飞秒激光仿生复眼制造进展

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摘要 复眼系统是自然界中普遍存在的一种视觉成像系统, 与单眼相比, 它具有体积小、视场角大、景深大以及对快速运动物体灵敏度高等优点. 人工仿生的复眼结构在机器人视觉、三维成像、目标跟踪、导航、监测、医学等领域具有极其重要的应用价值. 与传统复眼透镜制备技术相比, 飞秒激光微纳加工技术在三维制备、高精度加工、可程序化设计等方面具有突出的优势, 使得飞秒激光技术成为重要的仿生复眼制备方式. 本文总结了飞秒激光加工仿生复眼透镜的最新研究进展, 对激光增材和减材两种制备方式分别进行了阐述和分析, 对仿生复眼透镜的应用进行了简单的介绍, 最后探讨了飞秒激光制备复眼透镜领域存在的一些挑战, 并对该领域的未来发展方向进行了展望.

关键词 飞秒激光, 人工仿生复眼, 微透镜阵列, 激光烧蚀, 双光子聚合

节肢动物的复眼是生物界中的一种复杂的成像系统, 每只复眼由许多相同的小眼阵列组成, 每个小眼都是独立的感光单元, 包含角膜、晶锥、感杆束等结构^[1-5]. 复眼不仅具有极小的体积, 极轻的重量, 而且能够进行大视场成像, 在光学传感、成像、机器人视觉、三维信息探测等领域中具有广泛的应用前景^[5-18]. 因此, 以复眼作为仿生结构的原型, 科学家在仿生复眼透镜制备领域做了大量的探索和研究.

复眼透镜的制备有很多方式, 包括热压印法^[19-21]、光刻胶热熔法^[22-24]、喷墨打印^[25-27]、精密仪器加工法^[28,29]等. 例如, 热压印法是先利用离子束刻蚀的方式在硅片上形成半圆球型阵列, 然后用聚合物填充阵列并加热到玻璃化温度以上对其进行软化, 最后降温硬化得到透镜阵列. 光刻胶热熔法是指利用光刻技术先形成微圆柱阵列, 再利用加热的方式使光刻胶达到玻璃化温度, 由于表面张力的作用,

光刻胶微柱会形成球状的微透镜结构. 为了模拟昆虫的大视场特性和提高视场边缘的成像质量, 近几年来, 制备曲面仿生复眼逐渐成为研究焦点^[30-34]. 想要获得曲面复眼, 通常是在凸型或凹型的曲面上加工, 这就需要对平面复眼透镜制备技术进行一定的优化和改进, 制备方式有全息干涉法、软光刻、三维微透镜阵列投影技术等. 这些传统的制备方式虽然具有一定的可行性, 然而都受到加工精度的限制, 尤其在实现灵活的三维曲面结构时需要更复杂的工艺过程.

飞秒激光直写技术的出现, 在很大程度上解决了上述问题, 既能满足加工器件的灵活三维化, 又实现了尺寸小型化的要求, 有望成为制备复眼透镜的一大强有力工具. 通过逐点扫描的加工方式, 飞秒激光直写技术能够制备小尺寸, 高精度的三维结构, 且可设计性强^[35-38]. 表1直观地展示了各种复眼透镜制

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表1 仿生复眼加工方法优劣势对比

Table 1 Advantages and disadvantages of artificial compound eye fabrication methods

方法	优点	缺点	可制备复眼的小眼尺寸(μm)	文献
热压印法	一次性制备, 速度快	需要模板,	80	[19]
		加工程序多,	100	[20]
		易充填不完整导致表面,	200	[21]
		粗糙度大	330	
光刻胶热熔法	工艺成熟, 容易复制, 制作周期短	填充因子低,	100	[22]
		剂量控制精确度低,	100	[23]
		导致透镜尺寸精确度低	100	[24]
微液滴喷墨法	工艺步骤少, 材料利用率高	墨水黏度不易控制,	280	[25]
		喷射稳定性和透镜阵列	100	[26]
		可控性较差	25~50	[27]
精密机械加工法	可按需制备自由曲面透镜阵列	加工精度较低,	100	[28]
		粗糙度较大	200	[29]
飞秒激光加工法	双光子飞秒激光	飞秒激光能量高, 可以加工材料范围广,	3~10	[39]
	增材加工	从软材料的聚合硬质材料的烧蚀都能够实现; 三维曲面可设计加工, 实现如高	5	[40]
	刻蚀辅助飞秒激光减材加工	填充因子等需求; 加工精度高, 实现突破光学衍射极限的高精度制备	24.5	[41]
			10	[42]

备方式的优势和存在的一些不足.

飞秒激光具有极短的脉冲, 脉宽仅为 $10^{-15}\sim 10^{-12}$ s, 具有极高的峰值功率, 瞬时功率密度能达到百万亿瓦量级^[43~46]. 超短脉冲使它的能量吸收时间远小于热效应的弛豫时间, 因此对热效应起到抑制作用, 对加工的材料几乎不会造成热损伤, 因此飞秒激光被称为一种“冷加工”. 飞秒激光的超高瞬时功率使它与材料相互作用时表现出一种非线性吸收效应, 具有焦点处的多光子吸收现象, 能够突破光学加工衍射极限, 实现纳米尺度的结构, 且适用于多种材料的加工, 包括软聚合物材料, 以及硬质金属、半导体等材料. 此外, 飞秒激光加工作为激光直写技术的一种, 具有很强的设计性, 在制备复杂的三维结构中具有很优势. 飞秒激光加工技术已经被证明是先进微纳制造领域的手段之一, 在微光学、微流控、光生物医学等领域引起了广泛的应用研究^[47~55].

本文总结了飞秒激光加工复眼透镜领域的最新研究进展, 按照增材加工和减材加工的分类方式分别进行了阐述, 并介绍了人工仿生复眼透镜在不同领域的应用状况和前景展望.

1 飞秒激光加工技术

飞秒激光加工技术可以分为两种类型: (1) 利用

飞秒激光多光子聚合加工, 这是一种增材加工技术, 主要用于加工聚合物材料^[56~60]; (2) 使用飞秒激光烧蚀加工, 这是一种减材加工技术, 主要用于加工半导体材料、金属材料、介质材料等硬质材料^[61~66]. 下面分别介绍这两种类型的工作原理以及仿生复眼透镜制备有关研究.

1.1 飞秒激光双光子聚合加工

双光子聚合是指在一定强度的激光辐射下, 光引发剂同时吸收2个光子, 到达激发态, 引发感光聚合物单体的交联^[67]. 飞秒激光的高能量密度能够触发双光子吸收效应, 从而实现双光子聚合. 与单光子聚合不同, 单光子聚合对光强要求小, 因此只要在光线通过的地方就会产生聚合, 是一种体聚合或者面聚合, 而双光子聚合仅仅发生在高能量密度处, 就是飞秒激光的焦点位置, 其他位置光强不够, 不产生光聚合, 因此能够实现逐点加工, 制备高精度三维微纳器件.

图1是典型的双光子聚合加工系统之一, 整个系统可以分为4个组成部分: 激光光源和光束方向系统(图1左侧与中部下方), 光束操控和移动台系统(图1中部上方), 图像实时检测系统(图1右侧), 还包括计算机图像生成和处理系统(图1未展示)^[68,69]. 激光光

图1 (网络版彩色)飞秒激光双光子三维(3D)加工系统示意图^[68,69]

Figure 1 (Color online) Schematic of 3D femtosecond laser nanofabrication system via two-photon photopolymerization^[68,69]

源主要采用钛:蓝宝石激光器,利用掺钛蓝宝石作为增益介质,波长一般为800 nm,脉冲宽度为100 fs左右,重复频率为82 MHz,脉冲能量在0.1~1000 nJ范围内.光束方向系统还包括偏振光分束器、物镜等其他光学元件,它的作用是设计光束的方向,使光源最终聚焦在样品台平面.光束操控和移动台系统是对光束进行调整,通过实时图像检测系统来确保焦点落在待加工材料中.计算机图像生成和处理系统主要作用是设计所需三维结构并确保其合理性.加工前一般需要进行扫描结构和扫描路径的设计,利用3ds Max等软件建立所需形状的三维结构,设计合理的扫描轨迹,最终表现为一个三维点阵坐标.一般来说是先对每层结构进行扫描,再“自下而上”建立三维结构.

双光子聚合由于其逐点加工的优势,能够制备结构不单一的复眼透镜阵列,这突破了传统复眼透镜阵列结构重复、曲率相同所带来的缺陷,在改进透镜光学性能上具有重要意义.2015年吉林大学Tian等人^[39]利用飞秒激光直写结构的优势,制备出了具有渐变焦距的平面复眼透镜(MLADC),如图2(a)~(c)所示.传统的平面复眼透镜是曲率相同的透镜阵列,这种阵列理想状态是焦点能够在同一平面,进而呈现清晰的像,然而像场弯曲使光束焦点与理想光点不重合,像平面呈现一个曲面状态,导致平面传感器接收的像只能达到局部清晰,成像原理如图2(d), (f)所示.在生产中,会通过引入一系列折转透镜来纠正场曲,使得制造成本和加工难度变大,并且不利于小型

Figure 2 (网络版彩色)飞秒激光双光子聚合技术制备变化曲率的仿生复眼结构^[39]. (a) 复眼透镜阵列的扫描电子显微镜(SEM)俯视图;与(a)对应的60°(b)和90°(c)侧视图,刻度尺为35 μm; (d) 像场弯曲示意图,虚线和实线代表不同的视场,它们不能被聚焦在同一平面上; (f) 曲率均一的微透镜聚焦示意图;边角复眼透镜阵列的透视图(e)及聚焦示意图(g)

Figure 2 (Color online) Focal varying compound eye lens by femtosecond laser writing^[39]. (a)–(c) SEM images of compound eye lens. (a), (b), and (c) were taken from top, 60°, and 90° side directions, respectively. Scale bar: 35 μm. (d) Schematic of field curvature. (e) Perspective view of the MLADC. The heights and curvatures of unit lenses were different with their positions. Cross-section profiles of ordinary MLAs (f) and MLADC (g). The difference of focal plane between ordinary MLAs and MLADC is that the former (f) and latter (g) is flat and curved, respectively

化.而渐变的曲率很好地解决了这个问题,它的成像能够与像场弯曲带来的相差相互抵消,最终得到清晰的图像,其成像原理如图2(e), (g).

在制备三维结构时,双光子聚合技术避免了曲面模板的使用,“从无到有”制备三维结构.2014年,吉林大学Wu等人^[40]采用飞秒激光像素调制快速扫描(HVLS)的方式加工SU-8材料,制作了与昆虫复眼(图3(a), (b))一致的无间隙的仿生复眼结构,如图3(c), (d)所示.他们首先采用大的像素间距(400 nm×400 nm)对光刻胶进行激光扫描,得到复眼的曲面大眼轮廓,再采用精细的像素间距(100 nm×100 nm)在大眼曲面上加工小眼阵列,图3(e)为加工流程示意图.其中,两次扫描所用到的功率也有所不同,第1次采用15 mW高功率,第2次采用6 mW小功率.大的曲面结构和成像的小眼结构均为飞秒激光一步制备,结构的复杂性并未给加工带来难度上的增加,充分体

图 3 (网络版彩色)双光子聚合像素调制制备仿生人工复眼^[40]. 天然复眼(a)与制备的人工复眼(c)的SEM俯视图图像,都表现出了100%填充小眼结构(b), (d)). (a)~(d)的刻度尺分别为40, 10, 10和5 μm; (e)人工复眼加工模式示意图, II展示了半球形底座的加工, III展示了球面上密布小眼的加工, IV为最后的复合整体

Figure 3 (Color online) 3D artificial compound eye by voxel-modulation femtosecond laser writing^[40]. Top view of nature compound eye (a) and artificial compound eye (c), showing 100% filled micro-ommatidia (b), (d)). The scale bars in (a)–(d) are 40, 10, 10, and 5 μm, respectively. (e) Schematics for the fabrication of BIC eye by the HVLS method. Steps II, III, and IV show the fabrication of hemispherical macrobase, the processing of densely packed micro-ommatidia on the macrobase, and the final artificial compound eye structure, respectively

现了双光子聚合方式在三维加工方面的巨大优势.

1.2 飞秒激光烧蚀加工

飞秒激光辐照物体表面时,靶材料会吸收激光的能量,在作用区域瞬间气化或熔化,使材料表面得到改性或去除.由于飞秒激光具有高的局域能量密度,使它能够加工高硬度材料,如金刚石、蓝宝石等,被广泛用于制备复杂三维结构^[43,44].

飞秒激光烧蚀由于其逐点扫描加工的特性,往

往耗时很长,对硬质材料的加工导致得到的结构表面粗糙度高,降低了透镜的光学性能.因此往往先采用飞秒激光诱导产生表面缺陷,再辅以干法或湿法刻蚀的方式进行处理,一方面加快了腐蚀速率,另一方面也使缺陷面更加平滑,形成更高质量的光学器件.下面分别对湿法刻蚀辅助与干法刻蚀辅助飞秒激光烧蚀加工进行介绍.

1.2.1 湿法刻蚀辅助飞秒激光烧蚀加工

通常,硬质材料如石英、硅等在经过激光加工后,材料的化学势及微观结构会发生相应的改变.如果利用化学腐蚀处理样品,会导致激光加工过的区域腐蚀速度快,而未加工区域腐蚀速度慢,使得最终材料表面形成凹陷的阵列,可以描述为激光形成“种子区域”以及“种子区域”扩散为结构这样两个过程^[70–72].湿法腐蚀一般采用腐蚀性较强的化学试剂,如氢氟酸等.

化学湿法腐蚀辅助飞秒激光加工技术使得加工效率得到了提高,表面变平滑,在制备复眼透镜方面引起了许多研究^[41,73–77].2010年,西安交通大学Chen等人^[73]以石英玻璃为衬底,利用飞秒激光烧蚀和5%的氢氟酸湿法刻蚀辅助的方式(图4(a)),制备了间距60 μm的长方形透镜阵列(图4(b))和间距为30 μm的六边形复眼透镜阵列(图4(c)).除了石英玻璃衬底以外,其他硬质材料也可以作为衬底来制备复眼透镜阵列.2013年,西安交通大学Yong等人^[74]利用聚二甲基硅氧烷作为衬底,制备了直径8.68 μm,深度0.95 μm的大规模透镜阵列,其中包含278万个小透镜.

为了发挥自然界动物复眼的优势,结构上更加相近的曲面仿生复眼透镜的制备也逐渐成为研究课题.2016年,Deng等人^[41]采用翻模压印的方式制备了曲面复眼透镜,制作流程如图5(a)所示.首先,使用湿法刻蚀辅助的方式制备出凹面复眼透镜阵列;然后,通过热压印聚甲基丙烯酸甲酯(PMMA)对阵列结构进行转写,得到平面凸透镜复眼阵列;最后,将此阵列热压在半球形模具上软化实现曲面结构,缓慢冷却后得到硬质曲面复眼透镜.该仿生复眼具有约三万个小眼结构,每个小眼的尺寸约24.5 μm(图5(b), (c)).通过控制玻璃球模具的直径尺寸,能够对复眼透镜的尺寸进行调节,整体结构能够达到5 μm的大直径尺寸.该工作提供了一种简单、快速、低成本的曲面复眼透镜的制备方式.

直接在球面衬底上加工微透镜阵列是另一种制

图4 (网络版彩色)湿法辅助飞秒激光加工制备微透镜阵列^[73]. (a) 湿法辅助飞秒激光制备过程的示意图; (b) 制备的长方形透镜阵列的场发射扫描电子显微镜(FE-SEM); (c) 制备的六边形蜂窝状透镜阵列的FE-SEM

Figure 4 (Color online) Fabrication of concave microlens arrays by femtosecond-laser-enhanced local wet etching method^[73]. (a) Schematic of the fabrication process. (b) FE-SEM images of the rectangular microlens array. (c) FE-SEM images of the hexagonal microlens array

备曲面仿生复眼的方式. 2016年, 西安交通大学Bian等人^[75]使用如图6(a)所示的凹面玻璃透镜作为衬底, 用氢氟酸刻蚀辅助激光加工的方式(图6(b)), 制备了三维凹面透镜结构, 接着热压印聚二甲基硅氧烷(PDMS)对其进行翻模(图6(c)), 得到了仿生三维复眼透镜(图6(d)). 这种方式的难点在于, 在加工的同时需要不断调节激光聚焦的位置, 因为对凹面透镜加工时, 随着半径的减小, 加工焦点位置下移, 需要大量的实验及精细的调节来达到目的.

湿法腐蚀加快了结构的成形效率, 然而在加工结构的时候, 仍然是采用逐点扫描的加工方式实现“种子区域”的制备, 在大面积制备三维结构时, 就失去了一定的优势. 光场调制技术可以解决这个问题, 区别于逐点扫描的方式, 它是将一束光调制为多束光, 利用多焦点同时曝光加工出所需结构. 光场调制技术包括多光束并行加工技术、面型光场加工技术

等^[42,78~86]. 多光束并行加工是将一束激光通过分束器等元件分成能量相等的几束均匀光, 进而实现多焦点同步加工, 提高加工效率^[81,82]. 面型光场加工技术是用空间光调制器(SLM)对光波波前进行调制, 如振幅调制、相位调制, 对空间光场进行设计, 调控光束分布^[41,83].

2018年, 吉林大学Cao等人^[42]利用空间光调制器(图7(a))对光束进行了设计整形, 利用飞秒激光刻蚀出结构后用氢氟酸湿法刻蚀辅助成型, 最终通过设计复杂的三维光场分布, 加工出了三维复眼透镜结构, 如图7(b)~(d)所示.

1.2.2 干法刻蚀辅助飞秒激光烧蚀加工

化学湿法腐蚀辅助飞秒激光加工的技术具有加工效率高、适应性强、表面均匀性高等优点, 被广泛应用于石英、玻璃、硅、碳化硅等材料基底上微透镜阵列和微纳结构的制备^[73,74,87,88]. 但是, 大多数湿法

图5 (网络版彩色)湿法辅助飞秒激光加工的三维超精密仿蜻蜓复眼^[41]. (a) 制作流程示意图; (b), (c) 高倍数放大的细节展示; (d) 仿生复眼的SEM图

Figure 5 (Color online) Artificial dragonfly-eye compound eyes via wet etching and thermal embossing^[41]. (a) Schematic illustration of the fabrication process for artificial compound eyes. (d) SEM images of structural organization of top (b) and side (c) portions of the artificial compound eye at high magnification. Insets are high resolution SEM images

图6 (网络版彩色)湿法刻蚀辅助飞秒激光在曲面衬底上直接制备三维复眼透镜的制备过程^[75]. (a) 飞秒激光在曲面透镜上逐点曝光; (b) 10%的氢氟酸超声腐蚀制备曲面微透镜阵列; (c) PDMS浇注固化; (d) 剥离模具得到人工复眼

Figure 6 (Color online) Schematic illustration of the fabrication process of the compound eye inspired curved microlens array^[75]. (a) Femtosecond laser point-by-point exposures on the curved lens. (b) 10% HF solution ultrasonic bath for the wet etching process to produce concave microlens array-in-lens. (c) PDMS pouring and solidifying. (d) Peeling replication mold and obtaining an artificial compound eye

刻蚀是不易控制的各向同性腐蚀, 会导致结构边缘侧向腐蚀严重, 造成设计结构的畸变和图形的失真, 显然不利于高精度结构的制备. 为了解决这一问题, 干法刻蚀应运而生^[89-92]. 广义上说, 所有不包含化学溶液腐蚀过程的刻蚀技术都能够称为干法刻蚀, 干法刻蚀包括反应离子刻蚀、感应耦合等离子体刻蚀、离子束刻蚀、反应气体刻蚀、聚焦离子束刻蚀等. 其中, 反应离子刻蚀、感应耦合等离子体刻蚀和离子束刻蚀3种方式目前应用比较广泛, 这些都是基于等离子体效应. 等离子体就是在电场作用下形成的电离化的气体. 当气体以这种形式存在时, 它的化学活性要比常态强很多, 因此能够加快与基底材料化学反应的速度, 从而实现刻蚀的目的. 另一种情况是通过电场的加速作用, 使等离子体被轰击到基底材料中, 与基底材料的原子进行交换, 从物理上改变了基底材料的组成, 而不发生化学反应, 属于物理刻蚀. 离子束刻蚀是典型的物理刻蚀, 而反应离子刻蚀和感应耦合等离子体刻蚀属于物理和化学刻蚀相结合的刻蚀方式.

图7 (网络版彩色)空间光调制辅助飞秒激光加工制备三维复眼透镜^[42]. (a) 空间光调制系统示意图; (b) 三维复眼透镜俯视示意图, 比例尺: 20 μm; (c) 与(b)对应的三维形貌; (d) 侧面深度信息

Figure 7 (Color online) Fabrication of 3D compound eye array with SLM treated femtosecond laser^[42]. (a) Schematic illustration of femtosecond laser system with SLM. (b) Top view of the close-packed compound micro-lens with 3D arrangement. The inset shows the corresponding light distribution. Scale bar is 20 μm. 3D topography (c) and height profiles from side view (d) of the micro-concave lens in (b)

2017年, 吉林大学Liu等人^[93]首次提出了干法刻蚀辅助飞秒激光加工技术, 他们利用感应耦合等离子体刻蚀辅助飞秒激光加工(DE-FsLM)的方式制备了仿复眼结构的凹微透镜阵列(图8(b), (c)). 首先在硅微透镜上加工出微孔阵列形状的改性区域, 接着将样品放入感应等离子体刻蚀系统(ICP)的刻蚀腔中, 在六氟化硫(SF₆)气体的等离子体环境下干法刻蚀, 实现了平面复眼透镜阵列的制备(图8(a)). 此外, 通过调整激光功率、脉冲数以及腐蚀时间, 能够对透镜阵列的直径和高度进行调整, 具有一定程度的可控性。

2 飞秒激光仿生复眼的应用

研究仿生器件的目的就在于尽可能地效仿大自然中优异的结构和功能, 将其应用于人类生产生活中, 推动科学和技术的发展。对于仿生复眼来说, 我们期待仿生复眼透镜能够达到自然界复眼的小体积、轻量化、大视场、广焦深、低相差这些优质的光学性

图8 (网络版彩色)干法刻蚀辅助飞秒激光加工复眼透镜^[93]. (a) 加工流程示意图; (b) 加工复眼结构的SEM图片; (c) 加工结构的三维激光扫描共聚焦显微镜图片

Figure 8 (Color online) Machining compound eye lens by dry-etching-assisted femtosecond laser^[93]. (a) Schematic diagram of the fabrication of silicon structures using DE-FsLM. (b) SEM images of all-silicon uniform-close-packed compound eye microlens array fabricated using DE-FsLM. The inset is the 60° tilted image of the structures. (c) 3D profiles obtained using laser scanning confocal microscopy (LSCM)

能, 将透镜集成到具有特定功能的系统后, 推动机器人视觉导航、目标跟踪、信息识别、三维探测等多种科学领域的发展。

目前制作的复眼透镜系统已经在多种学科领域显示出了巨大的应用价值。2000年, 日本大阪大学Tanida研究组^[7]设计了超薄平面复眼成像系统(thin observation module by bound optics, TOMBO)(图9(a)), 获取的子图像阵列能够用于高分辨率图像重构。在此基础上, 2004年, 该团队^[8,9]又提出基于TOMBO的指纹识别系统和三维成像系统。2013年, 美国伊利诺伊大学香槟分校Song等人^[10]研制了一种曲面“同位复眼相机系统”, 由柔性高分子聚合物所制备的透镜阵列和可拉伸的硅基光电探测器阵列双层结构组成(图9(b)). 器件尺寸为14.72 mm×14.72 mm, 包含180个直径为1 mm的小眼。该系统景深接近无限大, 能够完成160°视场角成像, 能够同时感知不同方向、多个物体的信息, 在机器人视觉、内视镜领域具有很大应用潜力。2013年, 瑞士联邦理工学院Floreno等人^[11]通过精密切割平面的集成复眼系统制备了一种曲面仿生复眼——CurvACE(图9(c)), 该系统体积为2.2 cm³, 质量仅为1.75 g, 能够完成180°×60°的大视

图9 (网络版彩色)复眼相机系统. (a) 超薄平面复眼成像系统TOMBO^[7]; (b) 同位复眼相机^[10]; (c) 曲面仿生复眼相机CurvACE^[11]

Figure 9 (Color online) Artificial compound eye imaging system. (a) Ultra-thin planar compound eye imaging system TOMBO^[7]. (b) Digital camera by Song et al.^[10]. (c) CurvACE system^[11]

场成像, 图像信息传输速率达到1500帧/s. 他们将其作为无人机的避障传感器, 成功完成了复杂地形中的飞行试验, 在微型飞行器导航、运动目标探测、可穿戴设备等领域具有重要应用价值.

采用飞秒激光技术制备的仿生复眼透镜在保证微型化的同时又具有优异的光学性能, 能够满足集成电路芯片制造的要求. 飞秒激光加工得到的复眼透镜能够轻易地达到微米级别甚至纳米级别的尺寸, 在制备小型化器件中展现了巨大优势. 通过技术的优化, 当前所制备的复眼透镜能够实现高保真度、大视场角等优质的成像性能. 通过飞秒激光双光子聚合技术加工SU-8光刻胶, 吉林大学Wu等人^[40]制备的仿生曲面复眼, 由150个直径仅为5 μm 的小眼组成, 整体复眼结构直径只有84 μm . 他们所制备的透镜实现了100%的填充因子(FF), 确保了高信噪比(SNR); 同时具有较大的数值孔径($\text{NA}=0.4$)和低表面粗糙度($\text{CA}=2.5 \text{ nm}$), 确保了高质量的成像(图2(c), (d)). 单个复眼的视场角为90°, 即双复眼的组合能够实现180°超大视角的目标探测. 所制备的复眼透镜与单透镜相比, 在30°和45°入射角下, 成像畸变分别降低了2倍和3倍(图10). 通过湿法刻蚀辅助飞秒激光烧蚀技术, 2015年Deng等人^[41]提出的仿生曲面复眼小眼直径仅为24.5 μm , 并制备了具有30000个紧密填充的小透镜阵列, 通过调整半球形模具的尺寸, 大眼的直径可调, 最大可达5 mm, 重量仅为67 mg(图5(b), (c)). 制备的透镜能够达到140°的广视场角, 同时几乎无成像畸变(图11).

对于飞秒激光制备的复眼透镜与功能化系统的集成, 研究者已经做出了一些努力, 充分证实了飞秒激光技术的兼容性. 2017年, 吉林大学Liu等人^[93]在

传统半导体技术制备的微机械元件——微悬臂梁上, 利用干法刻蚀辅助飞秒激光加工的方式, 实现了其与微孔结构的集成(图12(a)~(c)). 此外, 他们将激光直写技术、光刻技术和干法刻蚀技术相结合, 实现了在同一硅片上的结构激光直写和光刻图形的转移制备(图12(d)~(f)). 飞秒激光加工技术与半导体工艺在集成方面的初步探索, 表明了二者能够作为兼容的制备方式, 为未来人工仿生复眼系统的实现打下了基础.

3 结论与展望

昆虫的复眼是一种拥有大视场角、高时间分辨率、小体积、轻重量的结构, 通过对这种卓越结构进行学习, 人工仿生复眼研究蓬勃发展. 人工仿生复眼是集光学、生物学、信息处理等多学科为一体, 多种方法相结合的前沿研究领域.

经过仿生复眼制造工艺的不断发展, 飞秒激光制备技术由于其高加工分辨率、程序化设计、三维结构直写的优势, 日益显示出它在制备人工仿生复眼结构时独特的优越性. 本文从飞秒激光的增材加工技术和减材加工技术两个方面, 对飞秒激光制备复眼透镜进行了介绍, 对近年来国内外相关工作进行了总结和分析. 飞秒激光双光子聚合和刻蚀辅助的飞秒激光改性这两种方式, 都具有制备小型化、复杂三维仿生结构的能力, 确保了飞秒激光技术成为仿生复眼透镜制备领域新一代的主力军.

目前, 飞秒激光制备复眼透镜已经得到了一定的发展, 然而在未来的研究中仍然存在一些需要被解决的问题. (1) 从飞秒激光制备技术本身来说, 激光增材和减材的加工方式都具有自己的一些不足.

图 10 (网络版彩色)飞秒激光像素调制法制备的复眼透镜成像与单眼透镜成像视场性能的定量表征^[40]. 在 30° 和 45° 入射角下, 复眼成像的点扩散函数与单眼成像相比, 在 X 轴方向的成像畸变分别降低了 2 倍和 3 倍((a), (c)), 在 Y 轴方向上分别降低了 1.3 倍和 1.7 倍((b), (d))

Figure 10 (Color online) Quantitative characterization of the FOV properties of single lens/compound eye^[40]. Comparison of point spread functions (PSF) for the single microlens and compound eye under 30° and 45° light incidence: The imaging distortion of the compound eye was reduced by 2 and 3 times along the X-axis ((a), (c)); the imaging distortion was reduced by 1.3 and 1.7 times along the Y-axis ((b), (d))

图 11 (网络版彩色)湿法刻蚀辅助飞秒激光制备复眼透镜的宽视场成像和低成像畸变^[41]. 复眼透镜在 0°(a), 45°(b), 70°(c), 75°(d) 入射角下的输出成像; (e), (f) 在 0° 入射角下, 复眼透镜在 x, y 方向的点扩散函数, 几乎无成像畸变

Figure 11 (Color online) Experimentally observed wide FOV of the artificial compound eyes and good focusing ability^[41]. Output patterns of the artificial compound eyes irradiated by a laser at incident angles of 0° (a), 45° (b), 70° (c), and 75° (d). (e), (f) Intensity distributions of a single focal spot under 0° light incidence. The intensities along x- and y-axis are roughly identical

图 12 (网络版彩色)飞秒激光技术与半导体工艺的兼容性研究^[93]. (a)~(c) 悬臂梁微结构上微透镜的制备; (d)~(f) 激光直写技术、光刻技术、干法刻蚀相结合,同时制备出微通道和微透镜阵列

Figure 12 (Color online) Compatibility of femtosecond laser fabrication and semiconductor technology. (a)~(c) SEM images of microcantilever with a microlens fabricated by DE-FsLM^[93]. (d)~(f) Concave microlens on the bottom of silicon microchannel formed by combining lithography process and DE-FsLM^[93]

飞秒激光增材(即双光子聚合)制备复眼透镜作为一种逐点扫描的加工方式,加工耗时长,效率相对较低,有待大幅度提高;双光子聚合的高精度加工与实现大尺度结构这二者之间存在着矛盾,制备高精度、跨尺度的器件是其未来的努力方向. Wu等人^[40]采用的双光子引发和紫外曝光进一步聚合的方式,为解决该问题提供了思路. 飞秒激光减材(即激光烧蚀)加工技术尽管已经通过刻蚀辅助的方式提高了效率,能够得到光滑的表面结构,然而刻蚀的方式可控性较差,得到的样品形貌比较单一,透镜尺寸不易控制,仍需进一步优化技术. 另外,飞秒激光刻蚀作为一种减材的方式,所制备的结构为凹面透镜阵列,需要借助软光刻工艺翻模得到凸面复眼透镜. (2) 从飞秒激光加工制备的复眼透镜与其他器件的兼容集成

来说,也存在着一些问题:一方面,为了将复眼透镜应用到实际立体探测、快速跟踪等应用中,复眼透镜需要与波导、光接收器等硬件进行一体化集成,需要解决各部分功能组件的制备工艺兼容性以及集成面临的困难;另一方面,曲面复眼透镜的成像是非平面的,与工业化平面图像传感器(CMOS或CCD)的结合也是亟待解决的难点.

尽管飞秒激光制备仿生复眼透镜还存在一些问题,但是我们相信,通过对现有飞秒激光加工技术的进一步优化和创新,必将制备出更加精细的仿生复眼透镜,实现真正意义上的仿生结构和功能,这将使光学全视角成像、三维信息提取、目标定位等领域得到进一步的提升与发展,促进国民经济和国防科技的进步.

参考文献

- 1 Horridge G A. The compound eye of insects. *Sci Am*, 1977, 237: 108–120
- 2 Land M F, Fernald R D. The evolution of eyes. *Brain Behav Evolut*, 1933, 50: 253–259
- 3 Wu S D, Jiang T, Zhang G X, et al. Artificial compound eye: A survey of the state-of-the-art. *Artif Intell Rev*, 2017, 48: 573–603
- 4 Horridge G A. Review lecture: Apposition eyes of large diurnal insects as organs adapted to seeing. *Proc Roy Soc London*, 1980, 207: 287–309
- 5 Land M F, Nilsson D E. *Animal Eyes*. Oxford: Oxford University Press, 2012

- 6 Yuan W, Li L H, Lee W B, et al. Fabrication of microlens array and its application: A review. *Chin J Mech Eng*, 2018, 31: 16
- 7 Tanida J, Kumagai T, Yamada K, et al. Thin observation module by bound optics (TOMBO): An optoelectronic image capturing system. *Appl Optics*, 2000, 40: 1030–1036
- 8 Tanida J, Kumagai T, Yamada K, et al. Thin observation module by bound optics (TOMBO): Concept and experimental verification. *Appl Optics*, 2001, 40: 1806–1813
- 9 Tanida J, Shogenji R, Kitamura Y, et al. Color imaging with an integrated compound imaging system. *Opt Express*, 2003, 11: 2109–2117
- 10 Song Y M, Xie Y, Viktor M, et al. Digital cameras with designs inspired by the arthropod eye. *Nature*, 2013, 497: 9510
- 11 Floreano D, Pericet-Camara R, Viollet S, et al. Miniature curved artificial compound eyes. *Proc Natl Acad Sci USA*, 2013, 110: 9267–9272
- 12 Duparre J, Dannberg P, Schreiber P, et al. Artificial apposition compound eye fabricated by micro-optics technology. *Appl Optics*, 2004, 43: 4303–4310
- 13 Duparre J, Dannberg P, Schreiber P, et al. Thin compound-eye camera. *Appl Optics*, 2005, 44: 2949–2956
- 14 Duparre J, Schreiber P, Matthes A E, et al. Microoptical telescope compound eye. *Opt Express*, 2005, 13: 889–903
- 15 Duparre J, Wippermann F. Micro-optical artificial compound eyes. *Bioinspir Biomim*, 2006, 1: R1–R16
- 16 Kapustjansky A, Chittka L, Spaethe J. Bees use three-dimensional information to improve target detection. *Naturwissenschaften*, 2010, 97: 229–233
- 17 Ma M C, Guo F, Cao Z L, et al. Development of an artificial compound eye system for three-dimensional object detection. *Appl Optics*, 2014, 53: 1166–1172
- 18 Sun H B, Zhao H M, Mooney P, et al. A novel system for moving object detection using bionic compound eyes. *J Bionic Eng*, 2011, 8: 313–322
- 19 Pan C T, Wu T T, Chen M F, et al. Hot embossing of micro-lens array on bulk metallic glass. *Sensor Actuat A-Phys*, 2008, 141: 422–431.
- 20 Shen X J, Pan L W, Lin L W. Microplastic embossing process: Experimental and theoretical characterizations. *Sensor Actuat A Phys*, 2002, 97: 428–433
- 21 Yao D G, Nagarajan P, Li L, et al. A two-station embossing process for rapid fabrication of surface microstructures on thermoplastic polymers. *Polym Eng Sci*, 2007, 47: 530–539
- 22 Huang S Z, Li M J, Shen L G, et al. Fabrication of high quality aspheric microlens array by dose-modulated lithography and surface thermal reflow. *Opt Laser Technol*, 2018, 100: 298–303
- 23 Zhang H, Li L, McCray D L, et al. A microlens array on curved substrates by 3D micro projection and reflow process. *Sensor Actuat A Phys*, 2012, 179: 242–250
- 24 Qiu J F, Li M J, Zhu J J, et al. Fabrication of microlens array with well-defined shape by spatially constrained thermal reflow. *J Micro-mech Microeng*, 2018, 28: 085015
- 25 Luo Y, Wang L, Ding Y, et al. Direct fabrication of microlens arrays with high numerical aperture by ink-jetting on nanotextured surface. *Appl Surface Sci*, 2013, 279: 36–40
- 26 Zhu X Y, Zhu L, Chen H J, et al. Fabrication of high numerical aperture micro-lens array based on drop-on-demand generating of water-based molds. *Opt Laser Technol*, 2015, 68: 23–27
- 27 Zhu X Y, Lan H B, Yang J J, et al. Simple fabrication of high focal number micro-lenses based on a microfluid pulse jetting method. *Microsyst Technol*, 2018, 24: 2789–2802
- 28 Yan J W, Zhang Z Y, Kuriyagawa T, et al. Fabricating micro-structured surface by using single-crystalline diamond endmill. *Int J Adv Manuf Technol*, 2010, 51: 957–964
- 29 Gao P, Liang Z Q, Wang X B, et al. Fabrication of a micro-lens array mold by micro ball end-milling and its hot embossing. *Micromachines*, 2018, 9: 96
- 30 Zhu D, Li C, Zeng X, et al. Tunable-focus microlens arrays on curved surfaces. *Appl Phys Lett*, 2010, 96: 1792
- 31 Baker K M. Highly corrected close-packed microlens arrays and moth-eye structuring on curved surfaces. *Appl Optics*, 1999, 38: 352–356
- 32 Li L, Yi A Y. Microfabrication on a curved surface using 3D microlens array projection. *J Micromech Microeng*, 2009, 19: 5010–5019
- 33 He Q, Liu J Q, Yang B, et al. Fabrication and characterization of biologically inspired curved-surface artificial compound eyes. *J Micro-electromech Sys*, 2013, 22: 4–6
- 34 Radtke D, Duparre J, Zeitner U D, et al. Laser lithographic fabrication and characterization of a spherical artificial compound eye. *Opt Exp*, 2007, 15: 3067–3077
- 35 Hu A, Peng P, Alarifi H, et al. Femtosecond laser welded nanostructures and plasmonic devices. *J Laser Appl*, 2012, 24: 042001
- 36 Kawata S, Sun H B, Tanaka T, et al. Finer features for functional microdevices-micromachines can be created with higher resolution using two-photon absorption. *Nature*, 2001, 412: 697–698

- 37 Sun H B, Kawata S. Two-photon photopolymerization and 3D lithographic microfabrication. *Adv Polym Sci*, 2004, 170: 169–273
- 38 Zheng C, Hu A M, Chen T, et al. Femtosecond laser internal manufacturing of three-dimensional microstructure devices. *Appl Phys A Mater*, 2015, 121: 163–177
- 39 Tian Z N, Yao W G, Xu J J, et al. Focal varying microlens array. *Opt Lett*, 2015, 40: 4222–4225
- 40 Wu D, Wang J N, Niu L G, et al. Bioinspired fabrication of high-quality 3D artificial compound eyes by voxel-modulation femtosecond laser writing for distortion-free wide-field-of-view imaging. *Adv Opt Mater*, 2014, 2: 751–758
- 41 Deng Z F, Chen F, Yang Q, et al. Dragonfly-eye-inspired artificial compound eyes with sophisticated imaging. *Adv Funct Mater*, 2016, 26: 1995–2001
- 42 Cao X W, Chen Q D, Zhang L, et al. Single-pulse writing of a concave microlens array. *Opt Lett*, 2018, 43: 831–834
- 43 Chichkov B N, Momma C, Nolte S, et al. Femtosecond, picosecond and nanosecond laser ablation of solids. *Appl Phys A*, 1996, 63: 109–115
- 44 Couairon A, Mysyrowicz A. Femtosecond filamentation in transparent media. *Phys Rep*, 2007, 441: 47–189
- 45 El-Bandrawy M, Gupta M C. Femtosecond laser micromachining of silicon for mems. *Photon Proc Microelectron Photon*, 2003, 4977: 219–225
- 46 Yang D, Jhaveri S J, Ober C K. Three-dimensional microfabrication by two-photon lithography. *MRS Bull*, 2005, 30: 976–982
- 47 Xu B B. Fabrication and multifunction integration of microfluidic chips by femtosecond laser direct writing. *Lab Chip*, 2013, 13: 1677–1690
- 48 James E C, Catherine H C, Mengyan S, et al. Visible and near-infrared responsivity of femtosecond-laser microstructured silicon photo-diodes. *Opt Lett*, 2005, 30: 1773–1775
- 49 Ya C, Koji S, Katsumi M, et al. Three-dimensional micro-optical components embedded in photosensitive glass by a femtosecond laser. *Opt Lett*, 2003, 28: 1144–1146
- 50 Liao Y, Ju Y, Zhang L, et al. Three-dimensional microfluidic channel with arbitrary length and configuration fabricated inside glass by femtosecond laser direct writing. *Opt Lett*, 2010, 35: 3225–3227
- 51 Bricchi E, Klappauf B G, Kazansky P G. Form birefringence and negative index change created by femtosecond direct writing in transparent materials. *Opt Lett*, 2004, 29: 119–121
- 52 Li G Q, Li J W, Hu Y L, et al. Femtosecond laser color marking stainless steel surface with different wavelengths. *Appl Phys A Mater*, 2015, 118: 1189–1196
- 53 Richter S, Doring S, Tunnermann A, et al. Bonding of glass with femtosecond laser pulses at high repetition rates. *Appl Phys A Mater*, 2011, 103: 257–261
- 54 Calmano T, Paschke A G, Siebenmorgen J, et al. Characterization of an Yb:YAG ceramic waveguide laser, fabricated by the direct femtosecond-laser writing technique. *Appl Phys B Lasers Opt*, 2011, 103: 1–4
- 55 Ams M, Dekker P, Marshall G D, et al. Monolithic 100 mW Yb waveguide laser fabricated using the femtosecond-laser direct-write technique. *Opt Lett*, 2009, 34: 247–249
- 56 Deepak K L N, Rao S V, Rao D N. Femtosecond laser-fabricated microstructures in bulk poly(methylmethacrylate) and poly(dimethylsiloxane) at 800 nm towards lab-on-a-chip applications. *Pramana J Phys*, 2010, 75: 1221–1232
- 57 Farson D F, Choi H W, Lu C, et al. Femtosecond laser bulk micromachining of microfluid channels in poly(methylmethacrylate). *J Laser Appl*, 2006, 18: 210–215
- 58 Cheng C M, Li B, Leduc P R. Optical fabrication of three-dimensional polymeric microstructures. *Appl Phys Lett*, 2005, 87: 581
- 59 Kumi G, Yanez C O, Belfield K D, et al. High-speed multiphoton absorption polymerization: Fabrication of microfluidic channels with arbitrary cross-sections and high aspect ratios. *Lab Chip*, 2010, 10: 1057–1060
- 60 Zhu X, Naumov A Y, Villeneuve D M, et al. Influence of laser parameters and material properties on micro drilling with femtosecond laser pulses. *Appl Phys A Mater*, 1999, 69: S367–S371
- 61 Li Y, Itoh K, Watanabe W, et al. Three-dimensional hole drilling of silica glass from the rear surface with femtosecond laser pulses. *Opt Lett*, 2001, 26: 1912–1914
- 62 Li C D, Nikumb S, Wong F. An optimal process of femtosecond laser cutting of NiTi shape memory alloy for fabrication of miniature devices. *Opt Laser Eng*, 2006, 44: 1078–1087
- 63 Wang X C, Zheng H Y, Chu P L, et al. High quality femtosecond laser cutting of alumina substrates. *Opt Laser Eng*, 2010, 48: 657–663
- 64 Kim Y, Choi J, Lee Y, et al. Femtosecond laser bonding of glasses and ion migration in the interface. *Appl Phys A Mater*, 2010, 101: 147–152
- 65 Lin C H, Jiang L, Chai Y H, et al. Fabrication of microlens arrays in photosensitive glass by femtosecond laser direct writing. *Appl Phys A*, 2009, 97: 751–757

- 66 Kamlage G, Bauer T, Ostendorf A, et al. Deep drilling of metals by femtosecond laser pulses. *Appl Phys A*, 2003, 77: 307–310
- 67 Perry J W, Albota M, Ananthavel S, et al. Design of organic molecules with large two-photon absorption cross-sections. *Abstr Pap Am Chem Soc*, 1999, 217: U378
- 68 Zhang Y L, Chen Q D, Xia H, et al. Designable 3D nanofabrication by femtosecond laser direct writing. *Nano Today*, 2010, 5: 435–448
- 69 Bi Y G, Feng J, Li Y F, et al. Arbitrary shape designable microscale organic light-emitting devices by using femtosecond laser reduced graphene oxide as a patterned electrode. *ACS Photon*, 2014, 1: 690–695
- 70 Li Q K, Yu Y H, Wang L, et al. Sapphire-based fresnel zone plate fabricated by femtosecond laser direct writing and wet etching. *IEEE Photon Technol Lett*, 2016, 28: 1290–1293
- 71 Bellouard Y, Said A, Dugan M, et al. Fabrication of high-aspect ratio, micro-fluidic channels and tunnels using femtosecond laser pulses and chemical etching. *Opt Exp*, 2004, 12: 2120–2129
- 72 Liu K Y, Yang Q, Zhao Y L, et al. Three-dimensional metallic microcomponents achieved in fused silica by a femtosecond-laser-based microsolidifying process. *Microelectron Eng*, 2014, 113: 93–97
- 73 Chen F, Liu H W, Yang Q, et al. Maskless fabrication of concave microlens arrays on silica glasses by a femtosecond-laser-enhanced local wet etching method. *Opt Exp*, 2010, 18: 20334–20343
- 74 Chen F, Shan C, Liu K Y, et al. Process for the fabrication of complex three-dimensional microcoils in fused silica. *Opt Lett*, 2013, 38: 2911–2914
- 75 Bian H, Wei Y, Yang Q, et al. Direct fabrication of compound-eye microlens array on curved surfaces by a facile femtosecond laser enhanced wet etching process. *Appl Phys Lett*, 2016, 109: 221109
- 76 He S G, Chen F, Liu K Y, et al. Fabrication of three-dimensional helical microchannels with arbitrary length and uniform diameter inside fused silica. *Opt Lett*, 2012, 37: 3825–3827
- 77 Shan C, Chen F, Yang Q, et al. High-level integration of three-dimensional microcoils array in fused silica. *Opt Lett*, 2015, 40: 4050–4053
- 78 Weiner A M. Femtosecond pulse shaping using spatial light modulators. *Rev Sci Instrum*, 2000, 71: 1929–1960
- 79 Oishi Y, Suda A, Kannari F, et al. Intense femtosecond pulse shaping using a fused-silica spatial light modulator. *Opt Commun*, 2007, 270: 305–309
- 80 Frumker E, Silberberg Y. Femtosecond pulse shaping using a two-dimensional liquid-crystal spatial light modulator. *Opt Lett*, 2007, 32: 1384–1386
- 81 Dong X Z, Zhao Z S, Duan X M. Micronanofabrication of assembled three-dimensional microstructures by designable multiple beams multiphoton processing. *Appl Phys Lett*, 2007, 91: 124103
- 82 Kato J, Takeyasu N, Adachi Y, et al. Multiple-spot parallel processing for laser micronanofabrication. *Appl Phys Lett*, 2005, 86: 04412
- 83 Nedev S, Urban A S, Lutich A A, et al. Optical force stamping lithography. *Nano Lett*, 2011, 11: 5066–5070
- 84 Hacker M, Stobrawa G, Sauerbrey R, et al. Micromirror SLM for femtosecond pulse shaping in the ultraviolet. *Appl Phys B Lasers Opt*, 2003, 76: 711–714
- 85 Curtis J E, Koss B A, Grier D G. Dynamic holographic optical tweezers. *Opt Commun*, 2002, 207: 169–175
- 86 Poon T C, Schilling B W, Wu M H, et al. Real-time two-dimensional holographic imaging by using an electron-beam-addressed spatial light modulator. *Opt Lett*, 1993, 18: 63–65
- 87 Pan A, Gao B, Chen T, et al. Fabrication of concave spherical microlenses on silicon by femtosecond laser irradiation and mixed acid etching. *Opt Exp*, 2014, 22: 15245–15250
- 88 Khuat V, Chen T, Gao B, et al. Uniform nano-ripples on the sidewall of silicon carbide micro-hole fabricated by femtosecond laser irradiation and acid etching. *Appl Phys Lett*, 2014, 104: 219–225
- 89 Nagpal P, Lindquist N C, Oh S H, et al. Ultrasoft patterned metals for plasmonics and metamaterials. *Science*, 2009, 325: 594–597
- 90 Ji L, Chang Y F, Fowler B, et al. Integrated one diode-one resistor architecture in nanopillarsio_x resistive switching memory by nanosphere lithography. *Nano Lett*, 2014, 14: 813–818
- 91 Burek M J, Chu Y W, Liddy M S Z, et al. High quality-factor optical nanocavities in bulk single-crystal diamond. *Nat Commun*, 2014, 5: 718
- 92 Zhang X S, Han M D, Meng B, et al. High performance triboelectricnanogenerators based on large-scale mass-fabrication technologies. *Nano Energy*, 2015, 11: 304–322
- 93 Liu X Q, Chen Q D, Guan K M, et al. Dry-etching-assisted femtosecond laser machining. *Laser Photon Rev*, 2017, 11: 1600115

Summary for “飞秒激光仿生复眼制造进展”

Progress in femtosecond laser fabrication of artificial compound eye

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Compound eyes of arthropods are widespread and fascinating visual systems created by natural evolution. Compound eyes consist of many identical small eye units called “ommatidia”, each of which is an individual imaging system composed of cornea lens, crystalline cone and rhabdome. Compared with single eyes, compound eyes have distinct advantages in small volumes, large field of view, large depth of field, and high temporal resolution. Therefore, it has sparked considerable research interests in developing various manufacturing technologies towards the fabrication of artificial compound eyes that can be applied in robot vision, three-dimension imaging, motion detection and medical examination.

To date, various methods have been proposed for fabricating artificial compound eyes, such as hot embossing method, thermal reflow method, microdroplet jetting method, and ultraprecision machining method. However, these methods inherently suffer from low accuracy and multi-step processing. In particular, it is extremely difficult for these methods to acquire curved artificial compound eye lens, which is quite important for promoting the optical performance and practical applications of artificial compound eyes.

In recent years, femtosecond laser direct-writing (FsLDW) has emerged as a practical and promising technique for fabricating artificial compound eyes owing to its capability of three-dimensional (3D) processing and high fabrication precision. First of all, FsLDW is performed by point by point scanning process layer by layer, making it capable of realizing various 3D structures as designed. Second, the extremely high transient intensity of femtosecond laser pulses leads to a non-linear absorption effect (two-photon absorption or multi-photon absorption) with materials in a much smaller volume than the cubic size of wavelength, which endows it with a high resolution (tens of nanometers) beyond the optical diffraction limit. Moreover, the high power of femtosecond laser pulses also provides the ability to process various materials, from soft photopolymer materials to rigid substrates as hard as diamonds. For soft materials, the fabrication mechanism is two- or multi-photon polymerization of photosensitive polymers triggered by the high energy at the localized laser focus region. Through point by point process, two-photon polymerization technology by FsLDW becomes a powerful tool for fabricating complex 3D structures. In spite of this, its shortcoming is obvious as well. The single point scanning procedure causes a relatively low efficiency, which needs further improvement. For hard materials, femtosecond laser serves as an ablation source to form micro-hole, where the local material is removed or chemically modified. Femtosecond laser ablation can be combined with a subsequent etching treatment for improving efficiency, including wet etching and dry etching. The drawback of etching assisted femtosecond laser ablation technology lies in that usually only concave structures can be obtained, further soft embossing treatment is needed in order to acquire convex compound eye lens.

In this review, the latest progress in femtosecond laser fabrication of artificial compound eyes is summarized. Manufacturing of artificial compound eyes by FsLDW is introduced according to the two methods mentioned above: femtosecond laser two-photon polymerization that belongs to additive manufacturing and femtosecond laser ablation that is regarded as a subtractive manufacturing method. Then, the diverse applications of artificial compound eyes produced by FsLDW are described. At last, current challenges and future perspectives in this field are discussed.

femtosecond laser, artificial compound eye, microlens array, laser ablation, two-photon polymerization

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