为圆形的三维光波导结构，对多功能集成光子器件的发展将会起到积极的促进作用。

利用空间光调制器对飞秒激光整形，具有效率高、质量好和易操作等特点。基于空间光调制器光束整形技术，可以在玻璃、晶体和光学陶瓷等透明材料中快速高效地制备低损耗（<0.5 dB/cm）光波导结构，具有很强的实用性。

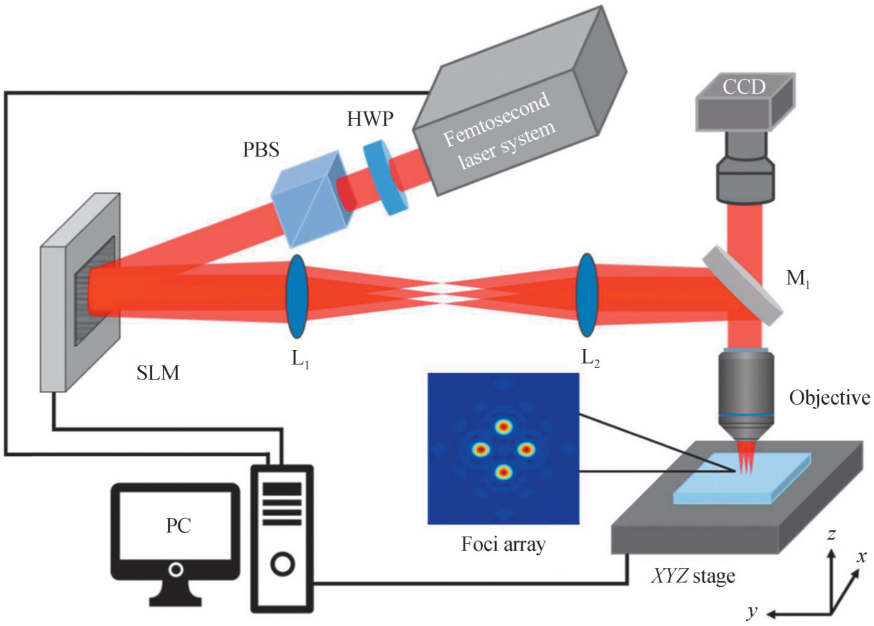


图 9　飞秒激光多焦点直写示意图[96]

Fig. 9　The schematic of femtosecond-laser multi-foci direct writing[96]

6　总结与展望

利用光束整形技术对飞秒激光焦点处的光场强度分布进行调控，可以提升飞秒激光直写光波导的质量和效率，对构建高性能的三维光波导器件具有重要意义。在整形飞秒激光直写光波导领域，狭缝光束整形简单易操作，可以有效提升光波导横截面的圆形对称性，但也不可避免地会损失大部分飞秒激光能量，像散光束整形能够实现飞秒激光焦点处能量的近圆形分布，可以使光波导横截面的纵向拉伸得到有效改善，但当利用该技术制备弯曲光波导及相关波导器件时，则需要动态调整柱面透镜对的方向，这使得加工过程变得非常复杂。

可变形镜光束整形可以实现与狭缝光束整形类似的功能，该技术克服了狭缝光束整形中能量损失大和加工灵活性差等问题，可以灵活地操控显微物镜之前线状焦点的宽度和方向，对圆形横截面光波导结构的快速制备具有重要意义。另外，利用飞秒激光时空域协同光束整形技术，也可以实现三维各向同性加工，能够大幅度削弱一些非线性副作用。截至目前，基于上述两种飞秒激光光束整形技术进行三维光波导结构制备的工作相对较少。在不久的将来，该领域可能会有更多更优秀的研究成果陆续涌现出来。

当利用飞秒激光直写技术制备光波导时，借助空间光调制器对飞秒激光高斯光束进行整形，不但可以有效改善光波导横截面的纵向拉伸和光波导模场分布的对称性，还可以在直写过程中对焦点处的激光能量分布进行动态调控，这对于复杂三维光波导器件的快速高效制备具有重要的应用价值。基于空间光调制器的飞秒激光直写技术种类繁多，已经在集成光学和非线性光学等领域取得了许多令人瞩目的成就。可以预见，该技术将会持续推动集成光子器件向前发展和进步。然而，受空间光调制器自身参数（如像素个数、刷新频率和分辨率等）的限制，所生成的光场的质量还有待提高。研发高质量的空间光调制器，并用于飞秒激光光束整形，对光波导器件性能的提升有重要意义，这也是飞秒激光微纳加工领域一个重要的研究方向。

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Research Advances of Optical Waveguides by Light-manipulation Based Femtosecond Laser Writing (Invited)

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Abstract: Integrated optical circuits play an essential role in the field of optical communication, by which the high-speed processing and transmitting of optical signals can be realized. Optical waveguide, in which the light will be confined into a micron or submicron volume for non-diffraction propagation, is one of the most importantly basic components in integrated optical circuits. The low-loss optical waveguides can be applied to fabricate high-performance photonic devices, e.g., beam splitters, frequency converters, and waveguide lasers. Hence, the fabrication of low-loss optical waveguides is of great significance to many applications in integrated optics and quantum photonics. The optical waveguides in transparent materials can be produced by ion exchange, ion implantation, and Ti-indiffusion. Nevertheless, these waveguides are limited to a 2D planar geometry. The 3D optical waveguides could be fabricated by femtosecond laser direct writing. Femtosecond laser direct writing is a maskless, efficient, and flexible 3D fabrication technique, which has become one of the most widely used techniques for precision machining of materials. The femtosecond laser possesses ultrashort pulse width and extremely high peak intensity, which could lead to the suppression of heat-affected zones and the appearance of nonlinear interactions (e. g., multiphoton absorption, tunneling ionization, and avalanche ionization), respectively. The microscopic objective is often utilized to focus NIR femtosecond laser into transparent materials, resulting in material modifications in focal regions. The material modifications can be classified into two types: Type-I modification and Type-II modification. The refractive index change is positive in the areas of Type-I modification, and the refractive index change is negative in the areas of Type-II modification. By using these two types of modifications, the single-line waveguide, dual-line waveguide, vertical-dual-line waveguide, multi-line waveguide, and depressed-cladding waveguide have been fabricated in transparent materials (e. g., glasses and crystals). In the past 20 years, a variety of photonic devices have been produced with femtosecond-laser-written optical waveguides, such as waveguide arrays, electro-optic modulators, and directional couplers. It can be anticipated that the novel, multi-functional, and high-efficient waveguide-based photonic devices will be created in succession with the in-depth study on laser-matter interactions. Although femtosecond laser direct writing has made a series of achievements in waveguide fabrication, there are still some challenges to rapidly produce low-loss optical waveguide with circular cross-section, due to spherical aberration at the interface caused by refractive index mismatch. In order to improve the waveguide quality and fabrication efficiency, the researchers are dedicated to develop the femtosecond laser writing technique based on light-manipulation. First, slit beam shaping. In this technique, a slit is inserted before the microscopic objective (slit orientation is parallel to laser-scanning direction), by which the aspect ratio of femtosecond-laser-induced track can be greatly reduced. It has been reported that the propagation loss of waveguide written by this processing technique can be reduced to less than 0.5 dB/cm, which is suitable to construct high-performance photonic devices. The slit beam shaping is an effective technique to improve the performance of femtosecond-laser-written waveguides. However, the existence of slit will inevitably result in a lot of loss of femtosecond laser energy, which is a disadvantage of slit beam shaping. Second, astigmatic beam shaping. As for this technique, an astigmatic cylindrical telescope is placed before the microscopic objective to reshape femtosecond laser, by which the waveguide with circular cross-section could be obtained as well. The minimum propagation loss of waveguide fabricated with this processing technique is less than 0.5 dB/cm, which is also applicable to constitute low-loss 3D waveguide configurations. It should be noted that, when fabricating 2D and 3D optical waveguides, the slit beam shaping and astigmatic beam shaping need to adjust slit orientation and cylindrical lens direction, respectively. It is this additional complexity that restricts the further applications of these two beam shaping techniques in integrated photonics. Third, deformable mirror beam shaping. In this technique, a 2D deformable mirror is utilized to reshape the spatial profile of femtosecond laser, by which the propagation loss of waveguide can also be reduced to some extent (~1.5 dB/cm). Fourth, simultaneous spatiotemporal focusing. This technique can strongly reduce nonlinear side effects, and have many potential applications for fabricating low-loss waveguides. However, the waveguide written by this processing technique has not been reported yet. Fifth, spatial light modulator beam shaping. It is a versatile and energy-efficient technique to control energy distribution of laser focus, which is promising to fabricate low-loss and high-quality optical waveguides. This paper, starting from the introduction of five beam shaping techniques, summarizes the latest research advances of waveguides fabricated by shaped femtosecond laser. An outlook is presented including several potential spotlights.

Key words: Light-manipulation; Femtosecond laser direct writing; Transparent material; Optical waveguide; Optical device

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