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微波光子集成芯片技术

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摘　要：微波光子集成芯片技术是微波光子雷达的重要支撑技术，不仅可以实现器件的多功能化，缩小微波光子雷达的体积，还可以大大提升微波光子雷达的稳定性与可靠性。该文介绍了目前常用的InP基、Si基和铌酸锂基等材料体系及其异质异构集成的光子集成芯片技术和可用于微波光子混合集成的光电集成芯片技术，并展望了未来发展趋势。

关键词：微波光子雷达；集成微波光子；集成芯片技术；光子集成芯片

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Integrated Chip Technologies for Microwave Photonics

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Abstract: Microwave photonic integrated chip technology is an important supporting technology of microwave photonic radar. It can not only realize the multifunction of devices, reduce the volume of microwave photonic radar, but also greatly improve the stability and reliability. This paper introduces the photonic integrated chip technologies based on the commonly used InP, Si, $LiNbO_3$ and their heterogeneous integrations and the optoelectronic integration chip technologies for microwave photonics. Finally, the future development trends is discussed.

Key words: Microwave photonic radar; Integrated microwave photonic; Integrated chip technology; Photonic integrated chip

1　引言

“微波光子学”是一门微波和光两种技术相融合的新兴交叉学科，被定义为利用电光和光电器件对微波频段信号进行处理，并应用到微波系统及光通信系统等领域的技术，可实现传统微波方法过于复杂或不易实现甚至根本无法实现的功能[1]。经过近30年的发展，微波光子技术已在雷达、卫星通信、宽带无线接入网、空天一体化信息系统等诸多领域呈现出巨大的应用潜力，将对现代信息技术的发展产生深远影响。在雷达应用方面，更是受到了世界各国的重点关注。目前，美国、欧盟及俄罗斯等均针对该技术做了长远的发展规划，并投入了大量的人力与财力[2]。美国DARPA在20世纪80年代开始支持微波光子雷达研究，并形成了高线性模拟

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光链路、光控波束形成网络和微波光子雷达射频前端3个研究阶段规划。目前，美国DARPA的研究已经进入第3阶段，设立了诸多项目，大大推动了微波光子雷达基础技术的发展。欧盟以意大利芬梅卡尼卡集团为代表也针对微波光子雷达发展制定了4步走发展路线，并以全光的雷达为最终发展目标。2013年意大利国家光子网络实验室完成了全球首个结合微波光子多载波产生、发射和接收的光子雷达收发机，2014年将该工作发表于《Nature》[3]，在全球掀起了微波光子雷达研究的热潮。俄罗斯也一直非常重视微波光子雷达研究，2014年俄罗斯政府以下一代雷达和电子战系统为应用目标，开始资助“射频光子相控阵”项目研究，旨在制造射频光子相控阵雷达。我国在微波光子技术方面的研究起步较晚，但近年来在微波光子雷达器件及系统方面也取得了瞩目的成就，研究单位包括国内诸多研究所和高校。

随着对微波光子雷达研究的不断深入，目前基于分立光电子器件构建的微波光子系统已经逐渐显现出了其价格昂贵、功耗高、可靠性及稳定性低等缺点，难以满足微波光子雷达工程化应用需求。因此，微波光子雷达对微波光子器件提出了新的要求，即：在实现高速、大带宽及大动态范围同时，器件和系统还应具有尺寸小、重量轻、功耗低等特性[4–6]。集成化、芯片化已成为微波光子技术发展的必然趋势。芯片集成不仅能大幅降低微波光子雷达系统体积和功耗、提升整体稳定性，同时还能减小器件插入损耗、降低封装成本。另外，集成化、小型化的微波光子器件更满足大规模阵列化应用需求，这对微波光子相控阵雷达发展具有重要意义。

微波光子雷达需求的芯片主要包括光子集成芯片、微波电路芯片及驱动电路芯片等。若将微波光子集成芯片分为：单一功能光子集成芯片、多功能光子集成芯片和微波光子混合集成芯片3个层次，目前国外在第1层次单一功能光子集成芯片方面的研究比较成熟，但仍在不断提高芯片性能，并研究新机理、新材料芯片；在第2层次芯片方面的研究比较早，且取得了不少令人瞩目的成果；针对第3层次微波光子混合集成芯片方面的研究，还尚处于研发阶段。与国外相比，国内起步较晚，多集中在第1层次芯片方面研究，与国外存在较大差距；在第2层次和第3层次芯片研究方面，国内研究都尚处于起步阶段，研究单位相对较少，主要受限于芯片加工能力。在微波光子雷达需求的芯片中，微波电路芯片及驱动电路芯片相对发展比较成熟，但微波电路芯片的带宽通常比较小，若能够进一步提升，实现其与光子芯片的大带宽匹配，则能在芯片层面更好地发挥微波光子技术的大带宽优势。

总之，光子集成芯片技术和用于微波光子混合集成的光电集成芯片技术是目前能够推动微波光子雷达功能组件小型化发展的关键技术。因此，本文以微波光子器件的集成化、芯片化需求为背景，介绍了目前InP基、Si基和铌酸锂基等常用材料体系及其异质异构集成的微波光子集成芯片技术，并对未来发展趋势进行了展望。

2　光子集成芯片

目前，光子集成技术常用材料体系主要包括：InP基化合物材料、硅基材料、$LiNbO_3$晶体材料和聚合物、石墨烯、等离子激元等新兴材料，每种材料在光源、调制、探测、低损耗传输及大规模集成等方面均展现着各自独特的优势。本节将主要介绍这几种常用材料体系的光子集成芯片技术。

2.1　InP基光子集成芯片

InP基化合物材料在光源、放大、调制、探测、衰减和集成光传输中都可应用，是多功能材料体系。InP基化合物材料的折射率高，具有较强的光约束能力，可实现高集成度。另外，InP基化合物材料在单片电路中也具有广泛应用，是光电混合集成的良好平台。因此，InP基化合物材料在大规模光子集成中具有巨大优势，其发展前景被众多研究人员看好。图1即是InP基大规模光子集成芯片，可以实现众多类型光子器件的单片集成。图2为典型InP基集成光子器件芯片[7–12]：(a)激光器，(b)电光调制器，(c)光电探测器，(d)偏振旋转器，(e)光耦合器，(f)阵列波导光栅(Arrayed Waveguide Grating, AWG), (g)光开关阵列。其中，激光器可实现大功率、低噪声，调制器可以实现大带宽、低半波电压、高消光比，探测器可以实现大带宽、高饱和、高响应度等，这些典型器件均能满足微波光子技术需求，具有广泛的应用。因此，InP基光子集成被认为是集成微波光子领域非常有前景的研究方向之一。

但是，InP基光子器件的材料及器件结构复杂，工艺难度较大，材料及加工成本高，在一定程度上限制了InP光子器件的大规模集成应用。图3是典型InP光子器件的材料及波导结构示意图。可以看出，虽然InP基的光子器件芯片可采用同一InP材料体系，但不同光子器件的材料和器件结构还存在区别。按照器件类型不同，可将InP光子器件分为激光光源型、电光调制器型、深脊波导器件型、浅脊波导器件型和偏振旋转器型[11]，或有源型光子器件和无

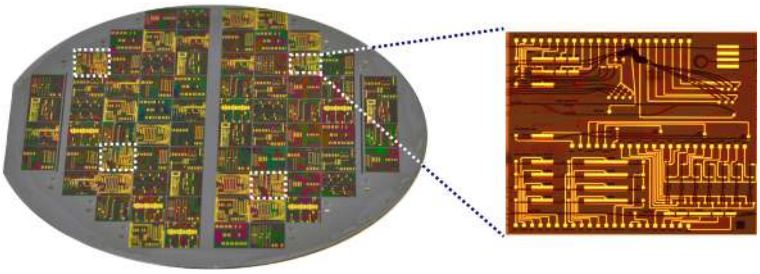
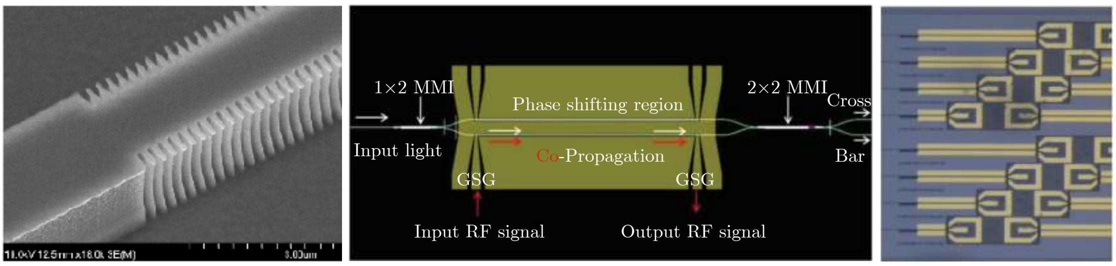


图 1 InP基大规模光子集成芯片[11]

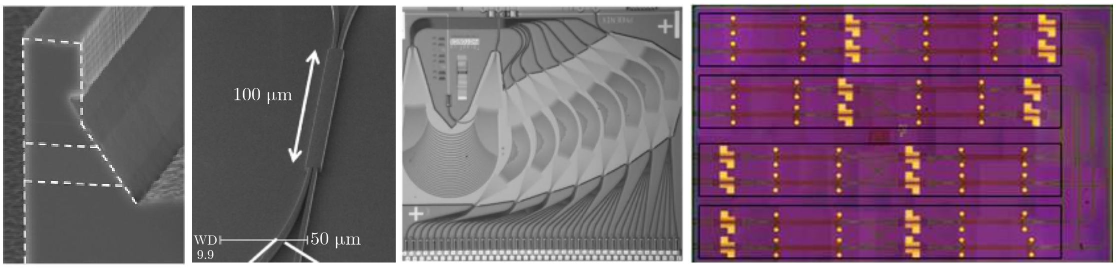
Fig. 1 InP-based large-scale photonic integrated chip[11]



(a) 激光器
(a) Laser

(b) 电光调制器
(b) Electro-optic modulator

(c) 光电探测器
(c) Photodetector



(d) 偏振旋转器
(d) Polarization converter

(e) 耦合器
(e) Coupler

(f) 阵列波导光栅
(f) AWG

(g) 光开关阵列
(g) Optical switch array

图 2 典型InP基集成光子器件芯片[7–12]

Fig. 2 Typical InP-based photonic integrated chips[7–12]

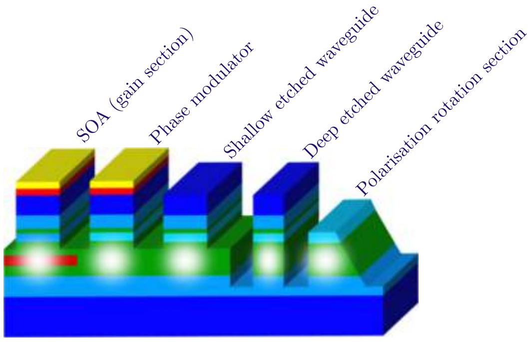


图 3 典型InP基光子器件光波导结构示意图[11]

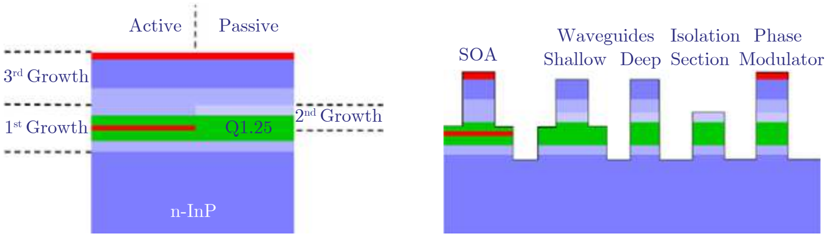
Fig. 3 The optical waveguide structure of typical InP-based photonic devices[11]

源型光子器件。在InP光子芯片研究中，大规模光子集成一直是最终目标。为了实现InP有源型和无源型光子器件的单片集成，可采用材料多次外延技术，如图4所示，将有源光子器件和无源光子器件区域的材料分区生长，统一制备。

此外，由于InP基光波导与光纤中的光模式在尺寸上存在较大差异，因此在芯片与光纤的耦合处会引入很大耦合损耗。该损耗是InP基光子器件插损的最大来源，同时也是影响InP光子器件是否满足实际应用需求的主要因素之一。为了降低InP基光子芯片与光纤之间由模式失配造成的损耗，在光子芯片输入/输出端口需采用模式转换结构[13–18]，常见结构如图5所示。可以看出，每种模式转换器的结构都比较复杂，具有较高的工艺难度，尤其是在垂直方向采用斜面过渡的模斑转换结构(如图5(a)，图5(c)所示)。

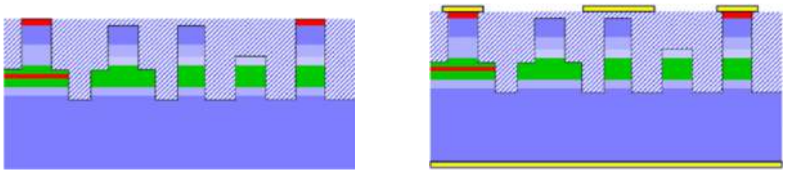
2.2 Si基光子集成芯片

Si基光子芯片常用的材料是SOI(Silicon-On-Insulator)[19]和SiN[20,21]，制备工艺成熟、材料成本低，在无源光子器件应用中具有非常明显优势[22]。目前，基于成熟的硅基工艺，已经发展出了硅基光源[23–28]、调制器[29–35]、探测器[36–40]、集成OEO(Op-



(a) 外延生长
(a) Epitaxial growth

(b) 波导刻蚀
(b) Waveguide etching

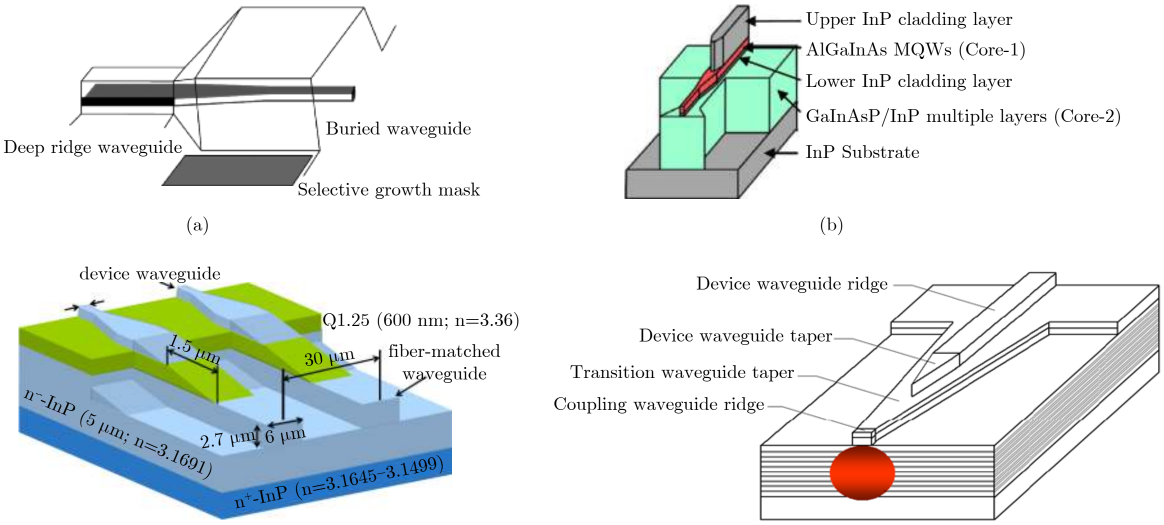


(c) 钝化和平坦化
(c) Passivation and planarization

(d) 接触与互连金属化
(d) Contacting and interconnect metallization

图 4 基于多次外延技术的InP基光子器件单片集成工艺[11]

Fig. 4 Monolithic integration of InP-based photonic devices based on the multi-epitaxial growth[11]



(a)　(b)

(c)　(d)

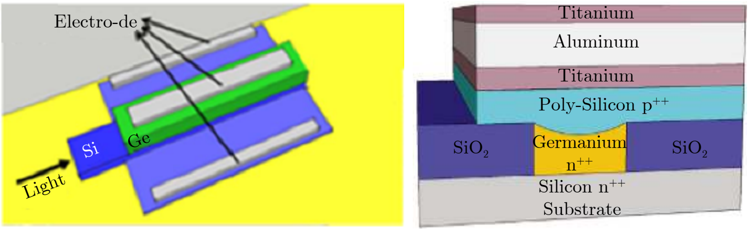
图 5 典型InP基光子器件模斑转换器[13–16]

Fig. 5 Typical spot-size converter of InP-based photonic devices[13–16]

toelectronic Oscillator)[41]、滤波器[42–44]、光开关阵列[45,46]、延时器[47–49]等集成光子芯片，如图6—图8所示。目前，基于硅材料的光学器件研究已经逐渐发展出了一门专一的学科，即硅基光子学。在成熟SOI加工工艺带动下，硅基无源光子器件发展迅速，功能较全面，研究已从单一功能芯片向多功能芯片发展。但硅基调制器的消光比还比较低，与传统的铌酸锂调制器差距较大，且带宽还需进一步提高。针对硅基光源的研究仍处于起步阶段，还需进一步深入研究。另外，SOI光波导损耗比较大，通常为几个dB/cm，无源器件的性能受到了一定限制。近年来，基于低损耗SiN光波导的无源器件得到了更广泛的关注与研究[50–53]，其非常适用于波束形成、延时阵列等芯片，如图9所示。

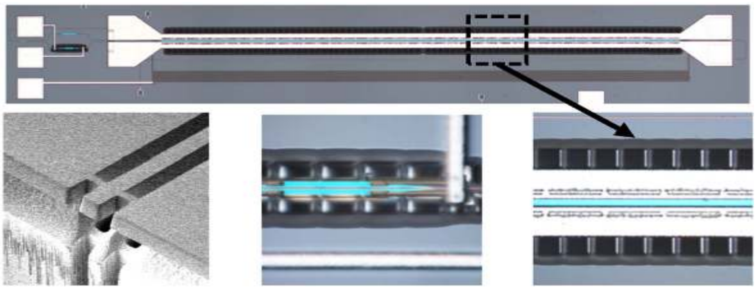
2.3 LiNbO$_3$基光子集成芯片

LiNbO$_3$材料具有优越的电光性能，与InP基材料和Si基材料相比，LiNbO$_3$材料的应用比较单一，主要集中在电光调制器[54–63]。基于LiNbO$_3$材料的电光调制器[55,56,64]是目前发展最成熟的电光调制器类型，在微波光子技术中已得到广泛应用。常用LiNbO$_3$电光调制器芯片中的LiNbO$_3$光波导通常采用质子交换或扩散工艺实现，工艺简单，光模式面积大，与光纤耦合损耗低。目前，这种商用LiNbO$_3$电光调制器的带宽都可以大于60 GHz，半波电压



(a) Ge-on-Si波导型光电探测器
(a) Ge-on-Si waveguide photodetector

(b) Ge-on-Si激光器
(b) Ge-on-Si laser



(c) Si电光调制器
(c) Silicon electro-optic modulator

图 6 Si基光子器件

Fig. 6 Si-based photonic devices

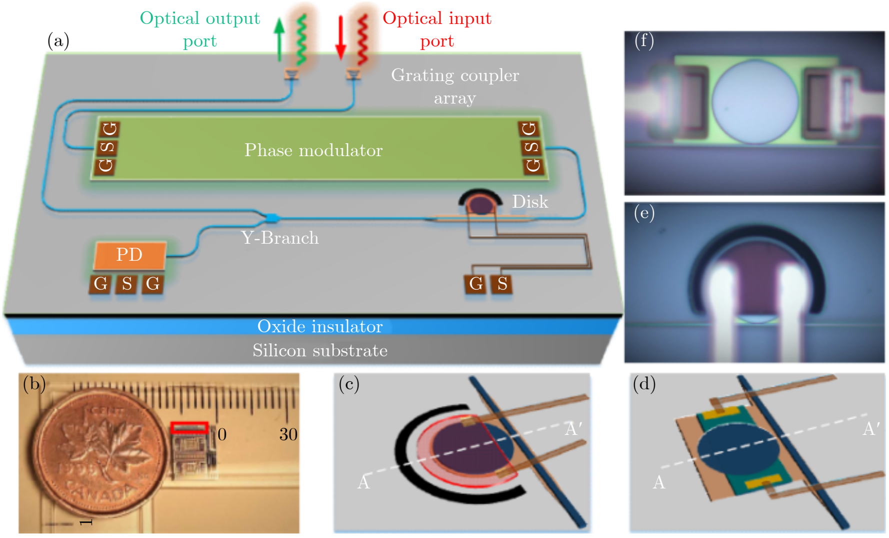


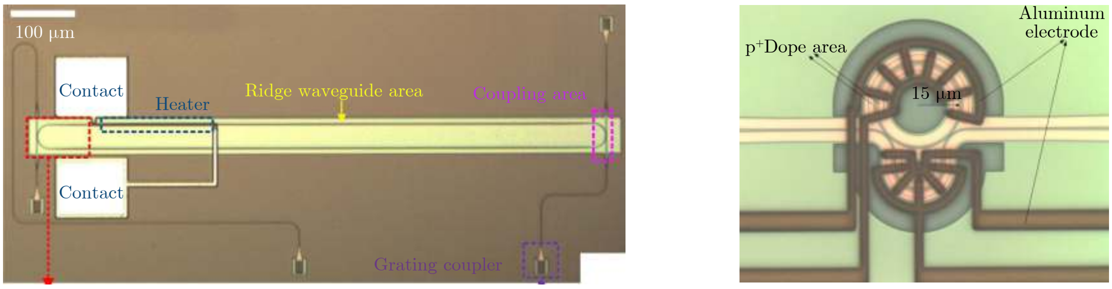
图 7 Si基集成OEO芯片[41]

Fig. 7 Si-based integrated OEO chip[41]

小于等于5 V。甚至，有文献报道这种调制器可以实现约100 GHz的带宽[65]。虽然，这种调制器的性能很好，但器件尺寸都非常大，通常有几厘米的长度，难以与其它光子器件实现小型化集成，无法满足微波光子系统未来小型化、集成化发展需求。近年，新发展出了一种基于$LiNbO_3$薄膜材料的电光调制器，如图10所示，该器件在带宽和尺寸等方面均呈现出了优于传统$LiNbO_3$体材料电光调制器的趋势。但目前这种新型$LiNbO_3$电光调制器还处于研发阶段，将来会在微波光子领域发挥重要应用价值[66,67]。

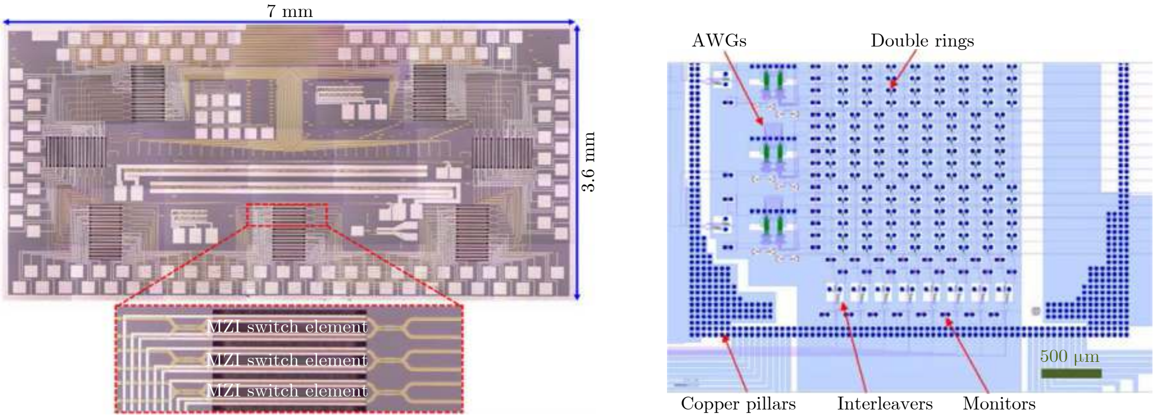
2.4 新型光子集成芯片

除了以上3种典型材料体系的集成光子芯片外，目前还出现了石墨烯、聚合物、等离子激元等新型材料体系的集成光子器件，且表现出了令人惊喜的性能，如图11所示。例如：基于石墨烯材料的电光调制器[68–72]，带宽可以达到几十GHz；基于有机聚合物材料的集成光波导传输损耗低、制备工艺简单、成本低廉，且热光特性良好，在集成光子谐振腔及热光开关方面都有广泛应用[73–80]，其中聚合物电光调制器的带宽可超过100 GHz[81]；等离子激元光波导对光具有很强的约束能力，能够突破衍射极限，且



(a) 光滤波器[43]
(a) Optical filter[43]

(b) 光延时器[47]
(b) Optical time delay[47]

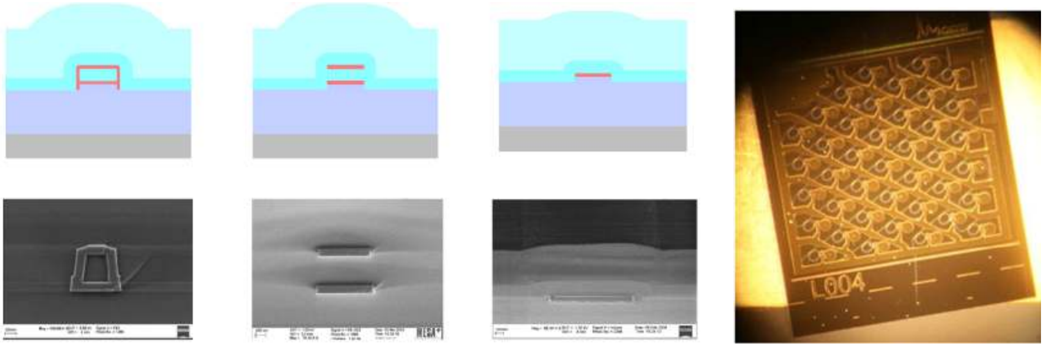


(c) 光开关阵列[45]
(c) Optical switching array[45]

(d) 光电集成光开关网络[46]
(d) Optoelectronic integrated switching[46]

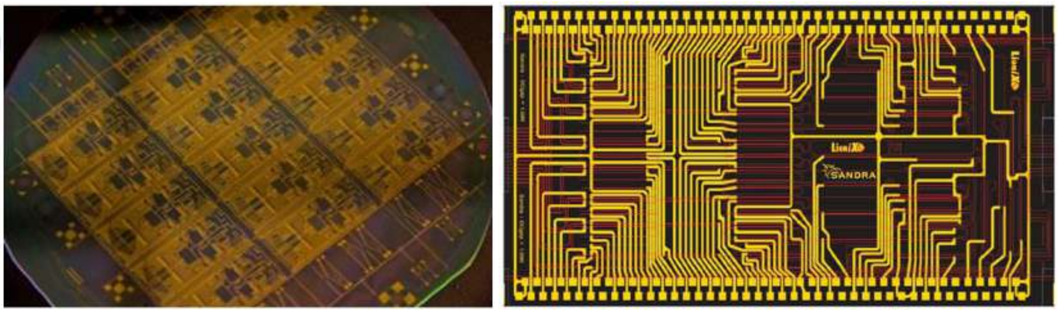
图 8 Si基光子器件

Fig. 8　Si-based photonic devices



(a) 光波导[21]
(a) Optical waveguide[21]

(b) 光延时器[51]
(b) Optical time delay[51]



(c) 光波束形成圆片[21]
(c) Optical beamforming wafer[21]

(d) 光波束形成芯片[5]
(d) Optical beamforming chip[5]

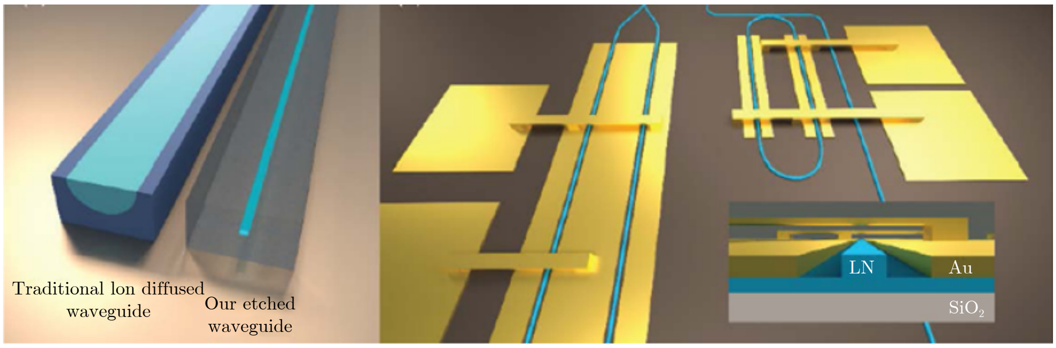
图 9 SiN光子器件

Fig. 9　SiN photonic devices

具有光电复用等优良特性，在微纳集成光子器件领域应用前景广阔。尤其，近年来还有研究人员将具有高电光系数的聚合物电光材料与狭缝等离子激元波导结合，实现了尺寸只有几十微米，带宽可超过70 GHz的超小型电光调制器，为实现高性能超集成电光调制器提供了非常可行的技术途径[82,83]。这些新技术为实现高性能集成微波光子器件提供了新方法，未来可能会在提升微波光子雷达性能方面发挥重要作用。

2.5 异质光子集成芯片

InP基材料、Si基材料和$LiNbO_3$材料在微波光子器件中都具有广泛应用，但不同的材料体系均具有各自的优点和缺点。例如：InP材料非常适用于激光器、调制器和探测器，而且发展成熟，但光波导传输损耗大，不利于大规模的光子芯片集成；Si基光子器件集成度高、工艺成熟、成本低，但在光源、调制器方面的发展还不是很成熟；铌酸锂材料仅仅在电光调制器方面具有独特优势，但在其他光子器件方面的应用还比较少。因此，利用同一材料实现多种光子器件的高性能单片集成，还存在一定的难度。异质异构集成技术可以发挥各种材料的优势，是实现大规模多功能光子集成芯片的有

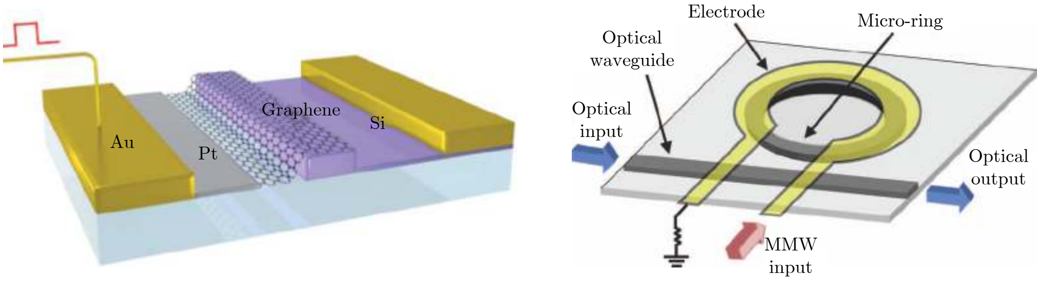


(a) $LiNbO_3$光波导
(a) $LiNbO_3$ optical waveguide

(b) 薄膜$LiNbO_3$电光器件
(b) Electro-optic devices based on $LiNbO_3$ film

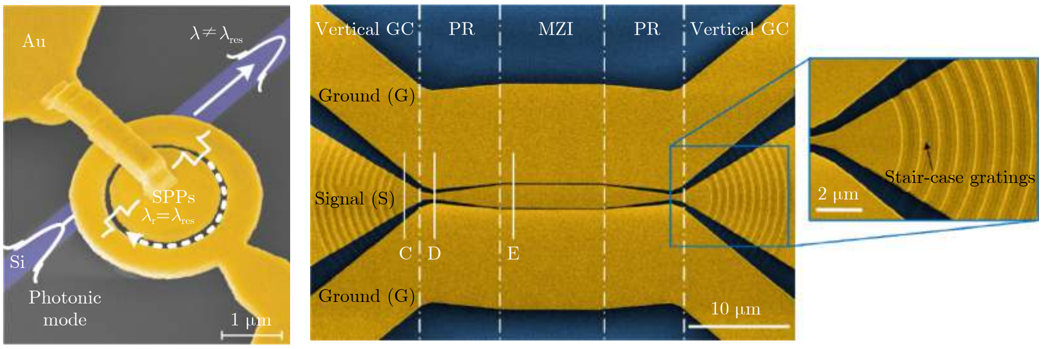
图 10 $LiNbO_3$基集成光子芯片

Fig. 10 $LiNbO_3$-based integrated photonic chip



(a) 石墨烯电光调制器
(a) Graphene-based electro-optic modulator

(b) 聚合物基电光调制器
(b) Polymer-based electro-optic modulator



(c) 等离子激元电光调制器
(c) Plasmonic electro-optic modulator

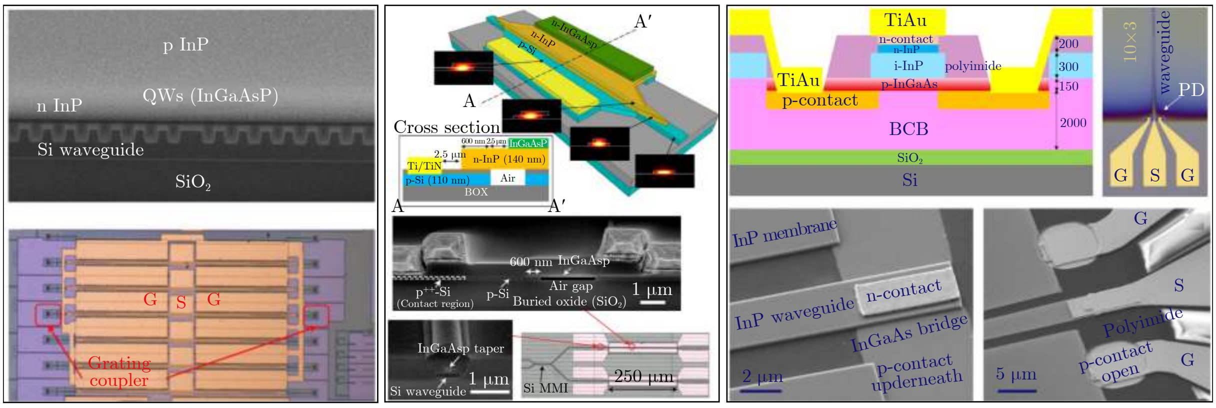
图 11 新型集成光子器件

Fig. 11 New integrated photonic devices

效技术途径。目前研究的异质光子集成技术主要是InP-Si光子集成、$LiNbO_3$-Si光子集成和光子异构集成。

InP-Si光子集成主要是为了结合InP材料在激光器、调制器及探测器方面的优势和Si材料在无源光子器件方面的低成本及CMOS工艺兼容等优势。基于InP-Si光子集成方法，目前已经研制出了InP-Si异质集成电光调制器[84–86]、InP-Si异质集成激光器[87–90]、InP-Si异质集成光电探测器[91]和其它更复杂的多功能芯片，如图12所示。

$LiNbO_3$-Si光子集成的主要目的是为了同时发挥$LiNbO_3$器件优越的电光特性和Si基光子器件的各种优势。图13展示了常见$LiNbO_3$-Si混合集成光波导结构(图13(b)—图13(g))及其与传统$LiNbO_3$光波导结构(图13(a))的区别[94]。目前，$LiNbO_3$-Si光子集成方向的研究焦点主要是基于Si基$LiNbO_3$薄膜材料(图13(b)—图13(e)，图13(g))的电光调制器[95,96]。Si基$LiNbO_3$薄膜材料的衬底为Si基材料，中间层为SiO_2，上表层为纳米厚度$LiNbO_3$薄膜。Si基衬底材料可满足基于CMOS工艺的大规模Si光子集成需求，纳米级厚度的铌酸锂薄膜材料可以将光限制在很小的尺寸内，大大提高电光调制效率，缩短调制器尺寸。而且，中间层为SiO_2的厚度可根据波速匹配需求灵活调整，这对提高调制器带宽非常有利。因此，与传统$LiNbO_3$体材料相比，基于Si基$LiNbO_3$薄膜材料的电光调制器能够实现更优异的性能指标。2018年哈佛大学研究团队采用图13(d)波导结构，成功研制出了带宽高达100 GHz、半波电压4.4 V、器件长度仅有5 mm的Si基$LiNbO_3$薄膜电光调制器，如图14所示，该成果发表于《Nature》，在光电子领域引起了针对该器件的研究热潮[97]。2019年，中山大学研



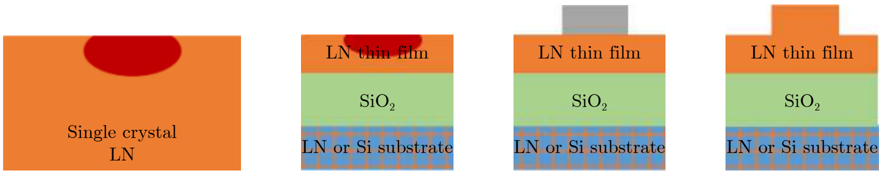
(a) 异质集成直调DFB激光器[90]
(a) Heterogeneous integrated direct-tuned DFB laser[90]

(b) 异质集成电光调制器[92]
(b) Heterogeneous integrated electro-optic modulator[92]

(c) 异质集成光电探测器[93]
(c) Heterogeneous integrated photodetector[93]

图 12 InP-Si光子集成器件

Fig. 12 InP-Si integrated photonic devices

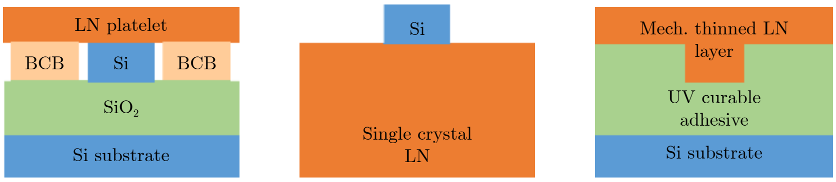


(a) LN体材料扩散型
(a) Diffused waveguide

(b) 薄膜LN扩散型
(b) Diffused waveguide based on LN film

(c) 基于薄膜LN的脊形加载型
(c) Rib loaded

(d) 薄膜LN刻蚀型
(d) Etched LN



(e) SOI波导上覆LN平板型
(e) LN on SOI

(f) LN体材料上覆Si波导型
(f) Si on bulk LN

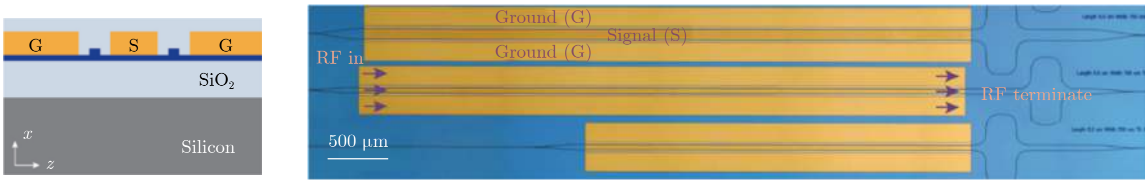
(g) 机械减薄LN倒脊型
(g) Mechanically thinned LN

图 13 传统$LiNbO_3$ (LN)光波导和常用$LiNbO_3$-Si混合集成光波导结构示意图[94]

Fig. 13 Structural diagrams of traditional $LiNbO_3$ optical waveguide and common $LiNbO_3$-Si hybrid integrated optical waveguides[94]

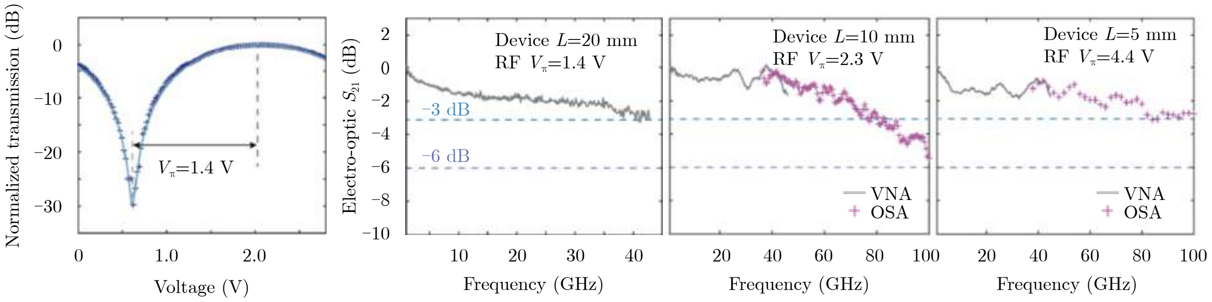
究人员又采用BCB材料实现了$LiNbO_3$薄膜光波导与SOI光波导的混合集成[98]，研制出的电光调制器带宽高于70 GHz，消光比达40 dB，器件整体插损仅有2.5 dB，如图15所示。

InP-Si、$LiNbO_3$-Si光子异质集成是基于芯片工艺实现不同材料或光子器件集成的一种技术。除了这种光子异质集成技术外，德国Christian Koos教授研究团队[99–104]还开发出了一种和电路芯片中金丝互连技术类似的光丝互连技术(Photonic Wire Bonding, PWB)，该技术不仅可以实现不同光子芯片之间的互连集成，还可以实现光纤与光子芯片波导端口的耦合，如图16所示。PWB中互连光波导的损耗可以小于3 dB，且受工作波长影响较小，是实现大规模光子集成的一种崭新技术途径。



(a) 剖面示意图
(a) Cross-sectional schematic

(b) 显微镜图片
(b) Microscolpe image



(c) 消光比
(c) Measured extinction ratio

(d) 电光带宽
(d) Measured electro-optic bandwidths of modulators with different lengths

图 14 基于Si基$LiNbO_3$薄膜的电光调制器[97]

Fig. 14 Electro-optic modulator based on Si-based $LiNbO_3$ film[97]

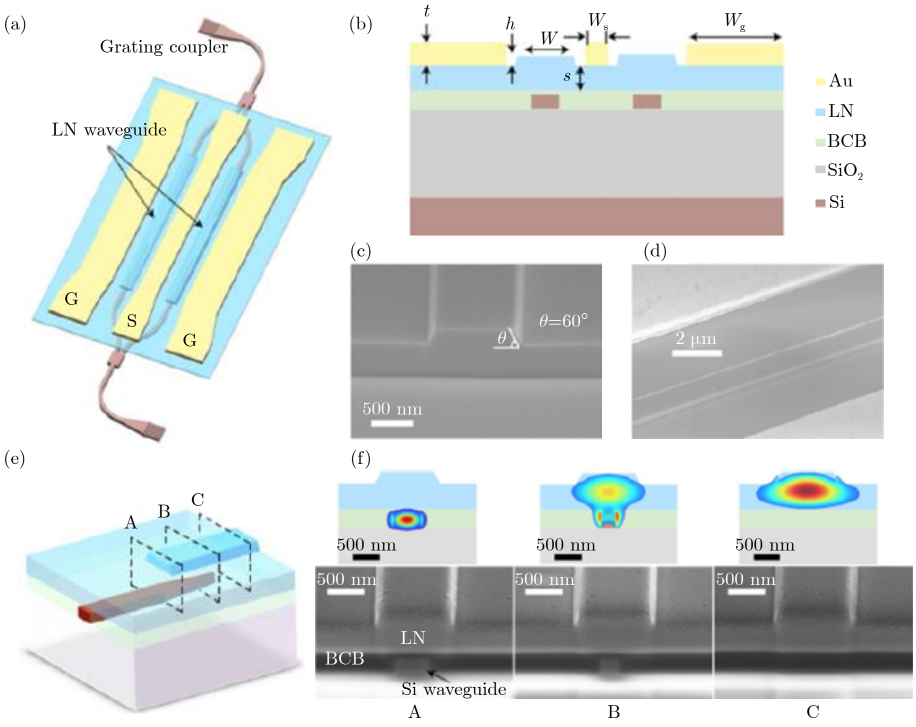


图 15 Si-$LiNbO_3$混合集成电光调制器[98]

Fig. 15 Si-$LiNbO_3$ hybrid integrated electro-optic modulator[98]

表1是以上介绍集成光子芯片技术中一些报道的集成光子器件及其性能。

3　光电混合集成芯片

光电混合集成是微波光子器件芯片发展的最终目标，目前实现这一目标的常见方案是基于引线互连的光电集成和光电单片集成。

基于引线互连的光电混合集成是最容易实现的一种，即直接采用金丝引线将光芯片与电路芯片的电极互连。2017年，日本研究人员[130]将InP光子芯片与跨阻放大电路芯片通过引线互连方式实现了光电混合集成光接收器芯片及模块，如图17所示，带宽可达40 GHz。2016年德国研究人员[131,132]实现了InP周期分段型IQ电光调制器与驱动电路芯片的引线互连，信号传输距离可超过80 km，如图18所示。

光电单片集成是将光芯片与电芯片集成到同一片上的技术，目前主要包括同片集成和异质异构集成2种。同片集成采用同一材料体系，在一个晶片上同时加工出光器件与电器件[133,134]。图19是Ge-Si光电探测器与Si基TIA电路的单片集成。图20是InP/InGaAs HBT和InP基光电探测器单片集成实现OEMMIC的方案。异质异构集成是通过键合和垂直互连技术将光子芯片和电路芯片堆叠集成到一起的技术，两个芯片的材料体系可以相同也可以不同，材料选择更加灵活，更能发挥每种材料本身的优势。图21为InP基光子芯片和基于CMOS工艺的Si基电路芯片通过堆叠实现光电异质异构集成的结构示意图[135]。

随着微波光子雷达发展需求的不断提升，光电集成化、芯片化已成为微波光子雷达器件的发展趋势和迫切需求，包括光电集成收发前端芯片、光电集成振荡器芯片、光电集成混频器芯片、光电集成波束形成芯片等。例如：2014年，Pascual Munoz等人[6]就提出了集成微波光子收发前端的构想，如图22所示。该芯片主要包含：激光光源(a)、可重

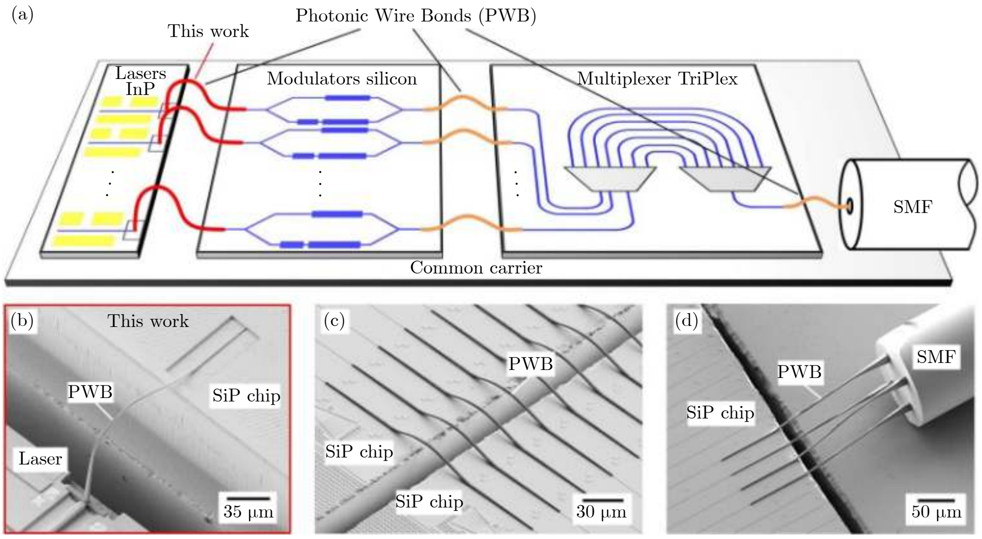


图 16 基于PWB技术的光子异质异构集成[104]

Fig. 16 Photonic heterogeneous integration based on PWB technology[104]

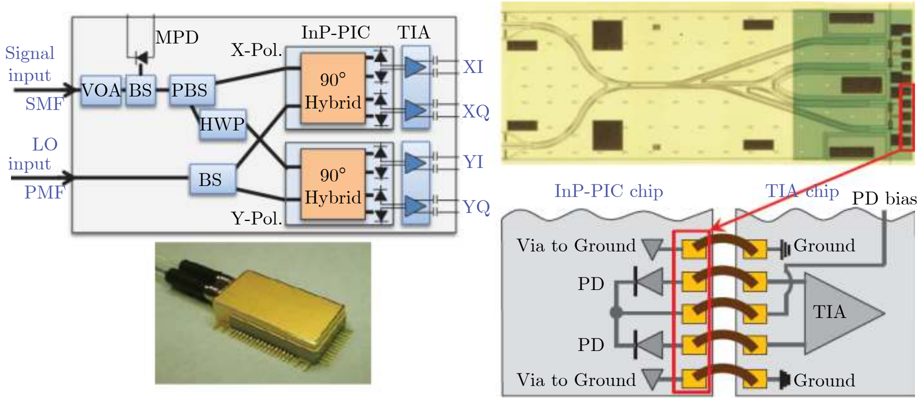


图 17 基于引线互连的光电混合集成接收器芯片及模块[130]

Fig. 17 Hybrid optoelectronic integrated receiver chip and module based on wire bonding[130]

构光信号调谐系统(b)、电光调制器(c)、光耦合器(d)和(f)、可重构光滤波器(e)、光电探测器(g)、RF放大器(h)、滤波器(i)、RF开关(j)、RF输入端/输出端口和光输入/输出端口等器件结构。该构想为

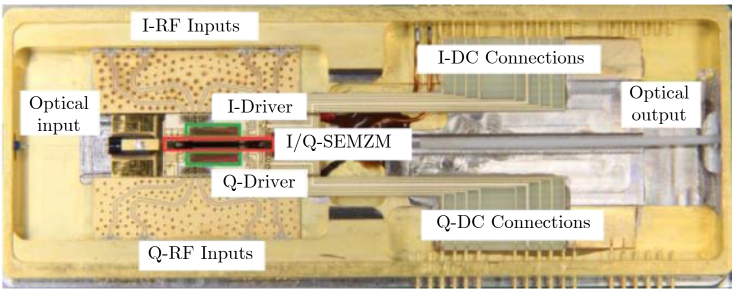
表 1 报道的一些集成光子器件及性能

Tab. 1 Some reported integrated photonic devices and their performances

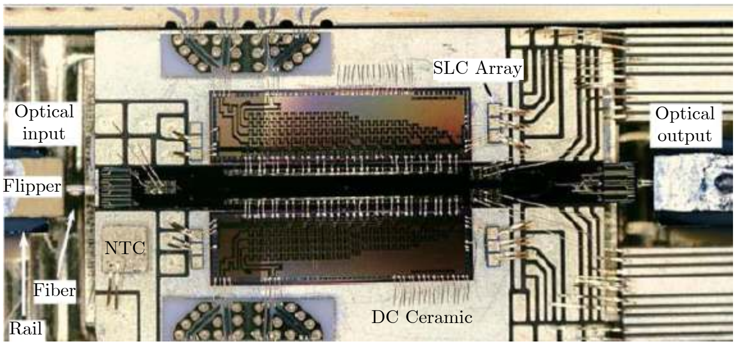
材料	时间	第一作者国籍	器件	指标
InP	1999	The Netherlands	波束形成[105]	通道：1×16，插损：28±1.0 dB，相位动态范围：360°
	2004	Germany	波导型PD[106]	带宽：100 GHz，响应度：0.66 A/W
	2010	USA	OPLL[107]	带宽：300 MHz
	2011	USA	可编程微波光子滤波器[108]	带宽：1.9～14 GHz, SFDR: 86.3 dB×Hz$^{2/3}$
	2013	China	DFB激光器阵列[109]	通道数：4
	2014	Germany	平衡PD[110]	带宽：80 GHz，响应度：0.5 A/W
	2016	Germany	DFB+IQ电光调制器[111]	带宽：43 GHz，耦合损耗：0.1 dB
	2017	Sweden	外调制激光器[112]	带宽：100 GHz，消光比：～30 dB
	2017	Japan	IQ调制器[113]	带宽：>67 GHz，半波电压：1.5 V，消光比：～30 dB
	2017	China	AWG+PD[114]	响应度：0.68 A/W，带宽：>16 GHz，通道数：13
	2017	Germany	波导型PD[115]	带宽：80 GHz，响应度：0.5 A/W
	2017	Germany	波导型平衡PD[116]	带宽：115 GHz，响应度：0.25 A/W
	2018	UK	开关阵列[10]	规模：4×4，串扰：–47 dB
Si	2004	USA	调制器[29]	带宽：1 GHz，调制效率：8 V·cm，插损：15.3 dB，静态消光比：16 dB
	2005	USA	拉曼激光器[23]	波长：1.67 μm，线宽：80 MHz，边模抑制比：55 dB
	2007	USA	调制器[30]	带宽：30 GHz，速率：40 Gbit/s，动态消光比：1.1 dB
	2007	USA	GeSi探测器[36]	带宽：31 GHz，响应度：0.89 A/W，暗电流：169 nA
	2009	USA	GeSi探测器[37]	带宽：36.8 GHz，响应度：1.1 A/W
	2011	China	延时线[47]	延时量：–15～85 ps
	2012	USA	GeSi激光器[26]	波长：1520～1700 nm，线宽：<1.2 nm，输出功率：>1 mW
	2012	UK	调制器[31]	消光比：3.1 dB，调制效率：2.8 V·cm，带宽：20 GHz
	2012	China	调制器[32]	消光比：3.9 dB@40 Gbit/s，调制效率：2.6 V·cm
	2012	China	延时线[48]	延时量：270 ps, FWHM=2.1 GHz
	2013	Australia	微波带阻滤波器[50]	FWHM=247～840 MHz，抑制比：60 dB，中心频率范围：2～8 GHz
	2013	Singapore	调制器[33]	消光比：5.56 dB，调制效率：26.7 V·mm，带宽：25.6 GHz
	2013	China	微波带阻滤波器[44]	10 dB带宽：1.85～4.55 GHz，中心频率调谐范围：7～34 GHz
	2013	The Netherlands	波束形成网络[52]	规模：1×4，最大延时：236 ps，工作频率：10.70～12.75 GHz
	2016	China	开关阵列[45]	规模：16×16，串扰：–30 dB，开关时间：22 μm，插损：5.2 dB
	2017	Japan	调制器[34]	带宽：17 GHz，调制效率：0.8～1.86 V·cm
	2017	Canada	集成微波带通滤波器[42]	FWHM=2.3 GHz，抑制比：17 dB，中心频率调谐范围：7～25 GHz
	2017	USA	波束形成网络[53]	规模：1×4，带宽：6 GHz，最大延时：209 ps
	2018	China	调制器[35]	带宽：60 GHz，速率：100 Gbit/s，调制效率1.4 V·cm，插损：5.4 dB
	2018	China	GeSi探测器[40]	带宽：25 GHz，响应度：0.88 A/W
	2018	Canada	集成OEO[41]	相噪：–80 dBc/Hz，频率：2～8 GHz
	2018	China	微波带通滤波器[43]	FWHM=170 MHz，抑制比：26.5 dB，中心频率调谐范围：2.0～18.4 GHz
	2018	USA	真延时[51]	损耗：0.89 dB/ns，延时量调谐范围：0～3.4 ns，带宽：10 GHz@500 ps
$LiNbO_3$	1998	Israel	调制器[117]	带宽：40 GHz，半波电压：4.2 V
	2007	Switzerland	可调谐谐振腔[118]	R=100 μm, Q=4×10^3，清晰度F=5
	2009	USA	调制器[65]	带宽：～100 GHz，半波电压：7 V，插损：3.7 dB
	2010	China	1×2 Y分支光开关[119]	串扰：–30 dB

续表 1

材料	时间	第一作者国籍	器件	指标
Polymer	1997	USA	调制器[81]	带宽：113 GHz
	2002	USA	环形滤波器、调制器[76]	Q=1.3×10^5，谐振调谐效率：0.82 GHz/V
	2015	China	开关阵列[120]	规模：1×32
	2016	China	调制器[121]	电光系数：50 pm/V，半波电压：1.94 V
SPP	2010	Denmark	热光开关[122]	器件长度：<100 μm
	2015	Switzerland	天线+调制器	工作频率：60 GHz，转换效率：–25 dB
	2017	Switzerland	调制器[83]	器件长度：几十μm，带宽：>70 GHz
	2018	Switzerland	环形调制器[123]	R=1 μm, Q=30, FSR≈115 nm
Graphe	2011	USA	调制器[68]	光带宽：1.35～1.6 μm
	2013	Turkey	调制器[124]	光带宽：450 nm～2 μm
	2015	UK	调制器[125]	调制深度：>0.03 dB/μm
Si-InP	2016	Belgium	激光器[90]	波长：1566 nm，边模抑制比：45 dB，波导输出光功率：6 mW，直调带宽：15 GHz
	2016	USA	探测器[126]	响应度：0.64 A/W，输出功率：12 dBm@40 GHz，带宽：48 GHz
	2016	The Netherlands	波导型探测器	带宽：67 GHz，响应度：0.7 A/W
	2017	Japan	调制器[92]	带宽：2.2 GHz，调制效率：0.09 V·cm，消光比：3.1 dB@32 Gbit/s
	2018	Belgium	外调制激光器[127]	波长：1567 nm，边模抑制比：40 dB，波导输出光功率：3 mW，带宽：20 GHz，静态消光比：15 dB
Si-$LiNbO_3$	2014	USA	环形调制器[128]	带宽：5 GHz, Q值：14000，谐振调谐效率：3.3 pm/V
	2016	USA	调制器[67]	带宽：>8 GHz，半波电压：2.5 V，消光比：13.8 dB
	2016	USA	调制器[96]	带宽：～40 GHz
	2018	USA	调制器[97]	带宽：100 GHz，半波电压：5 V，消光比：～30 dB
	2019	China	调制器[98]	带宽：>70 GHz，半波电压：<7.4 V，消光比：～40 dB，插损：2.5 dB
	2019	USA	电光可调谐光频梳[129]	调谐范围：10～100 MHz



(a) 封装模型图片
(a) Picture of the packaged module



(b) 芯片详图
(b) Detailed view of the chip

图 18 InP基周期分段型IQ电光调制器与驱动电路芯片的引线互连[132]

Fig. 18 Hybrid optoelectronic integrated between the InP-based IQ modulator and the driver circuit based on wire bonding[132]

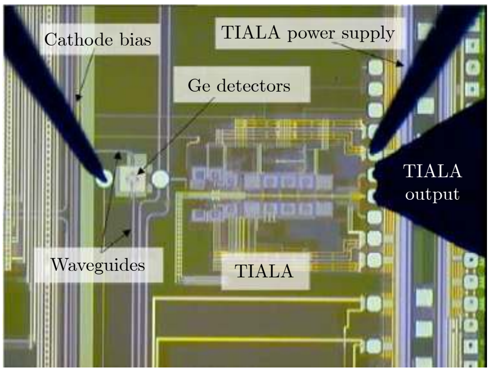


图 19 Si基光电单片集成[133]

Fig. 19 Si-based optoelectronic monolithic integration[133]

集成微波光子收发前端的发展提供了框架。为了实现微波光子雷达器件芯片集成化目标，光电异质异构混合集成是一种有效的技术途径，将对高性能、多功能微波光子雷达器件的研制起到重要推动作用。

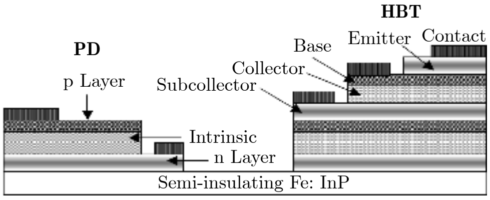


图 20 InP基光电单片集成[134]

Fig. 20 InP-based optoelectronic monolithic integration[134]

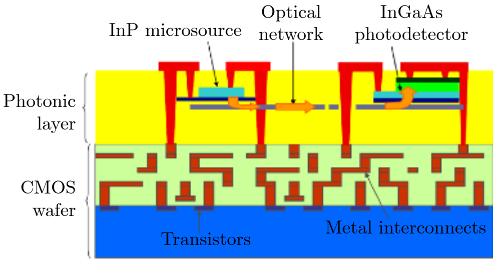


图 21 InP-Si光电异质集成[135]

Fig. 21 InP-Si hybrid optoelectronic integration[135]

4 结束语

微波光子技术是解决目前微波雷达装备中诸多电子瓶颈问题的颠覆性技术，微波光子器件是推动微波光子雷达发展的关键。目前，集成化、芯片化及多功能化已是微波光子雷达系统对各器件的迫切需求，集成芯片技术是解决该需求的核心技术。在光子集成方面，能够发挥各材料优越特性的异质光子集成将是未来发展趋势。在光电集成方面，近期采用引线互连方法更容易实现多功能、小型化光电集成微波光子功能模块，但从长远看，光电异质异构混合集成将是集成微波光子器件发展的必然趋势，将在未来高性能微波光子器件雷达研制中发挥重要作用。

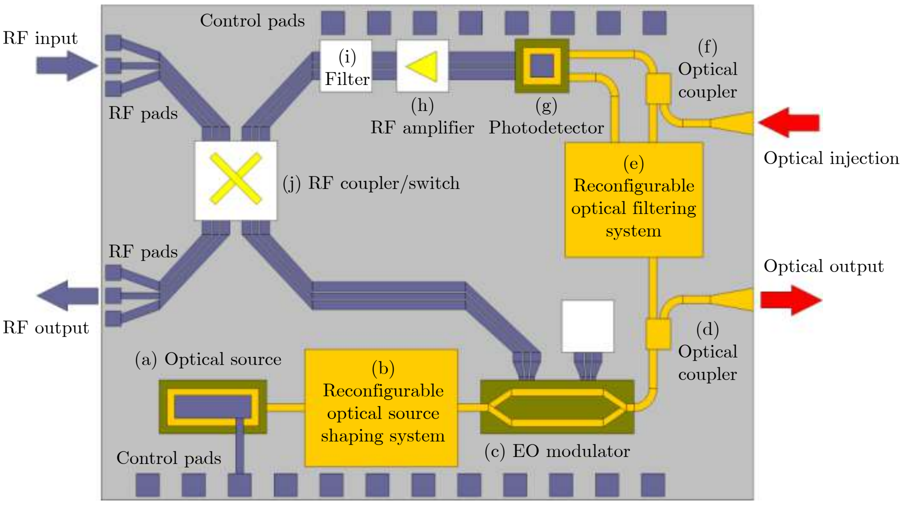


图 22 多功能集成微波光子收发前端芯片概念框架[6]

Fig. 22 Conceptual structure of multifunctional integrated microwave photonic transceiver chip[6]

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