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基于双光子聚合的片上光学互连（特邀）

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摘　要：集成光子芯片是将激光光源、低损耗波导、调制器、探测器等多类光电器件结合在一起，实现功能化集成，在高速光通讯、量子信息处理、光学传感等领域有具有重要的应用。然而由于不同的光电器件基于不同材料体系，实现多材料体系的光电器件集成极其困难。传统的异质集成和单片集成方法难以同时解决定位精度不足、低拓展性、高损耗、低带宽等一系列问题。基于飞秒激光的双光子聚合技术具有高精度和高穿透的优势，可以实现多材料体系的片上微纳光学元件增材制造，具有极高的加工自由度。本文对片上光学元件的激光增材制造这一领域进行综述，探讨了光子引线键合和微空间光路元件两种技术路径，总结了现有技术的发展现状，并对未来的发展前景进行了展望。

关键词：集成光学；增材制造；飞秒激光；双光子聚合；混合集成；光子引线键合；微空间光路元件

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0　引言

集成光子芯片具有低功耗、低延迟、小体积、大带宽等优势，是下一代通讯系统和数据互联的关键技术[1-3]。同时集成光学在光学传感[4]、量子信息处理[5-6]、光学操纵[7]等领域有迫切的应用需求。一个完整的光子芯片由光源、低损耗波导、调制器、探测器等部件组成[8-10]。目前，单一光学元件可以做到很高的性能，但是如何将这些光学元件可靠地集成在一起，是非常重要的挑战。例如，硅基光子集成与微电子产业中成熟的互补金属氧化物半导体（Complementary Metal Oxide Semiconductor, CMOS）工艺兼容，且硅具有高折射率，极大的降低了光斑尺寸，可以使光路紧凑，是集成低损耗波导的良好材料。但由于硅是间接带隙半导体，发光效率非常低，硅基光源的集成是极其困难的。Ⅲ/Ⅴ族半导体，如 InP（磷化铟）、GaAs（砷化镓）具有直接带隙的能带结构，是片上集成光源的最优解[11-12]。又如 $LiNbO_3$（铌酸锂）调制器[13]、Ge（锗）探测器[14]、YIG（钇铁石榴石）光隔离器[15]等器件，相比于硅基器件来说都有独特的优势。

为了实现这些性能优越的光电器件的有机集成，目前主要有有两种解决方案。第一种方案是混合集成[16-19]，在各自最优材料体系内加工不同的光电器件，后通过透镜耦合、光栅耦合或倒装焊等方法集成到一起，这需要极高精度的主动对准技术，离散的组装失去了紧密集成的意义，也很难进行具有高重复性的大规模光子集成。第二种方案是单片集成[20-22]，即在单一基底上键合或直接外延生长异质材料，再制备所需的功能芯片，但是工艺难度非常大，良品率不高，且技术很难移植。一种具有定位精度宽松、通用性强、损耗低、带宽大的光子集成技术显得尤为重要。

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受三维电沉积的金属[23]和导电聚合物引线键合[24]所启发，近来出现了一种直接光引线键合（Direct Optical Wire，DOW）技术[25]。该技术利用挤出聚合物液体中溶剂的快速挥发以创建拱形聚合物通路。微型移液枪内装有含聚苯乙烯的二甲苯溶液，当微移液器挤出聚合物溶液时，二甲苯迅速挥发，留下聚苯乙烯固体聚集体，产生连接两端的聚合物光学桥接。通过控制微型移液枪的拉速度，引线的局部尺寸受控变化。该技术可以实现光栅耦合器之间、光栅耦合器和光纤间的光学互联，损耗分别在6 dB和10 dB。该技术有两个局限：一是截面形状和路径不完全可控，精度低，且路径自由度小，不利于实现较小的对接和传输损耗。二是采用物理接触方式，很难做到重复和深入式加工。

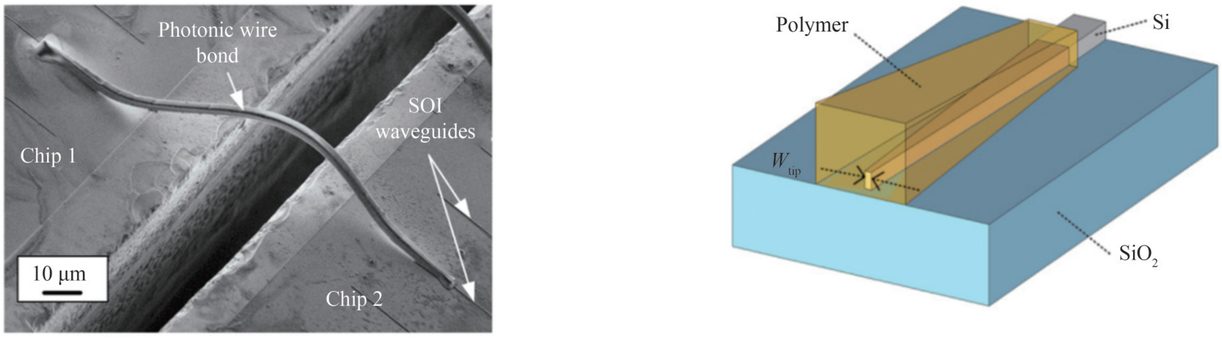
飞秒激光作为微纳加工的重要工具，更适合于片上光学元件的制造和集成[26-28]。飞秒激光具有高峰值功率，在焦点处会引发双光子吸收这一三阶非线性效应，引发光刻胶材料体系的交联。双光子吸收和光强的平方成正比，其吸收光强度会随着距离焦点的距离迅速衰减，所以双光子聚合（Two-Photon Polymerization，TPP）的加工体素远小于衍射极限，横向可达100 nm的精度。此外，双光子聚合可以实现真三维、无掩模和定制化加工，具有非常高的自由度。飞秒激光已经成为微纳增材制造领域不可缺少的工具，在功能材料纳米3D打印[29-30]、微光学元件[31-32]、光学操控[7]、微流控[33]、生物医学[34]等领域有广泛应用。本文针对光子芯片集成，对片上光学元件的激光增材制造这一领域进行综述，探讨了光子引线键合和微空间光路元件两种技术路径，总结了现有技术的发展现状，并对未来的发展前景进行了展望。

1　光子引线键合

1.1　无源材料体系的光子引线键合

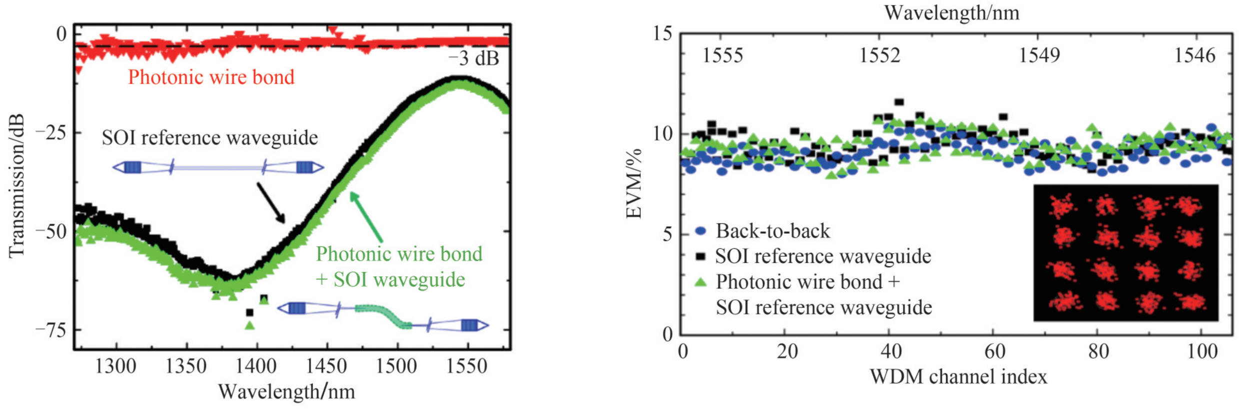
飞秒激光直写光刻胶，利用双光子聚合制造聚合物波导，实现不同光学接口间的光学直接互连，被称作光子引线键合（Photonic Wire Bonding，PWB）。这种技术类似光纤头中间接了根光纤跳线，所以又被称为光子跳线。在实际的片上互连中，器件接口的状态会有所差异，如接口的折射率分布、空间位置、尺寸、方向等。光子引线键合技术就是为解决多材料光电器件在尺寸、模场和空间布局的不匹配性应运而生的。利用该技术可以将器件的初始对准精度放宽至10 μm量级，极大地降低了主动对准的要求。

2012年，德国研究者利用飞秒激光在SU8光刻胶内部直写波导，实现了两个SOI波导的片间光学互连[35]，见图1（a）。在1 550 nm，Si和SU8折射率分别为3.48和1.57，两者折射率的巨大差值引起模场的巨大差异。为实现接口处的高效耦合，他们设计了绝热耦合结构，见图1（b），SOI波导和聚合物波导都被设计成倒锥形结构，且在较长的一段过渡区域内利用聚合物包裹SOI波导。SOI波导宽度在32 μm的长度上逐渐从500 nm缩小到几十纳米的尖端宽度，相反PWB从初始的高450 nm、宽760 nm的尺寸，分别均匀扩大至1.6 μm和2 μm。显影后，结构浸泡在折射率匹配液中。实验测得光子跳线在C波段具有低损耗宽带传输能力，平均损耗1.6 dB，见图1（c）。他们测试了总速率为5.25 Tbit/s的波分复用（Wavelength-Division Multiplexing WDM）数据流，每个载波都用16进制正交幅度调制（Quadrature Amplitude Modulation，QAM）进行信号调制。为了对信号质量进行定量测量，误差矢量幅度（Error-Vector Magnitude，EVM）被引入。EVM表示实际测量波形与理论调制波形之间的偏差，对比SOI参考波导的传输，平均EVM仅从9.1%增加到9.5%，见图1（d），这可以说明PWB没有引入明显的信号质量下降。结果表明，光子引线键合技术优于光纤和光栅耦合器的的互连，并且可以与电子束光刻（Electron Beam Lithography，EBL）制备的平面耦合技术

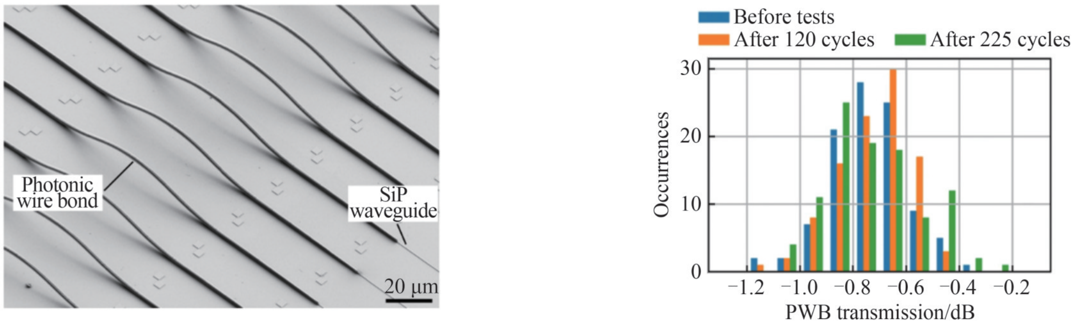


(a) SEM image of PWB between SOI waveguides[35]

(b) Inversed-taper coupling structure[35]



(c) Transmission measurement of a PWB[35]　　(d) EVM measured in different cases[35]



(e) Repetitive fabrication of PWB[37]　　(f) Coupling loss tested after temperature variation[37]

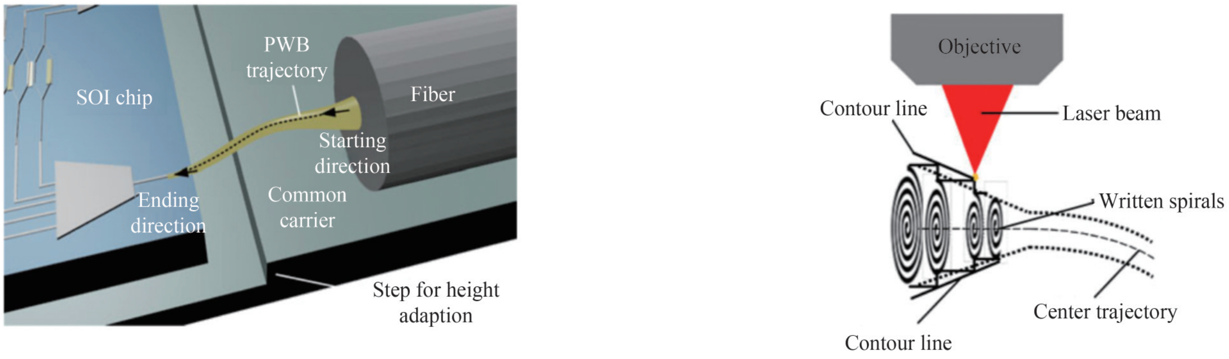
图1　基于PWB的SOI波导间光学互连

Fig. 1　Optical interconnection between SOI waveguides based on PWB

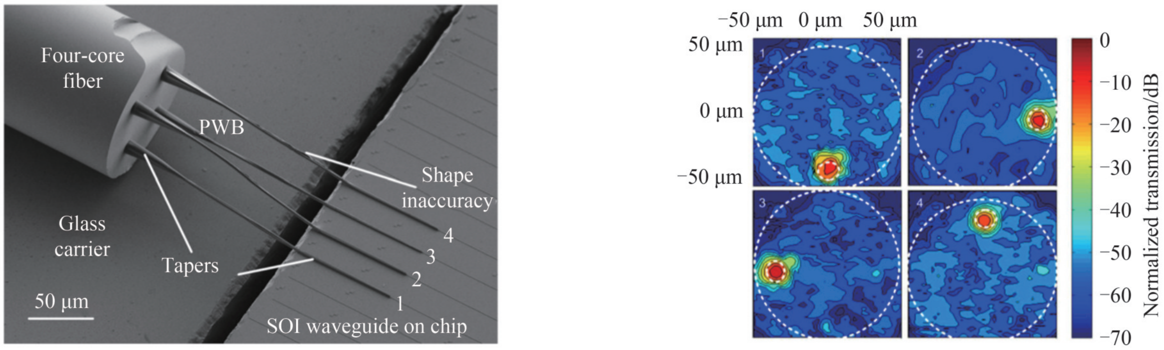
一较高下。该技术也被应用于Si_3N_4平台上，将PWB的波长拓展到了可见光[36]。

基于飞秒激光增材制造的聚合物波导具有很好的可拓展性和热稳定性[37]。经过选材和工艺的优化，同时结合先进的接口检测和图像识别技术，可以实现100根硅波导间引线的重复性加工，平均每根引线的加工时间在30 s，见图1(e)。经测试，研究者得到了平均0.73 dB、标准差为0.15 dB的低损耗数据。令人鼓舞的是，样品经过−40 ℃至85 ℃共225轮温度循环后，材料结构和组分完好，性能没有下降，见图1(g)。

该技术也被引入到了SOI波导和多芯光纤的互连上来[38]（见图2）。研究者对SOI波导与光纤的互连结构进行了设计和模拟。PWB在SOI波导端口的耦合口设计得到了延续，被设计成方形截面的倒锥形渐变结构。为了适应光纤圆形模场，PWB截面以绝热方式从方形逐渐变化为圆形，并以喇叭口结构直连至光纤纤芯以适应更大的光纤模式，保证了接口处的容错性。在写入结构时，为了避免逐层扫描引起的边缘分层问题，他们先在结构内部进行螺旋式加工使结构内部交联，然后写入外壳使结构更加平滑以减小损耗。实验测得多核光纤与SOI波导的插入损耗在1.7 dB至6.8 dB之间，高损耗可能是制造缺陷或轴向加工误差导致。可以预计，通过优化锥形耦合结构和制造工艺，光纤和波导间损耗会进一步降低。



(a) Concept diagram　　(b) Fabrication method demonstration



(c) SEM image of PWB between four-core fiber and SOI waveguide

(d) Spatially resolved normalized power transmission, corresponds to insertion losses of 3.5 dB, 1.7 dB, 2.5 dB, 6.8 dB, respectively

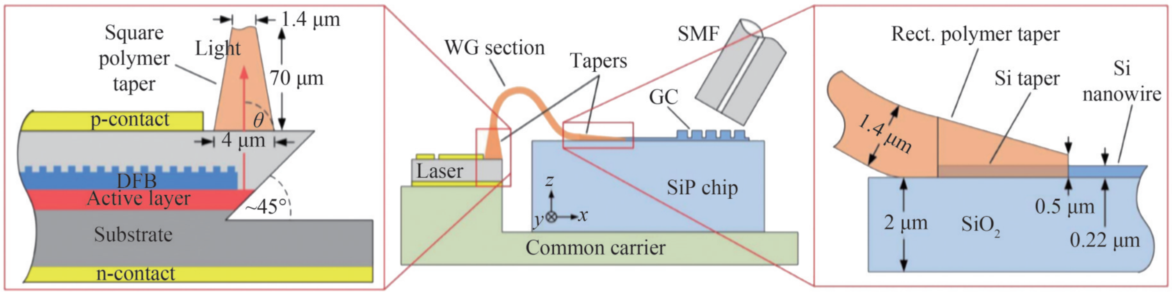
图2 SOI波导和多核光纤的片间PWB互连[38]

Fig. 2 PWB interconnection between SOI waveguides and multicore fibers[38]

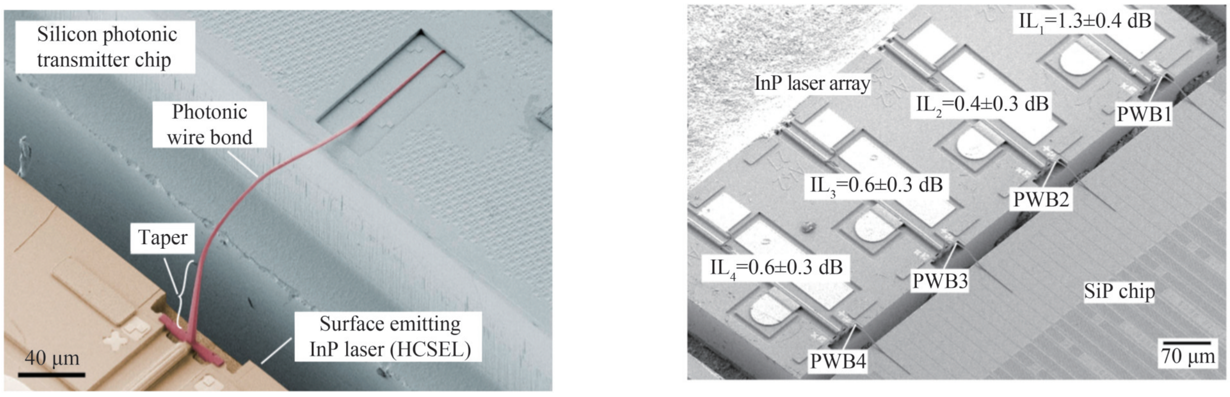
1.2 有源材料体系的光子引线键合

Ⅲ/Ⅴ族光源与硅光波导的高效耦合是集成光学的关键挑战之一。将有源材料体系和无源材料体系结合起来，是光子引线键合重要的技术出口。有学者演示了基于InP的水平腔表面发射激光器（Horizontal Cavity Surface Emitting Laser, HCSEL）和硅光子平台之间的高效耦合[39]。HCSEL由平面内InGaAsP分布式反馈激光器（Distributed Feedback Laser, DFB）激光腔和蚀刻的45°镜面组成，以偏转光线到表面出射（见图3）。由于HCSEL偏转镜倾斜角度存在误差，所以激光出射方向和芯片表面之间不一定是严格垂直的。因此，PWB结构的初始方向必须做出相应调整。同时，为了实现两个接口之间的模场匹配，PWB需要定制化设计耦合渐变结构，同时考虑PWB与激光器出射端口和波导接口的耦合效率和波导弯折引起的光能泄漏，以实现HCSEL激光的收集和偏转，以及硅波导小模场的转变。实验测的耦合损耗可以降低至0.4 dB。

同时，利用PWB技术，还可以实现InP激光器、硅光子调制器阵列和单模光纤三个孤立器件之间的光学



(a) Design concept of PWB between InP lasers and SiP waveguides[39]



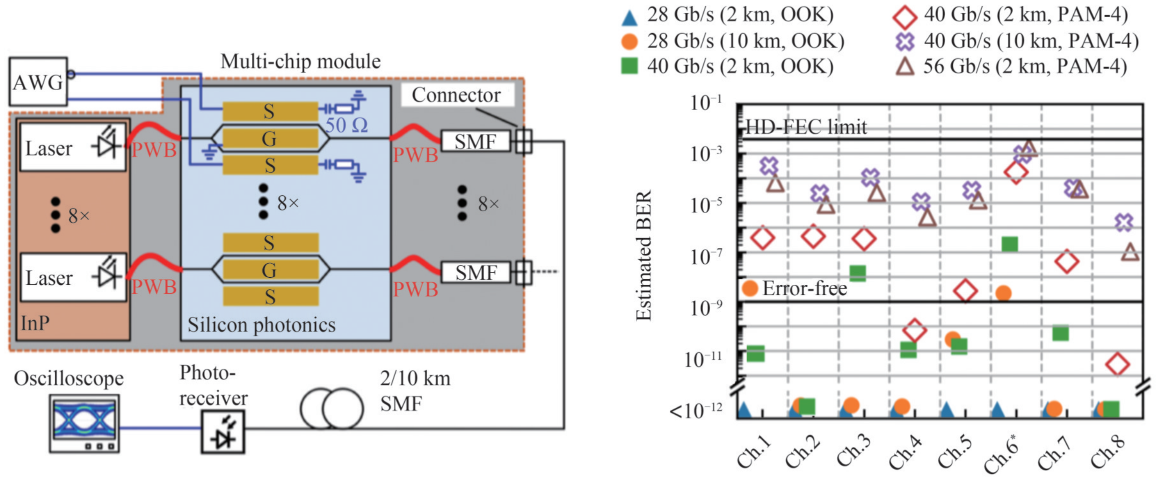
(b) SEM of a single PWB between laser and SiP waveguide[37]

(c) SEM of PWB array between InP lasers and SiP waveguides[39]

图3 InP激光器和硅芯片间的光子引线键合设计和测试

Fig. 3 PWB design and test between InP lasers and silicon chips

互连[37]。将两片含四个HCSEL的激光器阵列作为八路激光光源，通过第一个PWB阵列连接到耗尽型马赫-曾德尔调制器（Mach-Zehnder Modulator，MZM）阵列进行调制，又通过第二个PWB阵列连接单模光纤阵列实现信号输出，可以实现八通道通信功能（见图4）。每个通道提供高达56 Gbit/s的线路速率，从而实现448 Gbit/s的总线速率。此外，基于PWB互连的能够以732.7 Gbit/s的净数据速率运行的四通道相干发射器也被提出。可见，PWB技术可作为高速光通信的可靠技术方案。



(a) Experimental setup for transmission demonstrations using different modulation formats and distances

(b) Estimated bit error ratios for transmission over various distances, with different modulation formats and symbol rates

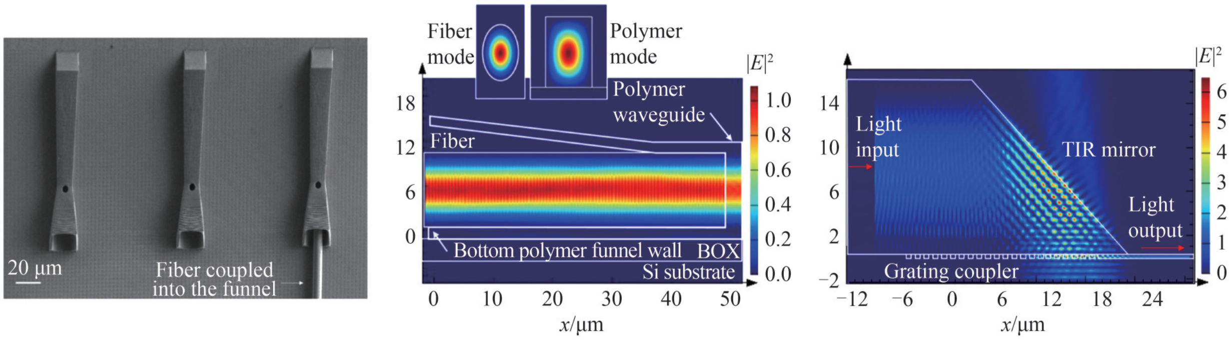
图4　基于PWB的八通道通信芯片[37]

Fig. 4　Eight-channel transmitter communication chip based on PWB[37]

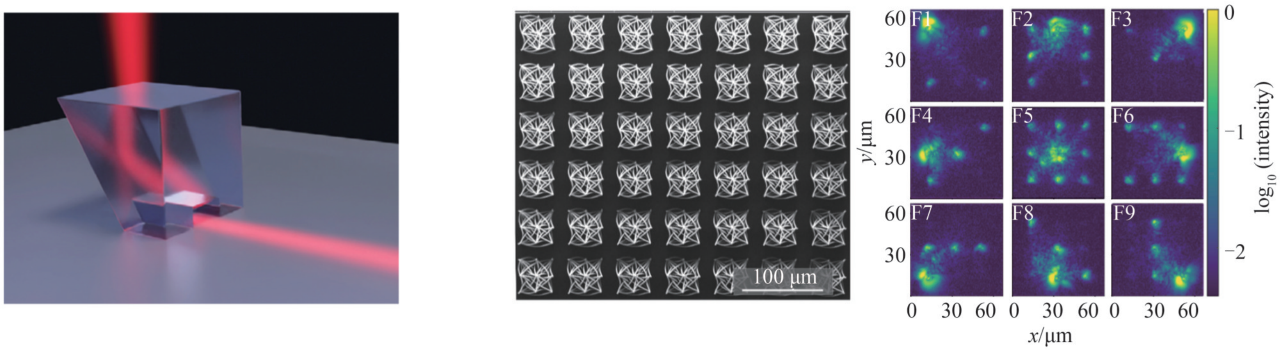
2　微空间光路元件

与光子引线键合技术不同，微空间光路元件的技术方案不涉及两个端口的直接物理连接，而是通过制备微型空间光路元件，如微型反射镜、微型耦合器、微棱镜等，对输入的空间光或者导波光信号进行处理后，再以空间光或导波光的形式进行输出。微空间光路元件可以实现光学信号的自由传导和特性变换，是集成光学的重要一环。

有研究者利用双光子聚合，巧妙地设计并制备了即插即用的光纤-波导耦合器[40]，该结构留了一个光纤接口，任意的输入光纤均可插入该端口，光信号经尾部的全内反射（Total Internal Reflection，TIR）结构进入硅光栅耦合器中，见图5(a)，经测试，相比于单模光纤和光栅耦合器间的损耗，聚合物耦合器只引入了0.05 dB的额外损耗。此外，单个耦合器的制作时间仅为三分钟，可以实现重复性的批量制造。利用飞秒激光直写的聚合物Otto棱镜结构，见图5(b)，可以将空间光转换为一维光子晶体中的布洛赫表面波，耦合效率超过40%[41]。近来，有研究者利用双光子聚合制备的三维多通道输入、多通道输出的分层耦合器，见图5(c)，演示了大规模、高度连接和复杂的光学互连的复杂3D路由拓扑，为大规模集成的光子神经网络做好铺垫[42]。这些微空间光路元件的增材制造打破了平面光刻结构的维度限制，可以极大提升片上光学元件的集成度并拓宽其应用自由度。



(a) Plug-and-play fiber to waveguide connector[40]



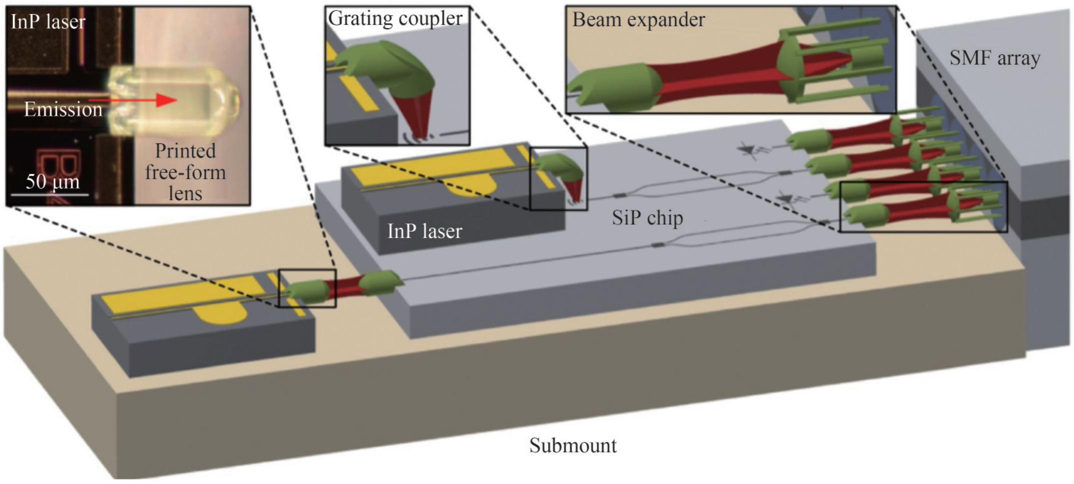
(b) Miniature otto prism coupler[41]

(c) Optical characterization of the Haar filter's connection topology[42]

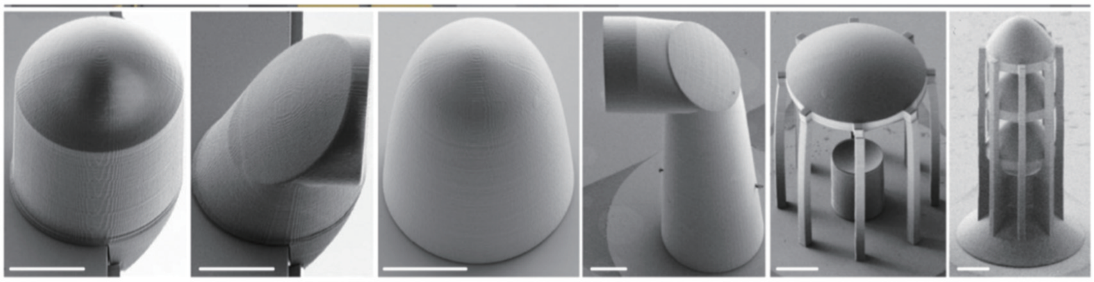
图5 基于双光子聚合加工的具有集成度的微空间光路元件

Fig. 5 Micro-space optical device with an integrated degree based on two-photon polymerization

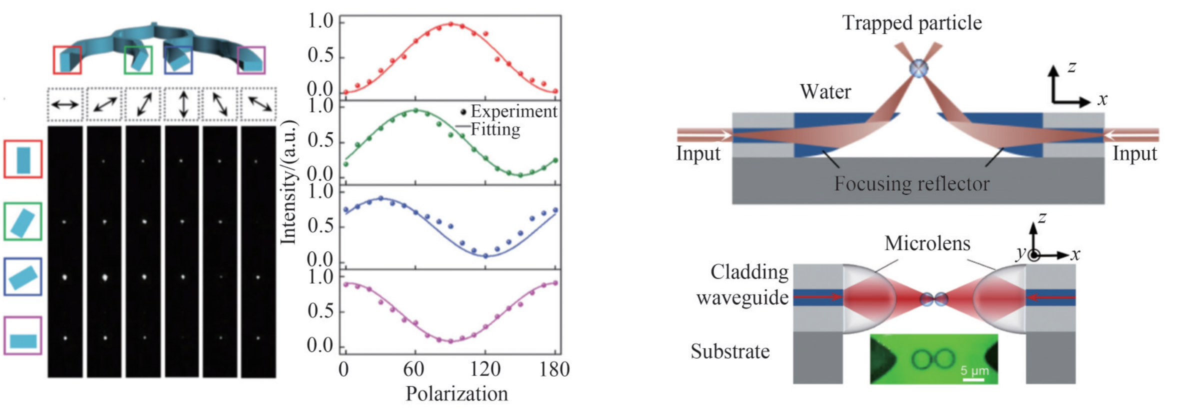
以飞秒激光直写的聚合物结构作为基本光学元件，实现片间的自由空间互连具有重要的意义。有研究者将几何光学的设计思路引入到集成光学[43]，他们设计了单透镜、透镜组、反射元件这些基本的光学元件，见图6(a)、6(b)并对其进行组合，可以实现光束的模斑尺寸变换、传播方向的转换，以适应异质材料光学接口间模式失配和角度错位等问题，在边缘发射激光器和单模光纤之间实现了高达88%的耦合效率，并且极大的降低了对齐公差。自由形式的微空间光路元件大大简化了光学系统组装，有利于提升光子芯片的集成度及其对光学信号的处理能力。基于TPP的片上偏振转换器能够可以对光束的偏振特性进行调控和路由[31]，能够实现1 550 nm处高于90%的偏振转换效率，是自由空间互连的重要组成部分。基于TPP的自由曲面微光学器件被应用于片上微型光镊[7]。研究者在波导端面分别加工了聚合物反射式和折射式透镜，在芯片两端通光实现了对悬浮颗粒的高效捕获。片上光镊具有结构紧凑、高捕获效率的优势，而且可扩展集成，在片上传感、粒子动力学等领域有应用前景。



(a) Demonstration of on chip free micro-space optical device[43]



(b) SEM image of free micro-space optical device[43]



(c) On-chip polarization rotators[31]

(d) On-chip optical tweezers based on freeform optics[7]

图6　自由微空间光路元件的组合，实现片上互连[43]

Fig. 6　Combining of free micro-space optical device to achieve on-chip interconnects[43]

3　总结与展望

光子芯片需要光源、低损耗波导、调制器、探测器等多类部件组成，然而单一材料体系实现其完整功能是极其困难的。目前，基于多材料体系的单一片上光电器件性能已经获得较好的优化，然而其有效集成一直是限制光电芯片集成的重大问题。无论是基于透镜耦合、倒装焊等方法的混合集成，还是通过晶圆键合或外延的单片集成，都难以同时解决低定位精度、低拓展性、高损耗、低带宽等一系列问题。此外，不同光学接口的折射率分布、空间位置、尺寸、方向的差异，进一步提升了器件互连的难度。把精度高、穿透性强的飞秒激光作为利器，在光刻胶内部直写任意三维聚合物结构，根据芯片自身的特点设计独特的光学元件，这是传统的光刻技术无法企及的。飞秒激光的高度自由化加工大大简化了传统光学高精度对齐的装配技术，并可以实现无掩模加工。光子跳线架起了无源有源芯片的桥梁，自由光路的微空间光路元件更拓展了空间光路的可能性。

基于双光子聚合的片上光学元件互连还面临一些局限。首先，多材料平台会引入更大的的空间复杂度，可能伴随几百微米的纵深和方向角的互异性。高数值孔径物镜可以实现高精度的加工，但是其工作距离较短，实际加工中往往需要在高精度和高空间自由度之间做取舍。这提出了对光学系统设计的进一步要求。其次，材料体系的分层结构会引入成像的复杂度，会干扰不同器件的位置识别，影响加工定位的准确度。这需要借助高轴向分辨的共聚焦或差动共焦显微成像技术，结合机器视觉以实现准确的加工定位。最后，光子集成向着高度集成化的方向发展，这对耦合器件的空间尺寸提出了要求。为了适应波导和光子引线折射率的较大差别，现有的光学接口需要几十微米的耦合距离。超构光子学基于人工设计的亚波长微纳结构，可以实现对电磁波多维度的精确调控，如超表面能够调节光束的偏振特性并产生特定的复杂光束，超透镜可以实现高效率、高数值孔径的聚焦，拓扑光子晶体可以实现高紧凑的光束偏转。双光子聚合微纳增材制造与超构光子学相结合，期待实现密集集成的多维度光学调控。

双光子聚合技术结合多材料的优势，可以实现更多的功能化集成。对聚合物前驱体进行预掺杂如金属、二氧化硅纳米粒子、稀土元素等[29, 44, 45]，可以改变加工结构的光学性质，甚至通过后去除聚合物成分的方法仅保留预掺杂成分，实现功能性微纳结构的三维加工，拓展双光子聚合在集成光学领域的可能性。可重构光学或光学可擦写在片上光学调控和信息保护方面有重要意义，双光子聚合技术可以考虑与光学相变材料或液晶材料相结合，在外加信号的调节下，实现光学性质的动态调节。

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On-chip Optical Interconnection Based on Two-photon Polymerization (Invited)

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Abstract: Integrated photonic chip is a combination of optoelectronic devices such as laser light sources, low-loss waveguides, modulators, detectors, etc., to achieving specific functionality. Integrated photonic chip provides important applications in high-speed optical communication, quantum information processing, optical sensing, optical manipulation, and so on. However, the fabrication of optoelectronic devices relies on different materials, it is extremely difficult to achieve photonic integration. The traditional heterogeneous integration and monolithic integration methods cannot simultaneously solve the problems such as low positioning accuracy, low scalability, high loss, and low bandwidth. Inspired by the direct wire bonding of three-dimensional electrodeposition of metals and conductive polymer, a Direct Optical Wire (DOW) technique has been recently proposed. This technology utilizes the rapid volatilization of solvents in extruded polymer liquids to create arched polymer pathways for conducting light between single-mode

fiber and gratings. However, the cross-section and path are not completely controllable and the accuracy is low, limiting the implementation of small interface and low transmission loss. Femtosecond laser has extremely high pulse power, which triggers the two-photon absorption at the focal point and cause crosslinking of the photoresist material. The two-photon absorption efficiency is proportional to the square of the light intensity, and the absorbed light intensity will rapidly decay with the distance from the focal point, so the resolution of Two-Photon Polymerization (TPP) can break the diffraction limit, with the lateral resolution below 100 nm. In addition, two-photon polymerization enables true three-dimensional, mask-free, and custom machining with high degrees of freedom, becoming an indispensable tool in the field of micro-nano additive manufacturing. In this paper, we review the field of laser additive manufacturing of on-chip optical components for photonic chip integration including Photonic Wire Bonding (PWB) and micro-space optical devices, and summarizes the development status of existing technologies, and the perspective of future development.

PWB uses femtosecond laser for direct writing of polymer waveguides, leading to direct optical interconnection between different optical interfaces. During on-chip interconnect, the interface of the optical device, such as the refractive index distribution, spatial position, size, and orientation, are different from each other. PWB technology is able to solve the mismatching of multi-material optoelectronic devices in size, mold field and spatial layout. It allows connection of optical devices with low alignment accuracy (at the order of 10 μm), reducing the need of active alignment. Researchers used femtosecond laser to write polymer waveguide inside the SU8 photoresist to achieve on-chip optical interconnection between two SOI waveguides. To enable efficient coupling at the interface, they designed an inverted cone structure, reducing the coupling loss down to 1.6 dB. PWB was also applied on Si_3N_4 devices and optical connection between SOI waveguide and multi-core fiber. It exhibits good repeatability and thermal stability. In order to eliminate edge delamination caused by layer-by-layer scanning, spiral machining was carried out inside the structure to crosslink the structure, and a smooth shell was then written to reduce loss.

Efficient coupling of Ⅲ/Ⅴ group light sources to silicon photonic circuits is one of the key challenges of integrated optics. PWB can also solve this key problem. The coupling between an InP based Horizontal Cavity Surface Emitting Laser (HCSEL) and a silicon photonic platform has been achieved. Due to the error in the tilt angle of the HCSEL deflector, the laser emission direction and the surface of the chip are not strictly vertical. Thus, the initial orientation of the PWB structure has to be adjusted accordingly. At the same time, in order to achieve mold field matching between the two interfaces, the shape of PWB has to be customized. For example, by processing the coupling gradient structure, the collection and deflection of the HCSEL laser can be achieved. Combining InP laser, silicon photonic modulators and Si waveguide, an eight-channel transmitter exhibits very good performance, offering an aggregate line rate of 448 Gbit/s.

Different from the PWB technology, the technical scheme of the micro-space optical device does not involve the direct physical connection between two ports. However, through optical fabrication of micro-space optical device, such as micro reflectors, micro couplers, micro prisms, etc., the input space light or guided light signal can be processed, and then output in the form of space light or guided light. Micro-space optical device can realize the free conduction and characteristic transformation of optical signals, which is an important part of integrated optics. The concept of on-chip micro-space optical elements by TPP has long been proposed. A couple of optical devices, such as three-dimensional photonic crystals and phase-type Fresnel waveband sheets have been fabricated, while the latter achieves a diffraction efficiency of up to 68%. The fabrication of multilayer couplers, artificial compound eyes, and on-chip polarization rotators have also been demonstrated.

With high precision and strong penetration, femtosecond laser is used as a tool to fabricate various three-dimensional polymer structures. Unique optical components are designed according to the characteristics of the optical chip, which is unattainable using traditional lithography technology. The highly freedom of femtosecond lasers greatly improve the alignment accuracy and enables mask-free machining. In the future, laser additive manufacturing will be applied to fabricate more complex microstructures based on more materials. Technical developments such as accurate image recognition and positioning in complex

environments, wide horizontal and longitudinal range of processing, and reconfigurable fabrication, are expected to extend its application in three-dimensional optical chips.

Key words: Integrated optics; Additive manufacturing; Femtosecond laser; Two-photon polymerization; Hybrid integration; Photonic wire bonding; Micro-space optical device

OCIS Codes: 222.4000; 220.4210; 220.4610; 130.3120; 230.3120

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