大规模集成硅基光电子芯片封测技术

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汇报内容

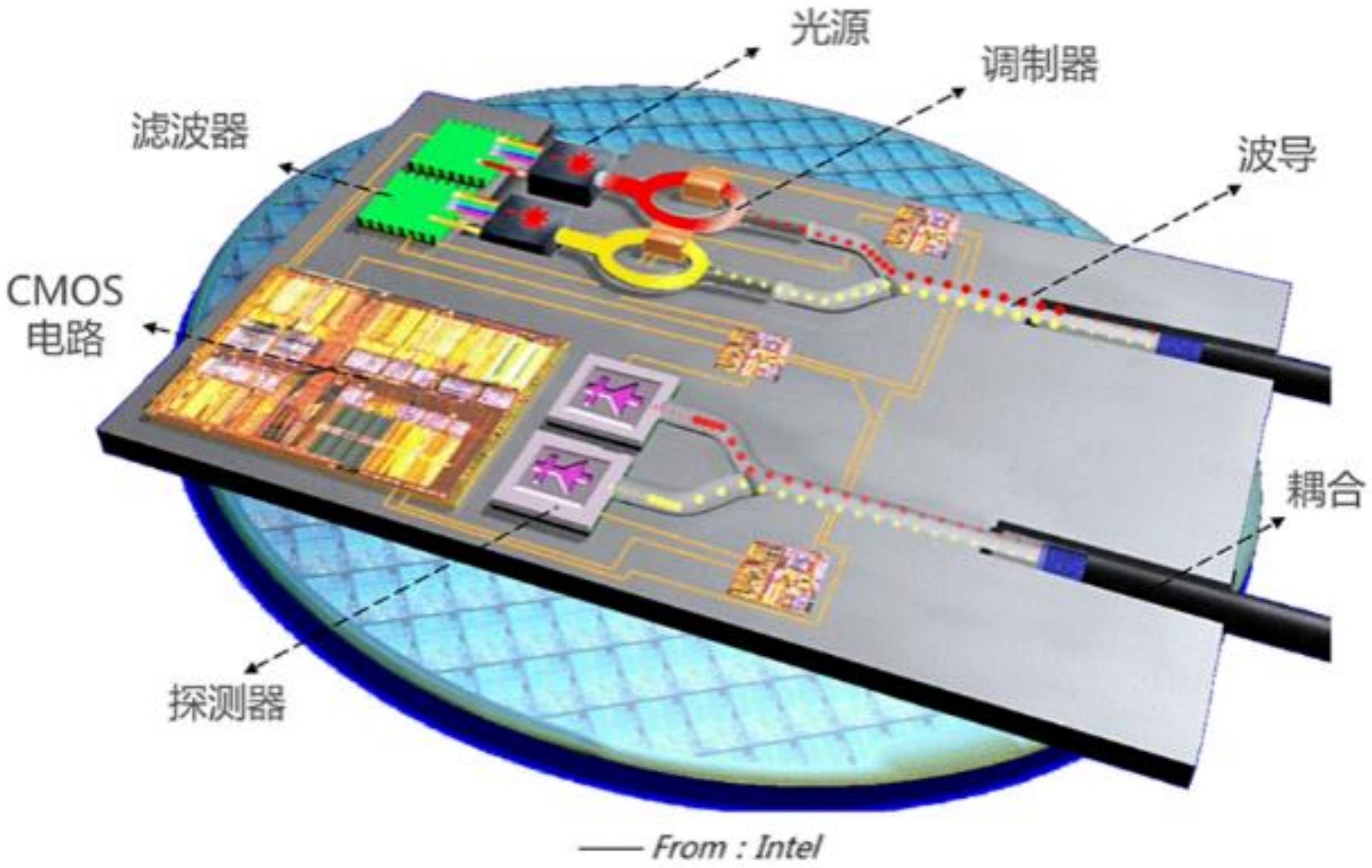
■ 光电子封测平台

- 光学封装
- 电学封装
- 器件测试
- 失效分析

■ 两个实例

- 大规模光开关
- 激光雷达芯片

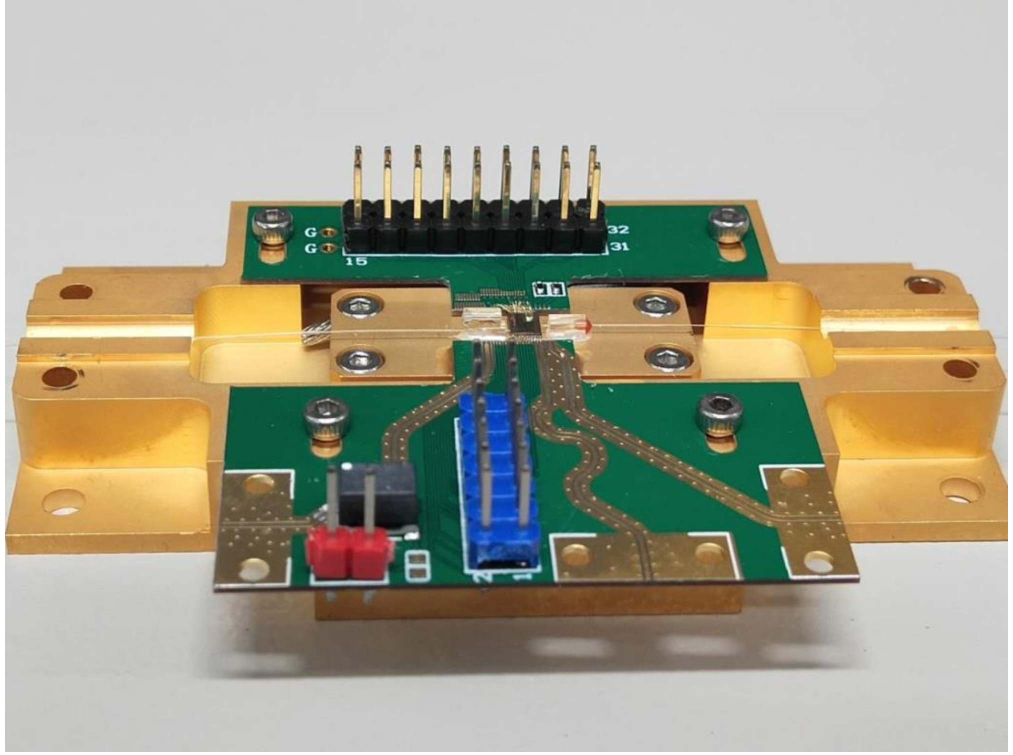
硅基光电子集成芯片



硅光优势

- 低损耗光波导，多种无源器件
- 低成本、高密度、大规模集成
- 成熟CMOS兼容制备工艺
- 与集成电路的光电集成

硅光芯片封测面临的问题



■ 光学封装

- 如何实现高密度光波导I/O接口和光纤连接?

■ 电学封装

- 如何实现硅光芯片的高密度电I/O接口连接?

■ 失效检测

- 如何定位芯片和模块问题部位和实效原因?

■ 控制电路

- 如何产生高密度多端口控制电信号?

光电子芯片封装测试平台


封测万级超净室

服务项目
Service Items

光电子芯片封装
管壳设计、
电学引线键合、倒装贴片、
光纤/光纤阵列/透镜耦合封装

光电子芯片及器件测试
单芯片和晶圆自动化测试，
包括调制器、光开关、光波导、
光放大器、光耦合器、
光探测器和激光器等器件

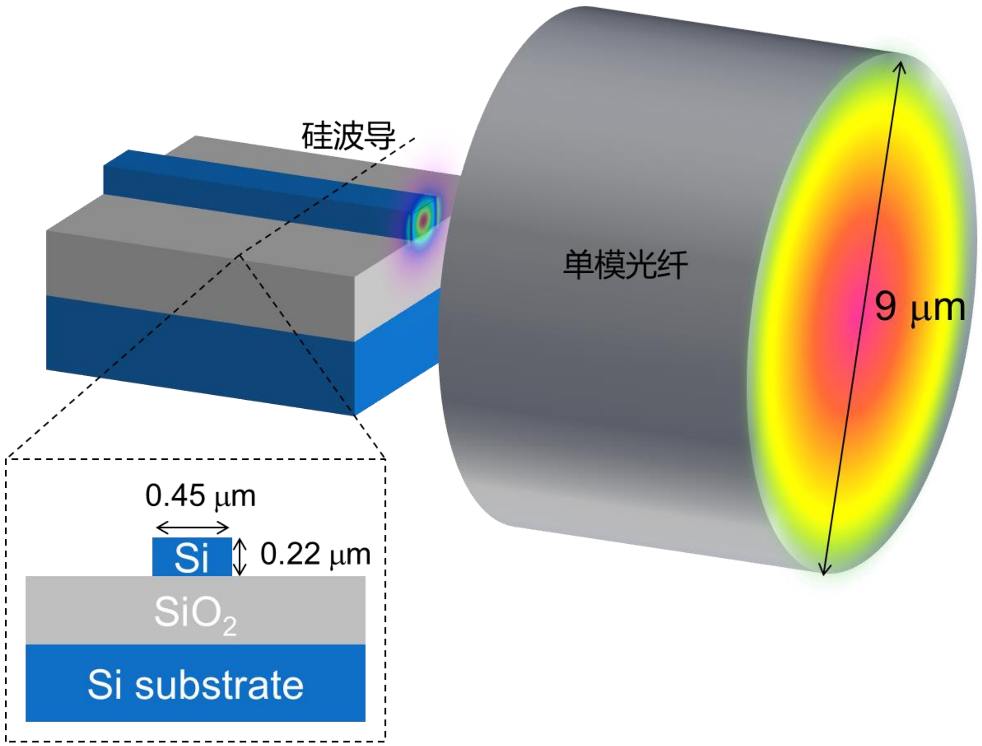
失效分析
可以进行芯片的电路修复、
芯片精细切割、封装可靠性分析、
3D XRM射线成像、SEM电镜成像、
材料分析等服务

- **光纤耦合封装**
  - 水平耦合封装工艺成熟
  - 滴胶固化工艺持续优化
  - 垂直耦合工艺探索中
  - 自动耦合机功能开发中
- **电学引线键合**
  - 20微米细线键合
  - 多排电极键合
  - 高速短线键合

- **器件性能测试**
  - 无源器件测试：插损、消光比、PDL等
  - 有源器件测试：S参数、I-V曲线等
- **晶圆自动测试**
  - 部分设备程序开发
  - 完成晶圆耦合测试

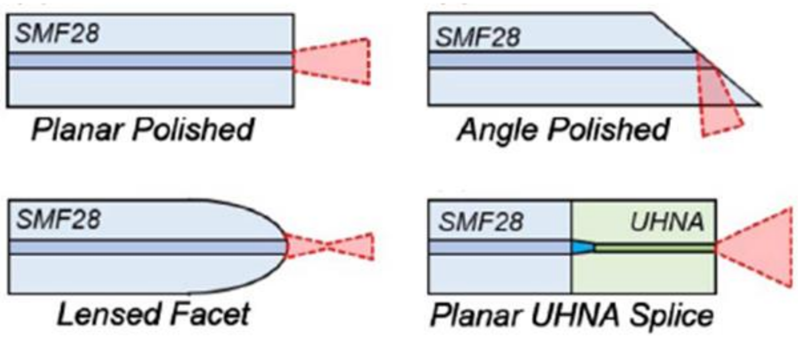
- **失效分析和微加工**
  - XRM：样品内部CT分析
  - FIB：TEM样品制备、电路修复、形貌分析、微纳加工

硅光波导耦合：光纤选择

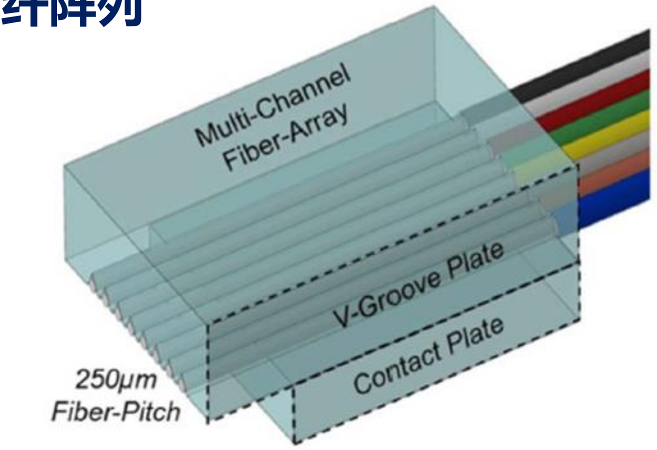


单模光纤和硅波导模场严重失配 → 直接端面耦合效率低

■ 光纤端面结构

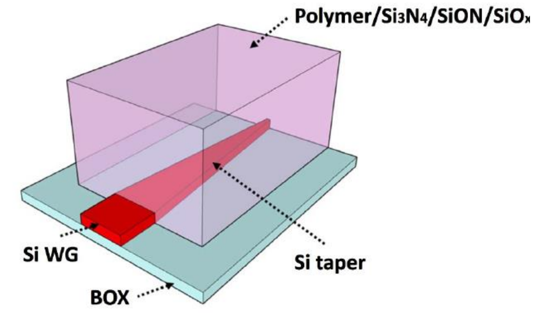


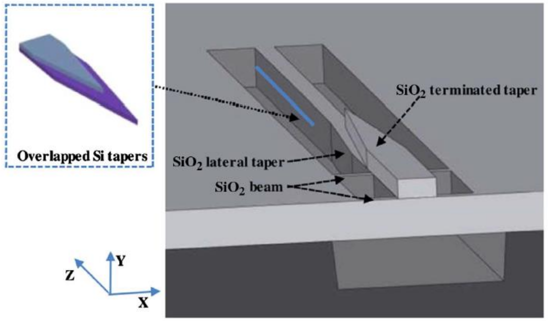
■ 光纤阵列

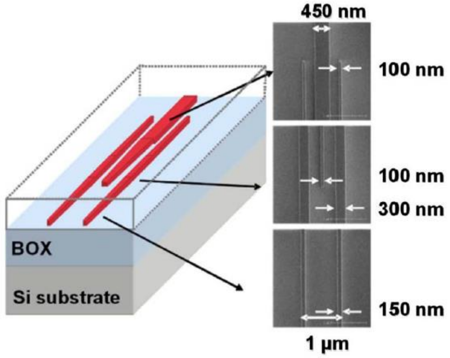


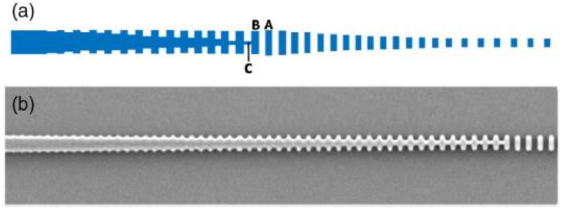
硅光波导耦合：波导耦合器设计

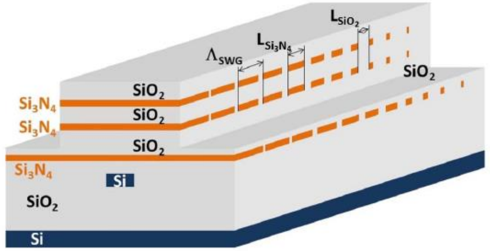
■ 水平耦合





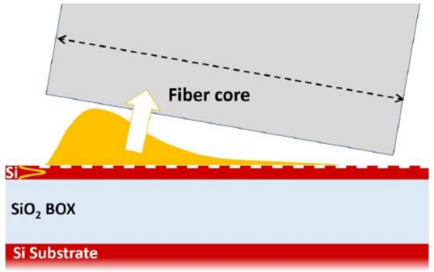


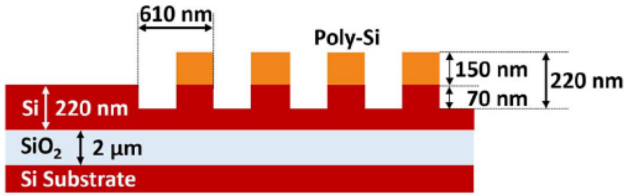


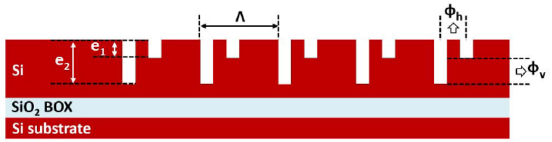


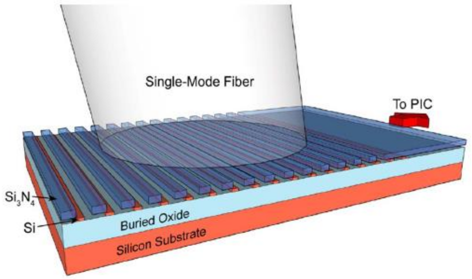
- 扩展模斑，与光纤匹配
- 工艺兼容性
- 工艺偏差容忍度

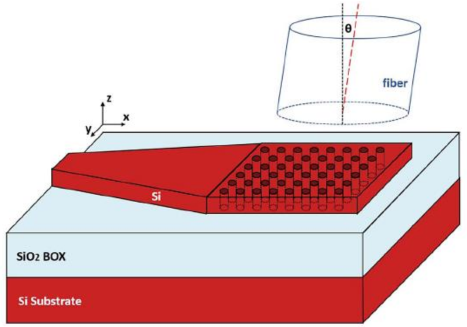
■ 垂直耦合









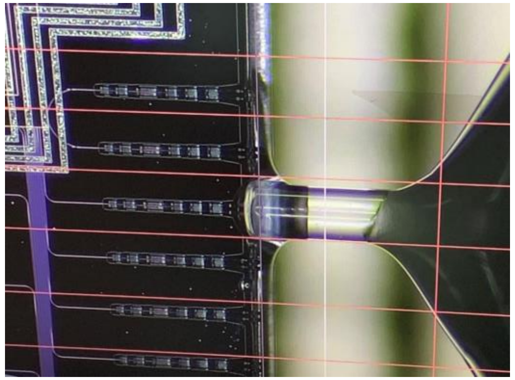


- 光栅衍射效率
- 定向发射能力
- 光学工作带宽

光学封装：①光纤水平耦合封装

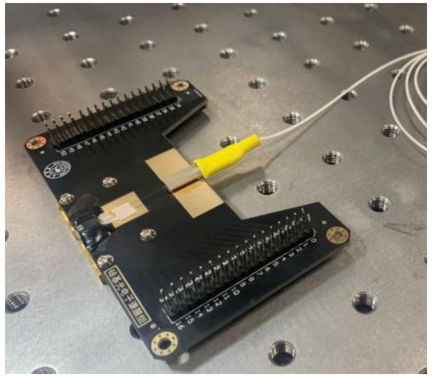
光纤类型	通道数	耦合附加损耗（dB）
单模光纤	1	0.3
单模透镜光纤	1	0.5
单模光纤阵列	<20	0.8
单模光纤阵列	20-38	1.5
单模透镜光纤阵列		视透镜模斑和通道数而定
其他定制光纤		视透镜模斑和通道数而定

单根平头光纤封装（模斑10μm）



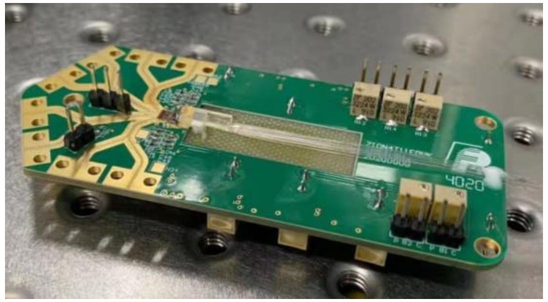
波导端面SSC耦合器

单根锥形光纤封装（模斑3μm）

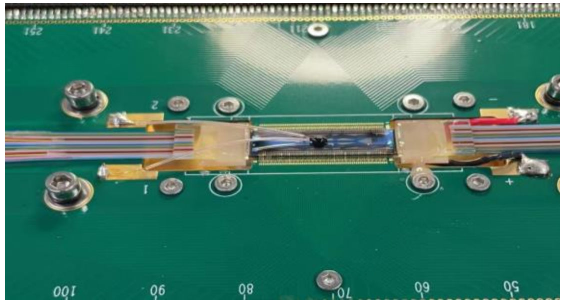


根据PD电流监控耦合

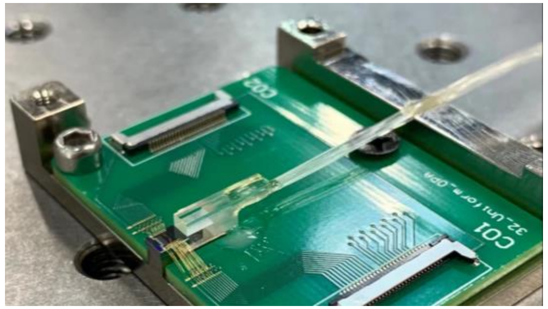
单边14通道单模光纤阵列



双边46通道单模光纤阵列

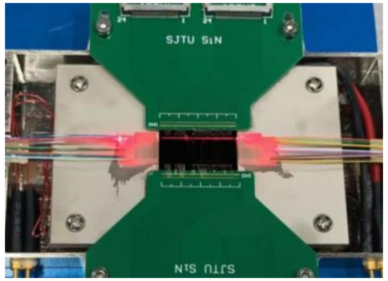


8通道6微米芯径单模光纤阵列

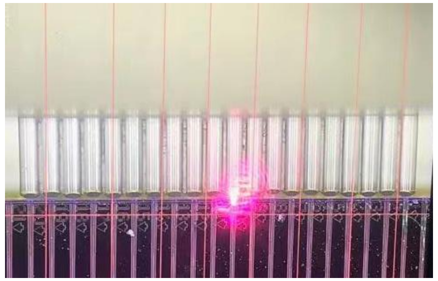


10通道6微米芯径单模光纤阵列

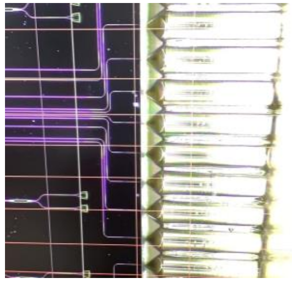
特殊间距单模光纤阵列



20通道楔形光纤阵列



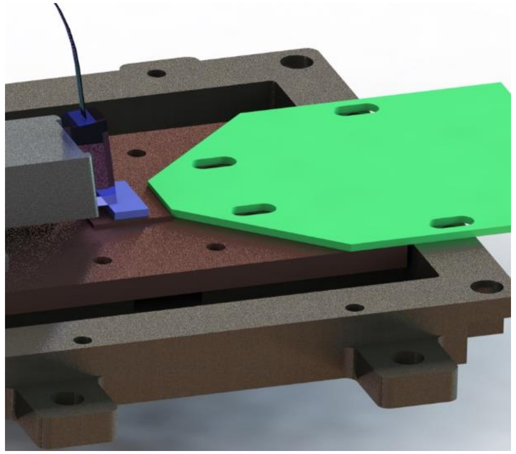
20通道锥形光纤阵列



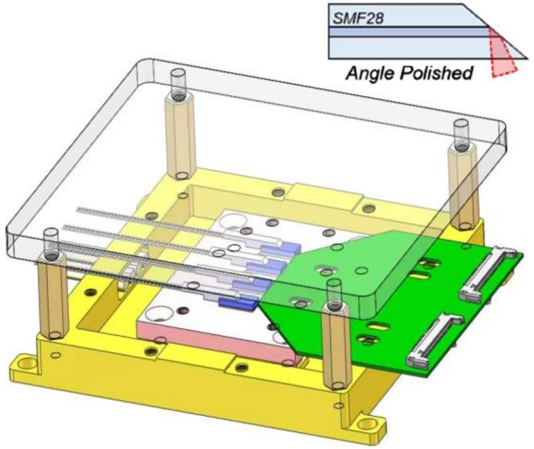
光学封装：②光纤垂直耦合封装

光纤类型	通道数	耦合附加损耗（dB）
单模光纤	1	0.3
单模光纤阵列	<20	0.8
单模光纤阵列	20-38	1.5
其他定制光纤		视透镜模斑和通道数而定

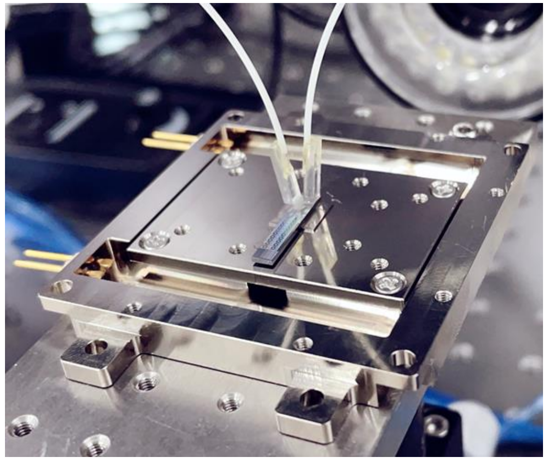
管壳设计（垂直耦合）



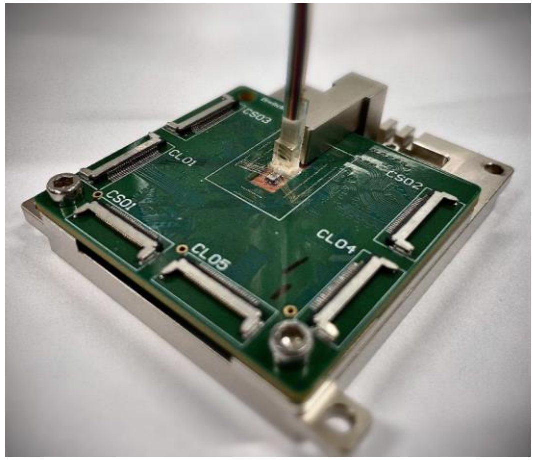
管壳设计（水平反射式）



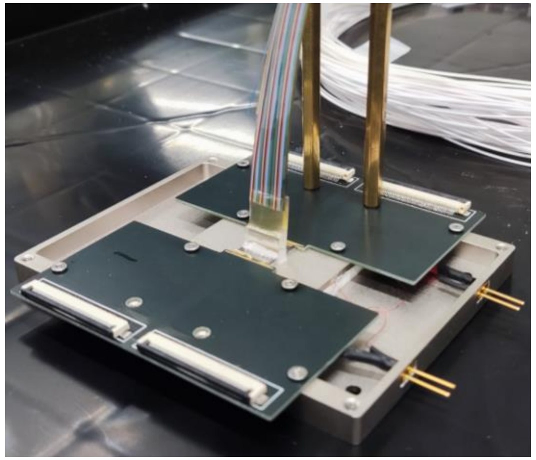
双边单通道光栅垂直耦合



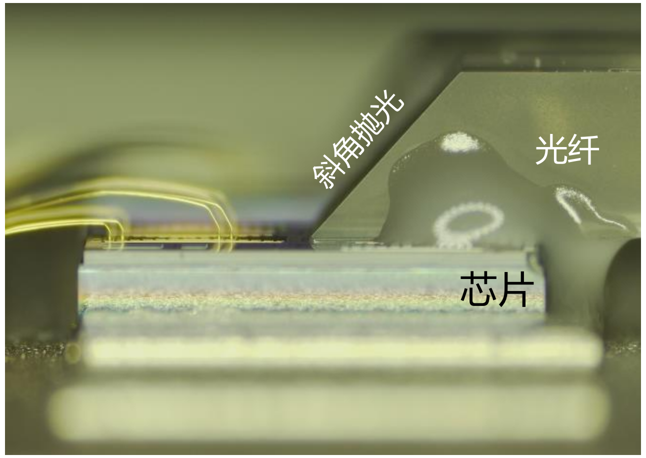
单边20通道光栅垂直耦合



单边81通道光栅垂直耦合



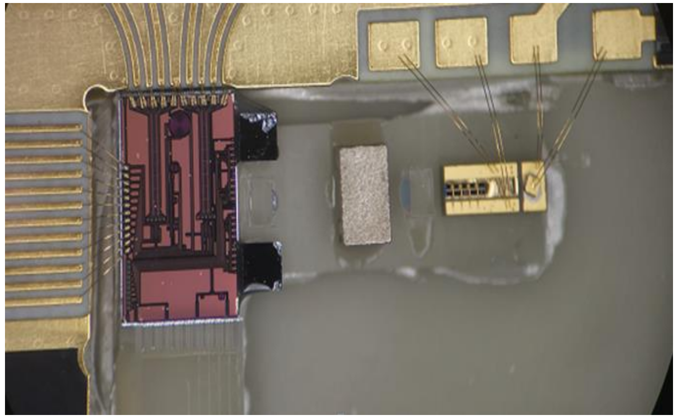
单边水平反射式光栅垂直耦合



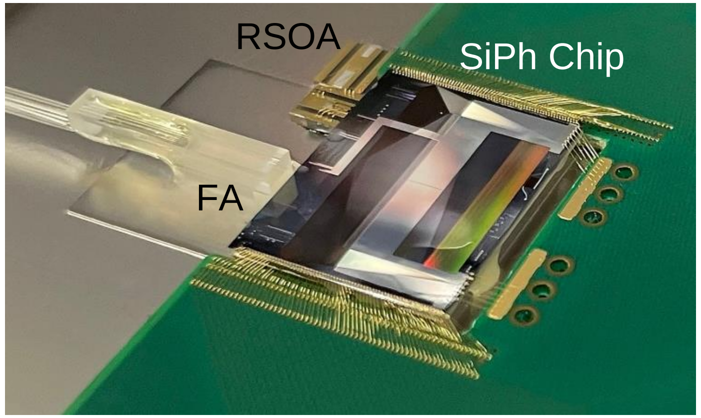
光学封装：③透镜和端面耦合封装

- **激光器—透镜—PIC芯片/光纤耦合**
  - 利用透镜实现模斑转换，耦合效率~60%-80%
- **异质异构芯片直接端面耦合**
  - 通过波导SSC实现高效耦合

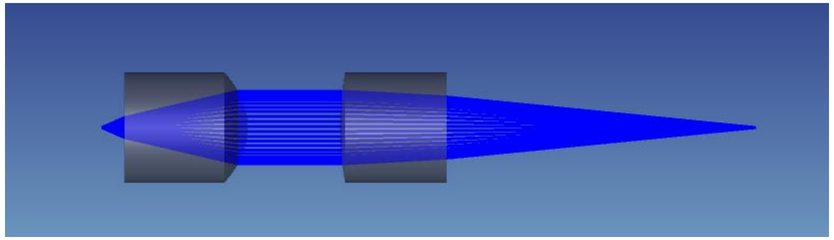
激光器-双透镜（隔离器）-硅光芯片

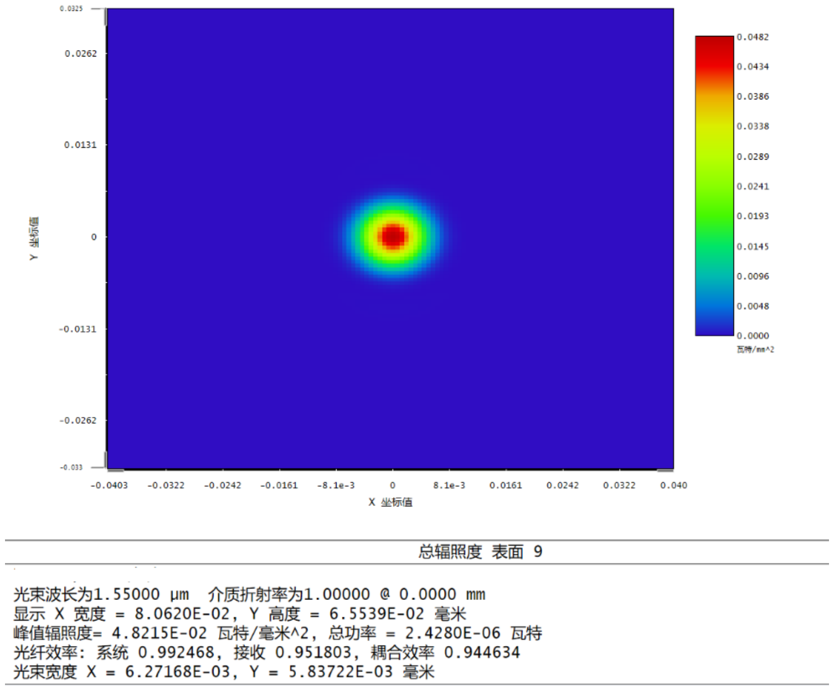


半导体增益芯片-硅光芯片



Zemax光路仿真





总辐照度 表面 9

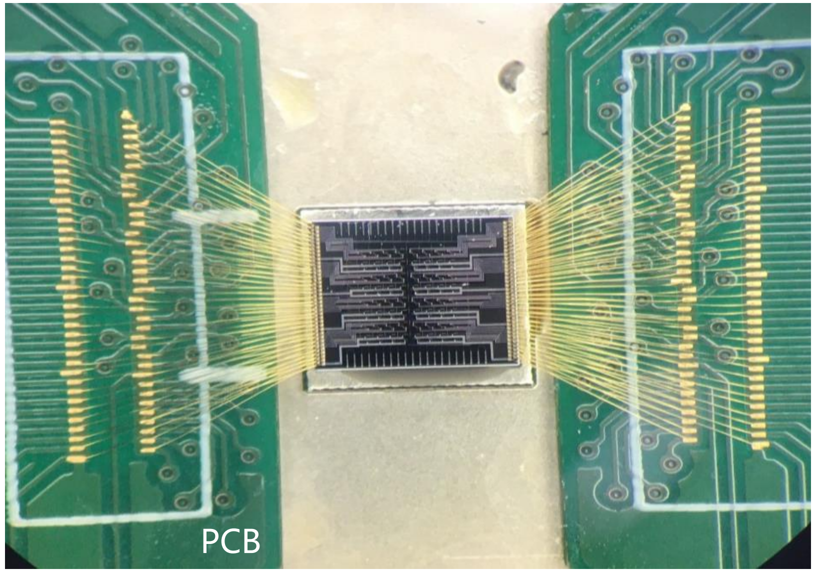
```
光束波长为1.55000 µm  介质折射率为1.00000 @ 0.0000 mm
显示 X 宽度 = 8.0620E-02, Y 高度 = 6.5539E-02 毫米
峰值辐照度= 4.8215E-02 瓦特/毫米^2, 总功率 = 2.4280E-06 瓦特
光纤效率: 系统 0.992468, 接收 0.951803, 耦合效率 0.944634
光束宽度 X = 6.27168E-03, Y = 5.83722E-03 毫米
```

电学封装：①引线键合

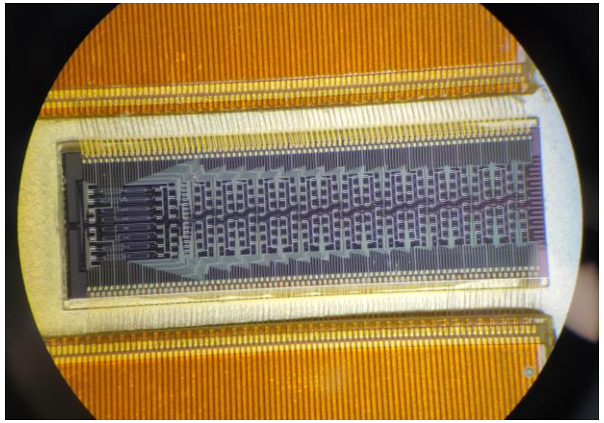
自动引线键合

- 高密度多层（4层）打线和射频打线
- 根据线长选择合适的线弧类型和参数

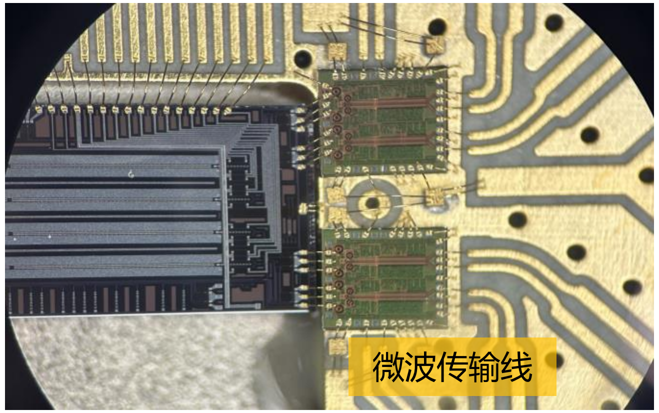
高密度多层打线：
✓ 键盘尺寸≥70x70μm
✓ 排布周期≥100μm



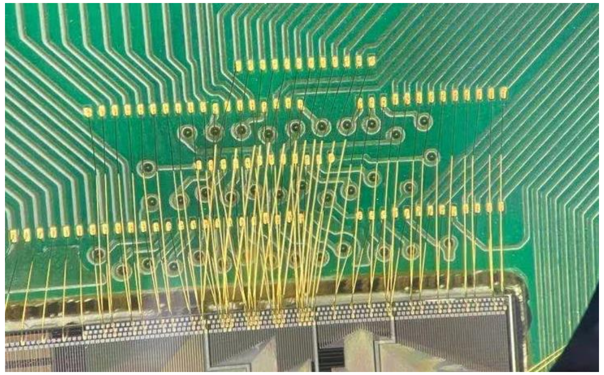
双层打线



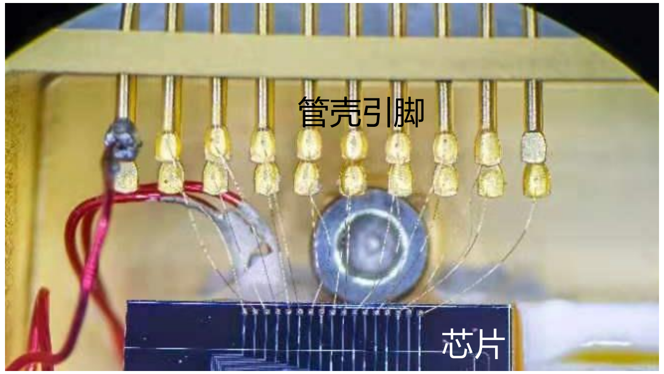
射频打线



四层打线



深腔打线

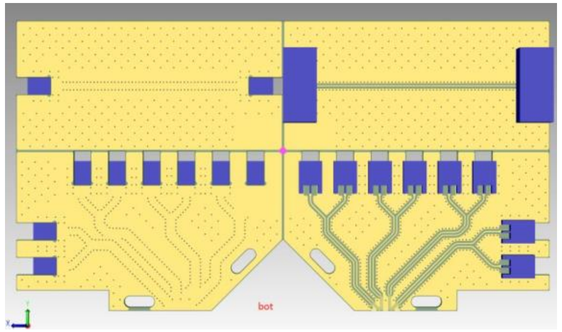


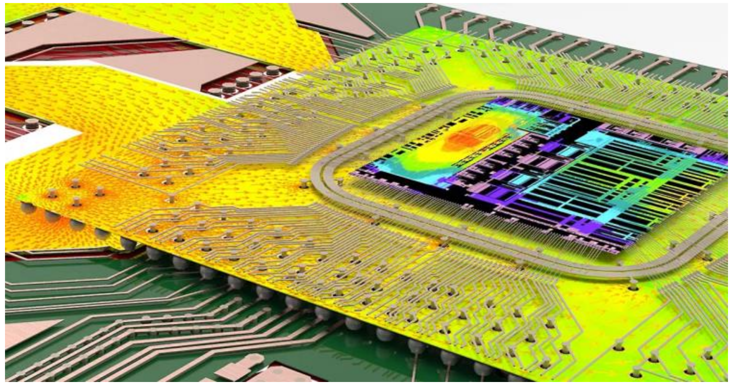
电学封装：②高速射频封装

■ 高频封装（带宽>40GHz)

- 根据芯片电极版图GDS文件，设计封装电路板和选择射频接头
- 电路板预留测试线，作为板端性能测试参考

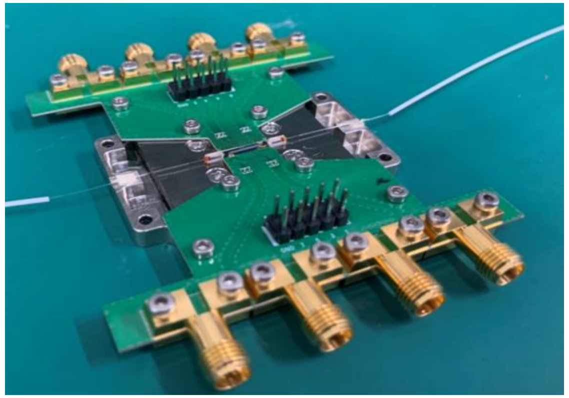
射频电路板设计



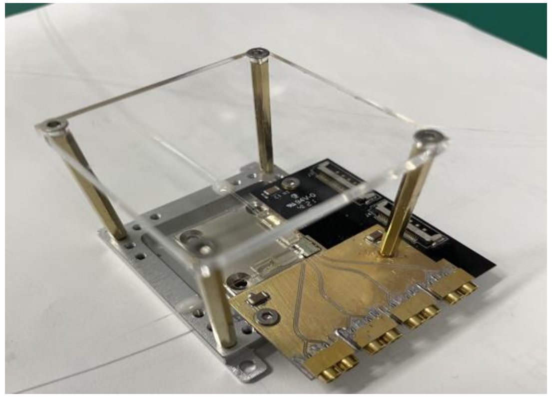


射频传输仿真分析

调制器差分对信号，SMA接口

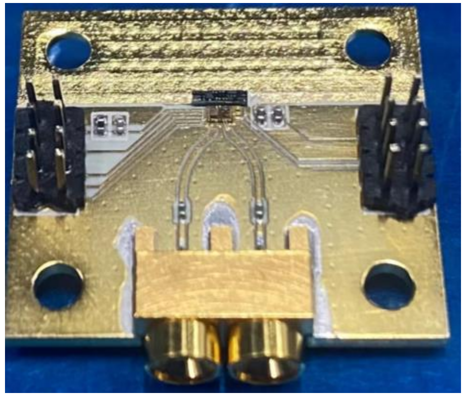


8通道射频信号，GPPO接口



8通道差分射频信号，GPPO接口

探测器射频输出，GPPO接口

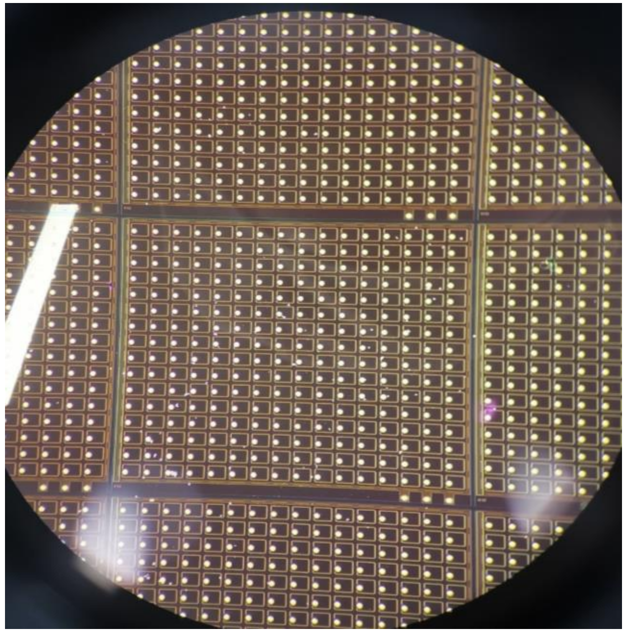


电学封装：③倒装焊接

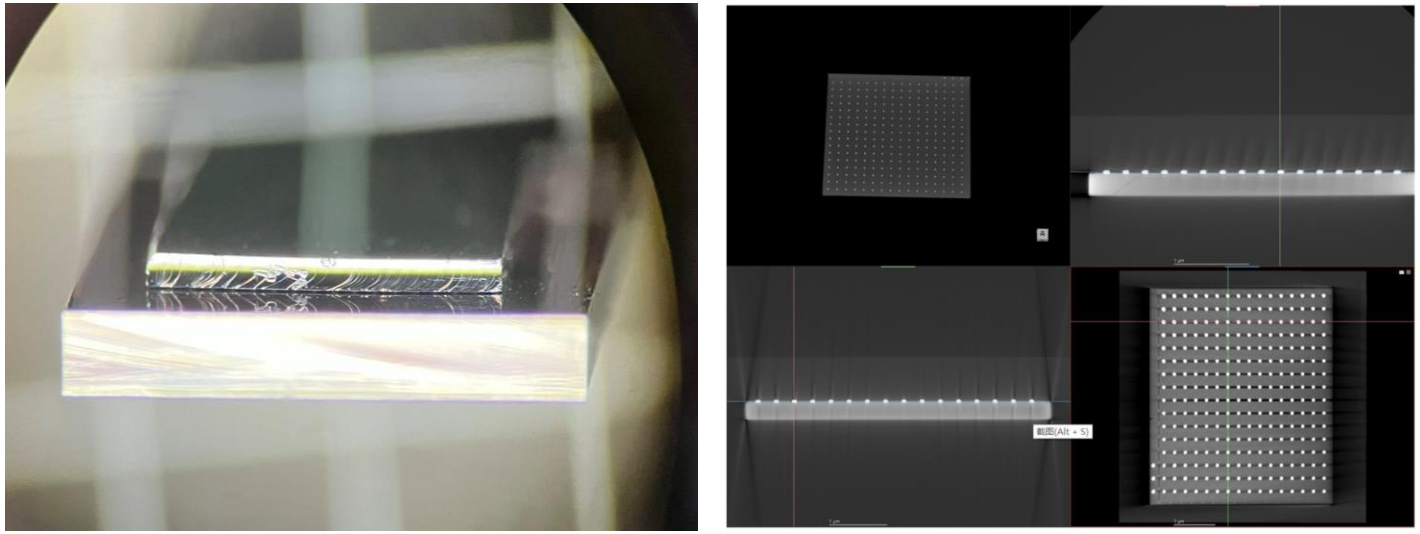
先进封装工艺
- 晶圆级自动植球（Au）
- 芯片间倒装焊

亚微米贴片
- 铟焊料焊接、UV固化、金球热压焊接、超声焊接和多芯片共晶焊
- 贴片对位精度±0.5μm

晶圆级自动植金球（4英寸）



芯片倒装超声焊接



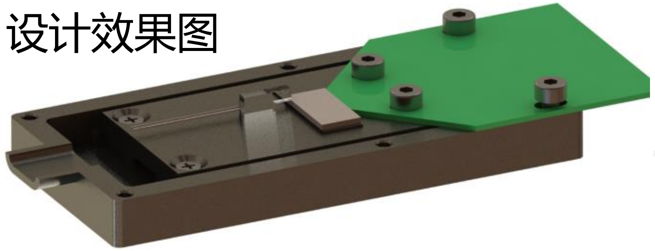
相比引线键合，金属连线更短，适合高密度和高速电学3D封装

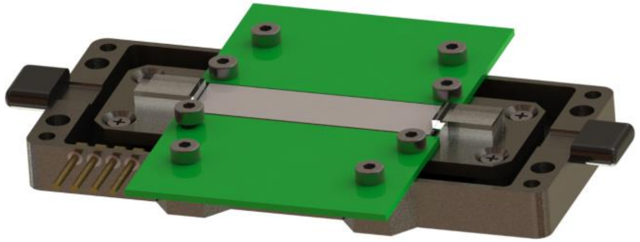
模块化技术：①温控管壳设计

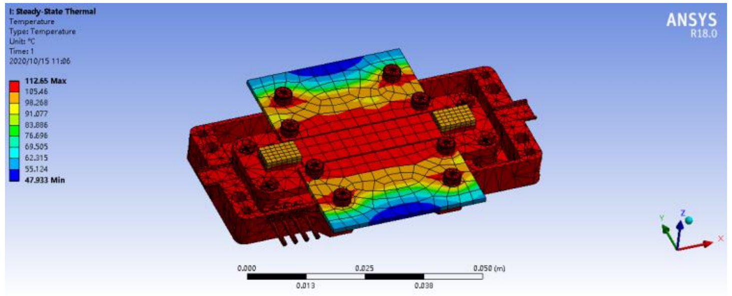
管壳热力学仿真

- 根据芯片发热量，进行热力学建模仿真，设计管壳和TEC选型
- 对于大功率芯片，可设计水冷散热

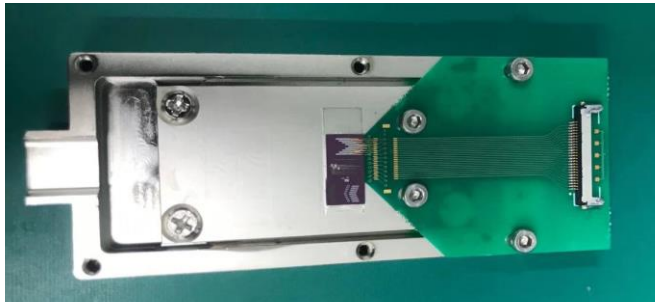
设计效果图

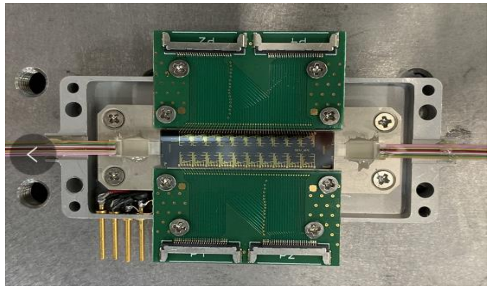


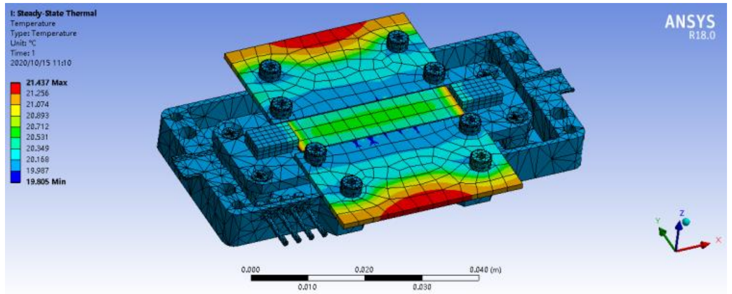




实物图





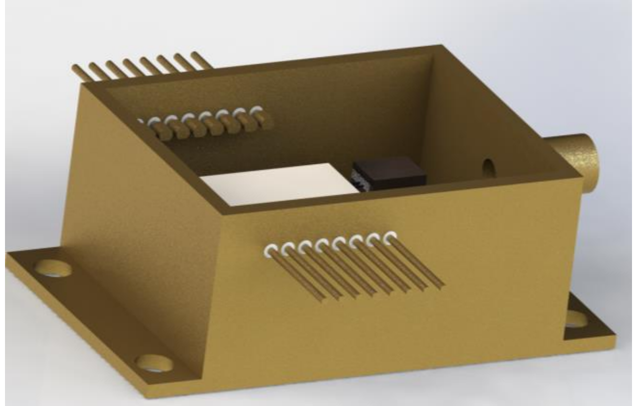


模块化技术：②气密性封装

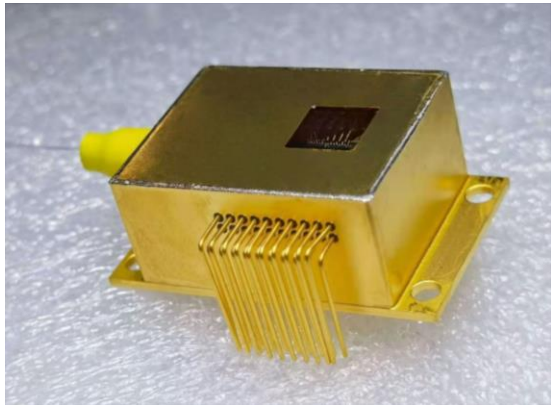
管壳气密性封装

- 密封气体：氮气
- 有效防止高低温环境和高湿度对器件造成的影响
- 可设计和定制封装管壳

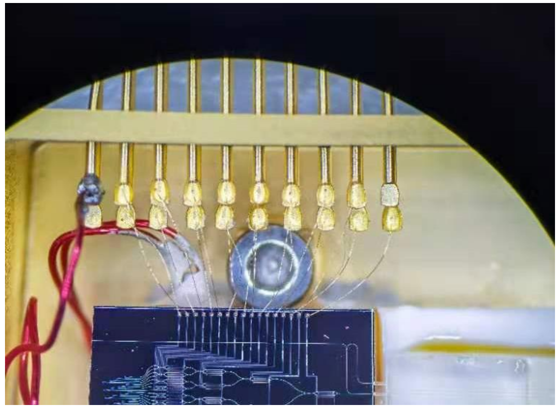
管壳设计



平行封焊封盖

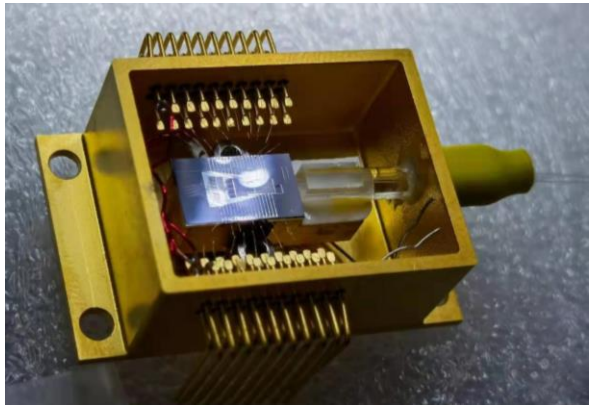


金丝线尾点胶固定



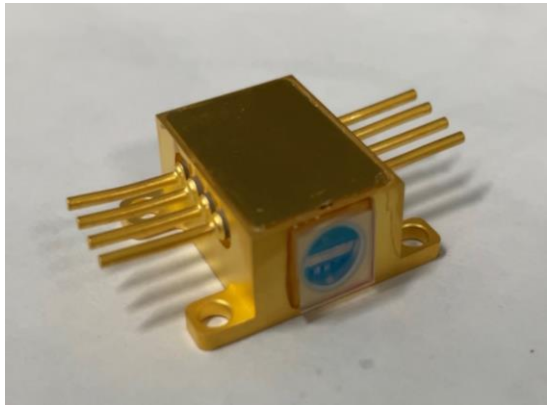
增加电学封装的可靠性

管嘴密封

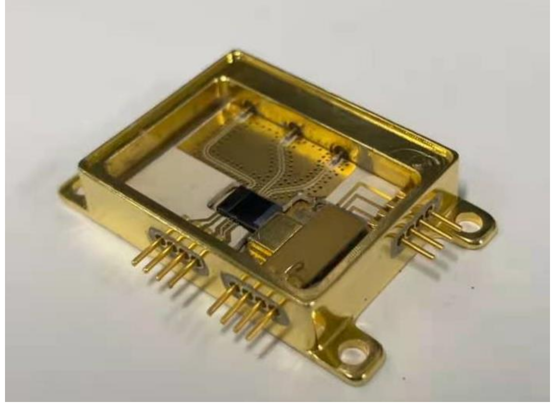


保证封装气密性

窗口输出气密性封装

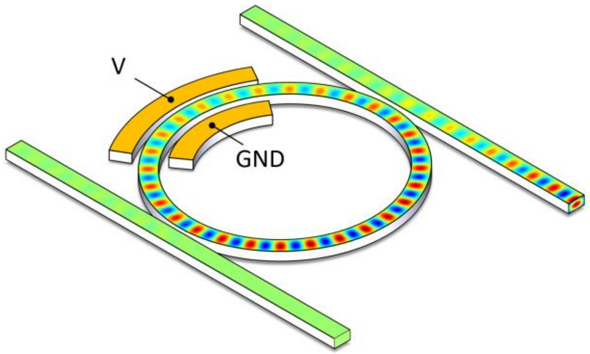


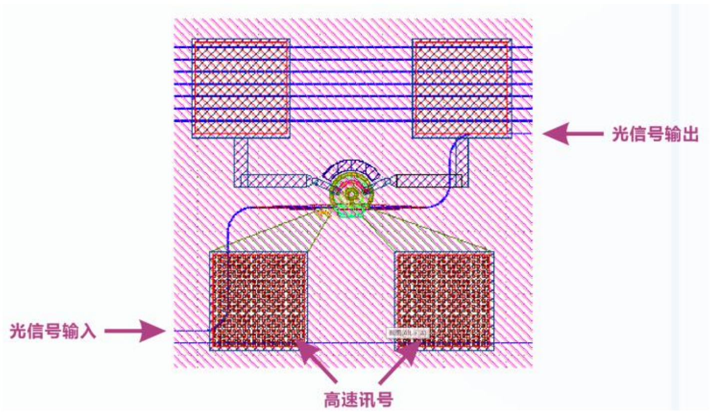
射频气密性封装



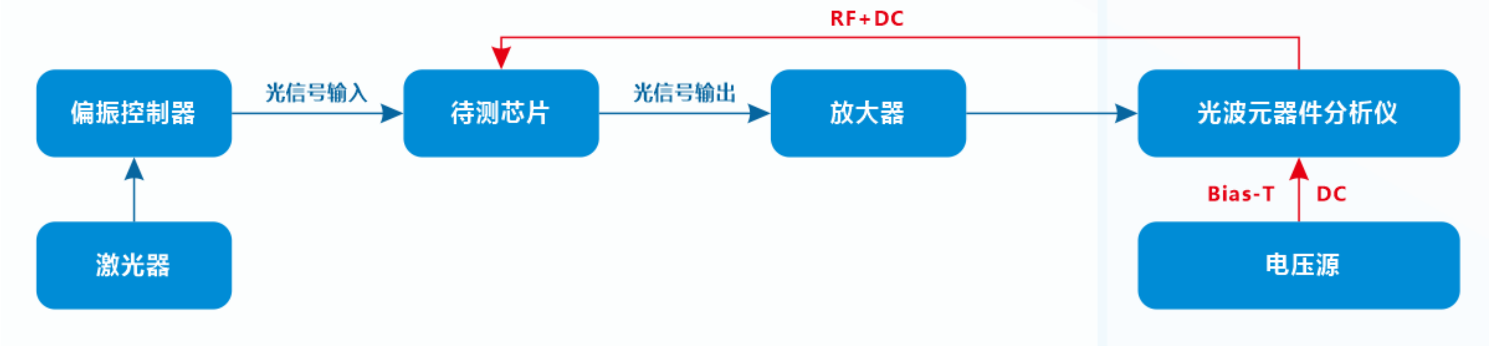
器件测试：①调制器测试

■ 器件结构





■ 测试系统


RF+DC

偏振控制器

光信号输入

待测芯片

光信号输出

放大器

光波元器件分析仪

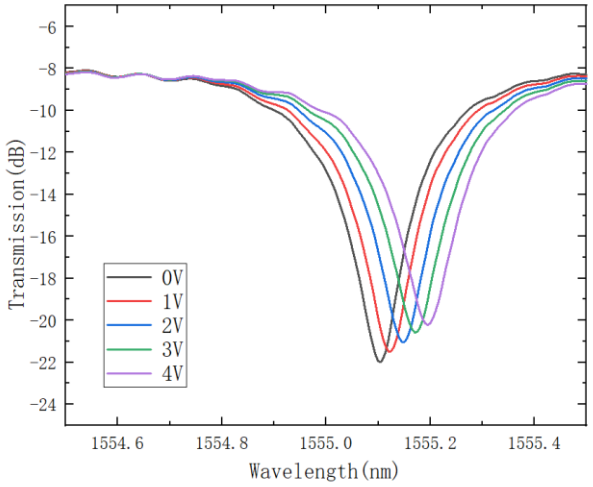
激光器

Bias-T

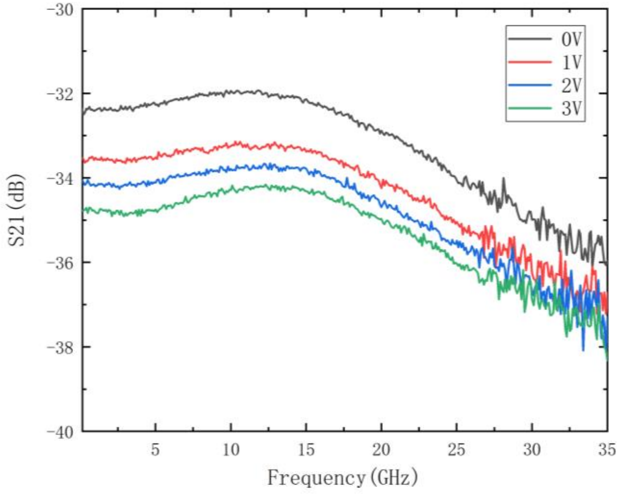
DC

电压源

传输频谱

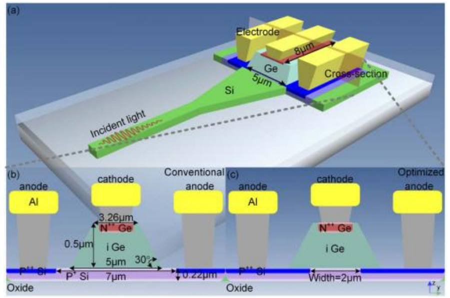


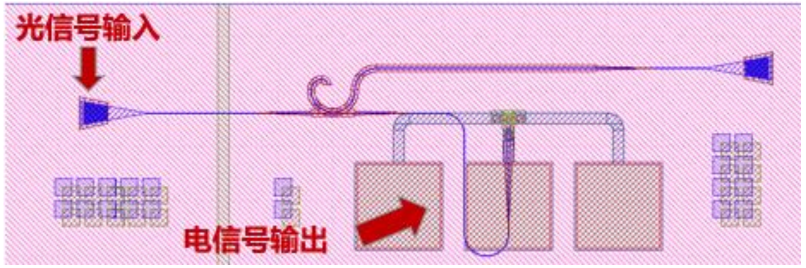
电光响应S参数



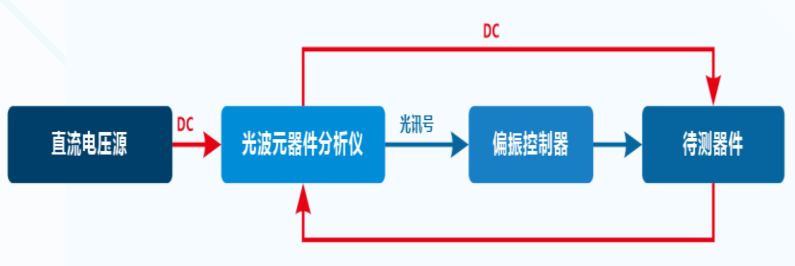
器件测试：②探测器测试

■ 器件结构

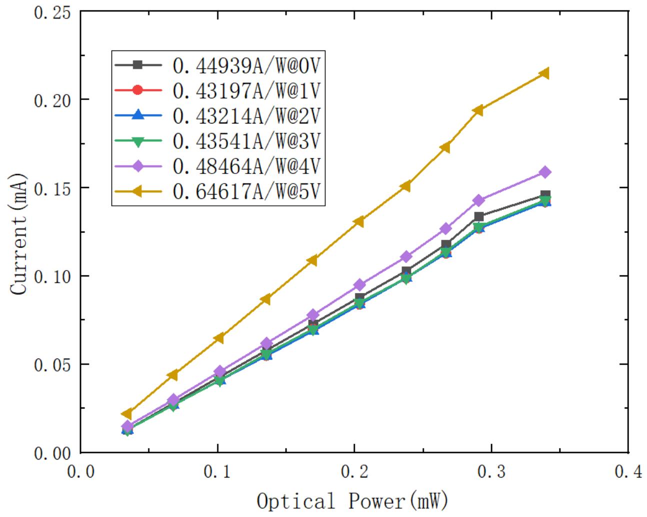




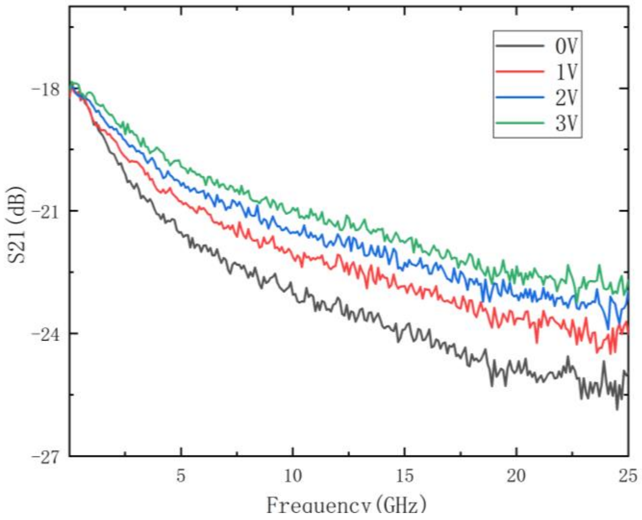
■ 测试系统



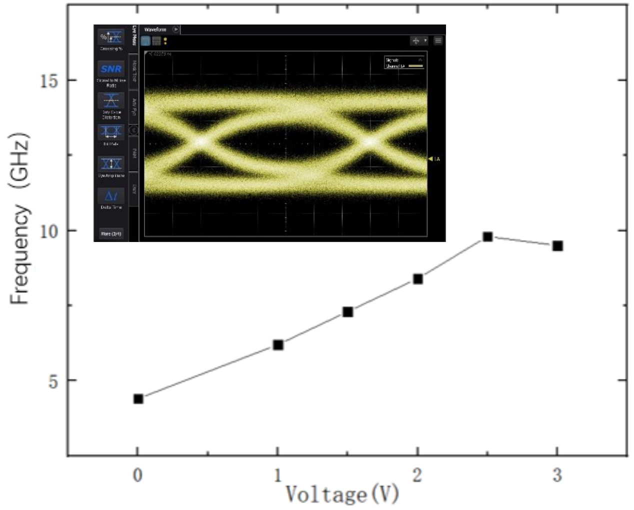
光电流探测



光电响应S参数

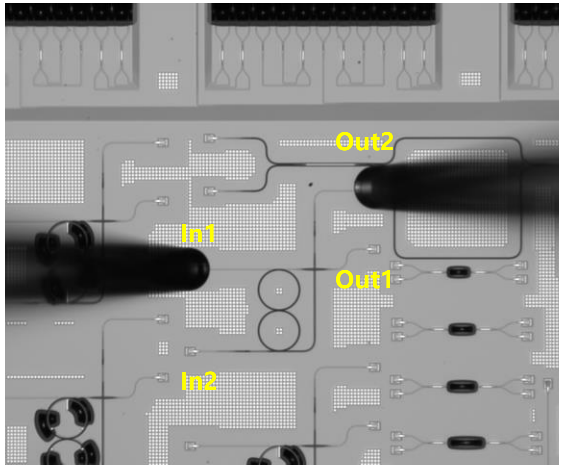


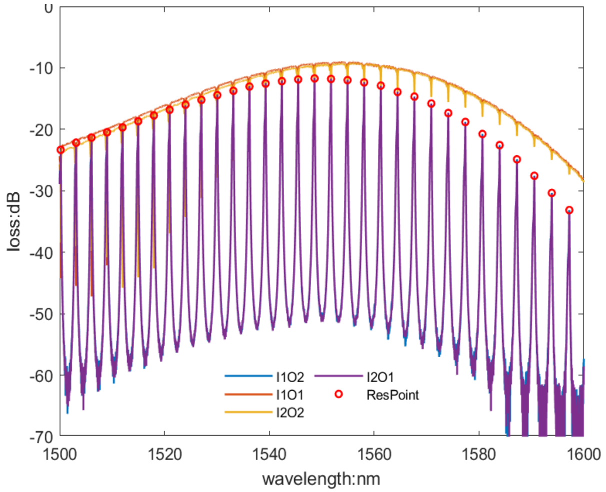
微波工作带宽和眼图

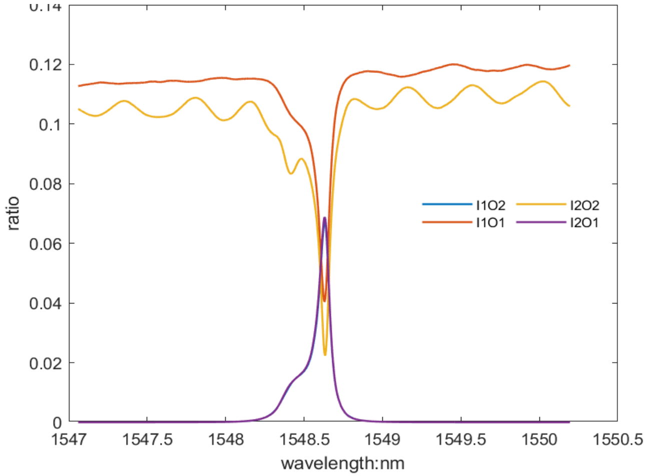


晶圆测试：①光栅耦合测试

- **单光纤垂直耦合测试**
  - 耦合时间：3-4s
  - 耦合重复性：<0.2dB
- **光纤阵列垂直耦合测试**
  - 耦合时间：2-3s
  - 耦合重复性：＜0.5dB







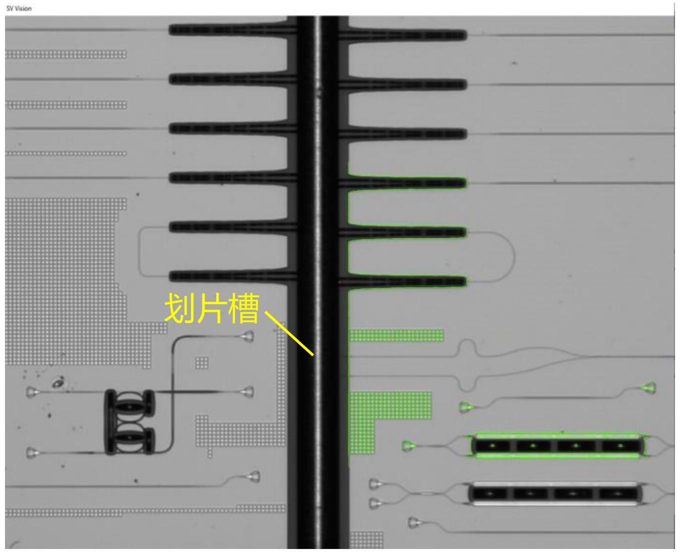
晶圆测试：②端面耦合测试

■ 晶圆级端面耦合测试

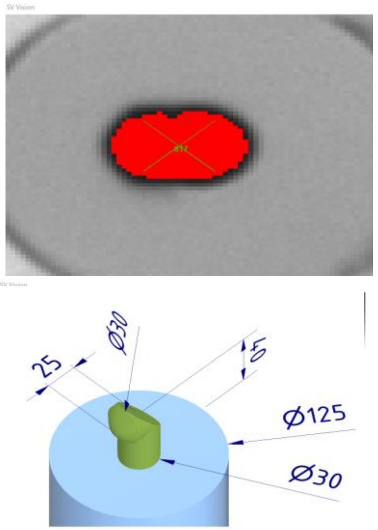
- 光纤探针：PWB 打印微结构（光路90度转角）
- 高精度微米级图像识别，校准光纤角度
- 识别光纤探针位置，放入划片槽中与波导端面耦合

■ Bar条端面耦合测试

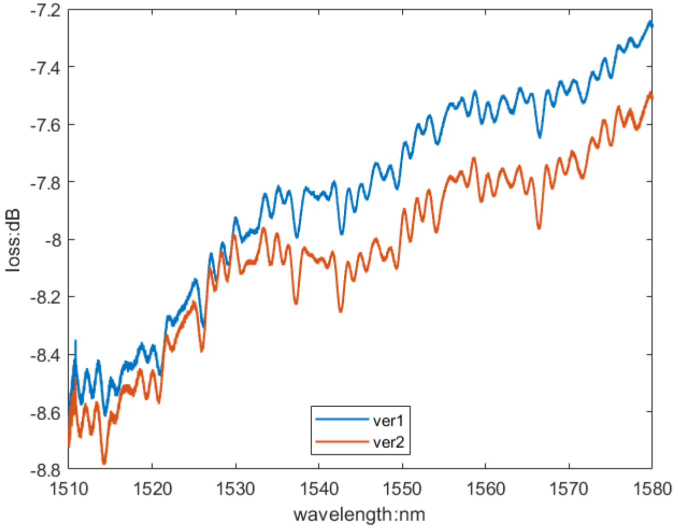
- 通过高倍镜判断FA以及 bar条边沿，使 FA 与 bar条中波导光斑实现精确角度匹配和轴向匹配
- 耦合损耗重复性 < 0.5dB



- 测试芯片



- PWB光纤探针

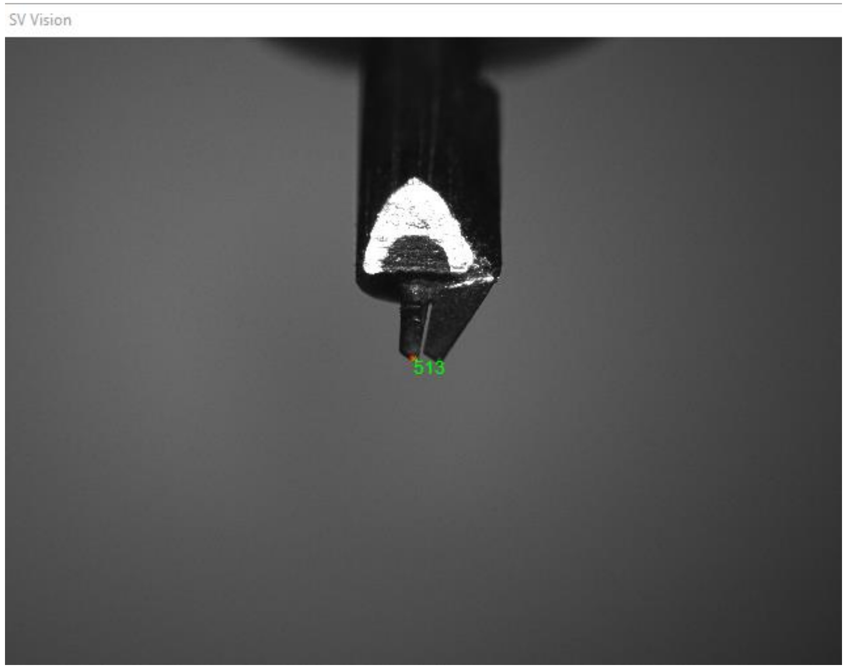


- FA端面耦合测试重复谱线

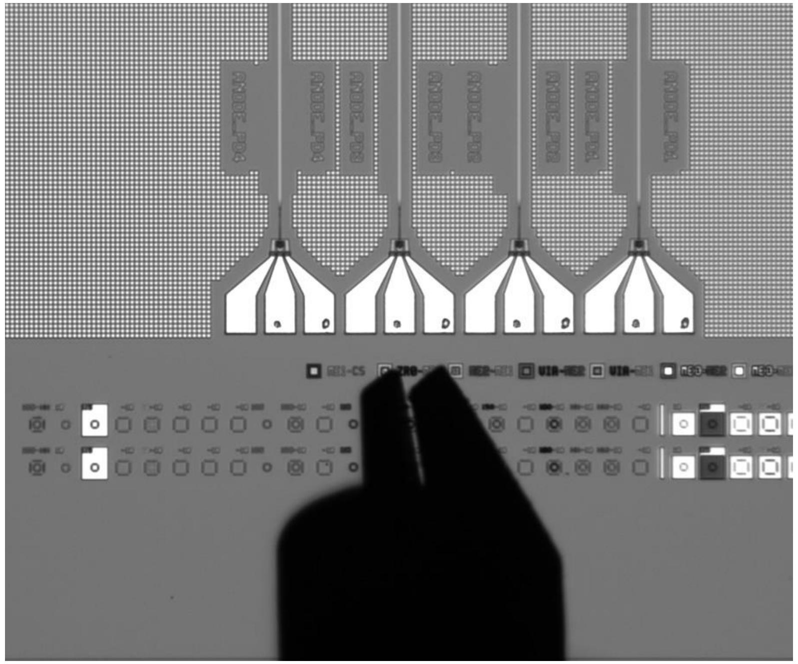
晶圆测试：③电学测试

电信号测试

- 高精度微米级图像识别：识别探针针尖，精确获取位置
- 压放位置、压放痕迹均一性良好
- 单个器件压放+测试时间小于 1s



- 探针识别

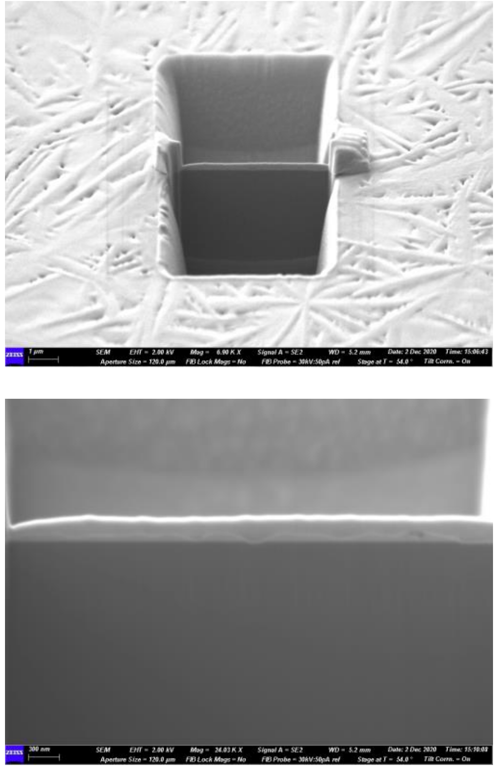


- 电学测试

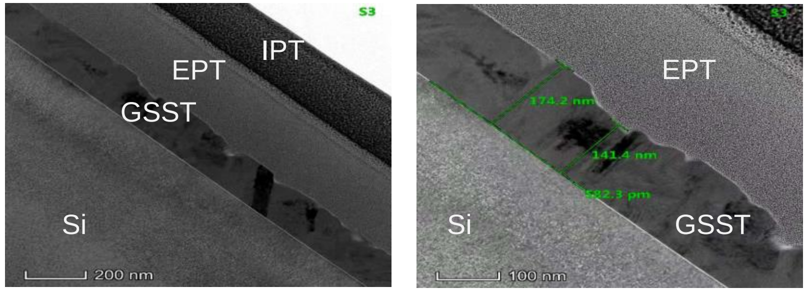
器件分析：①TEM制样和材料测定

- 在目标区域制备TEM样品，做U形切割，放置于铜网上进行TEM观察
- 通过TEM能测试材料的化学成分和分布情况

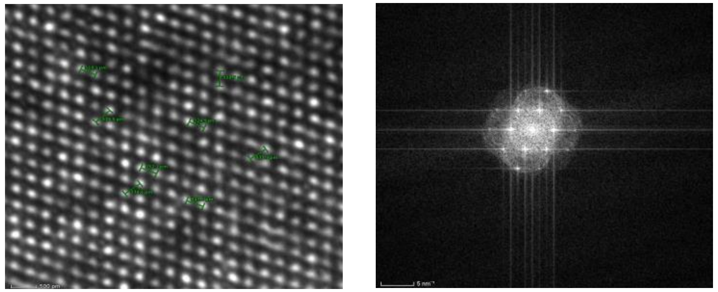
- TEM制样



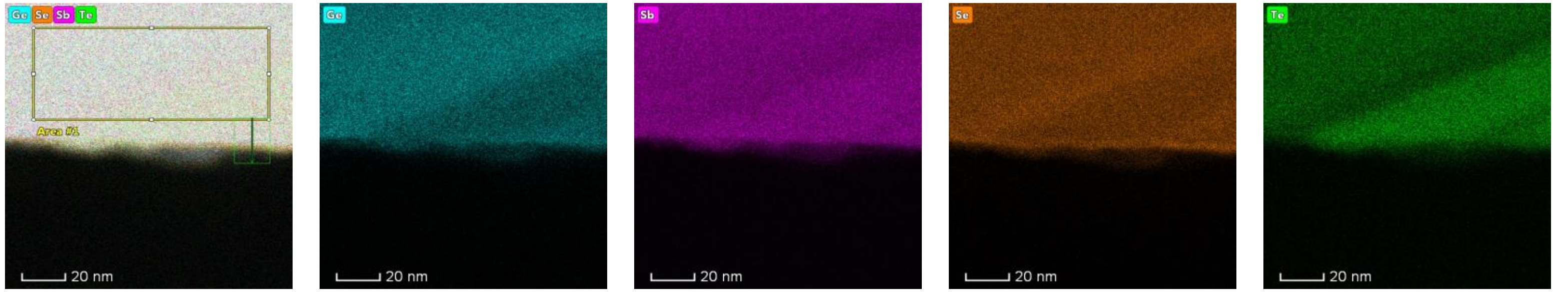
- 材料厚度测量

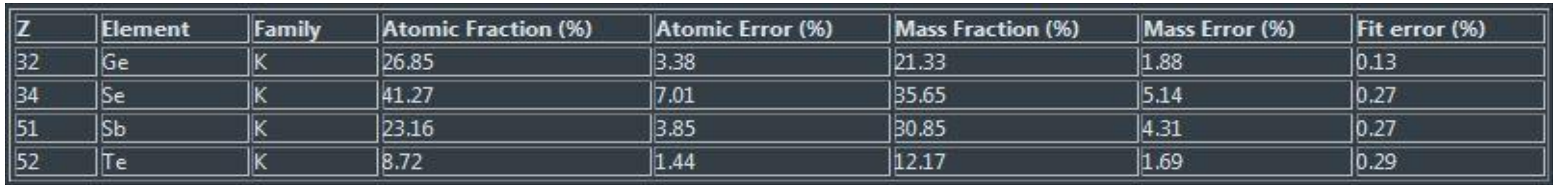


- 晶格间距测量和衍射图案



- 成分分析，观察Ge Se Sb Te四种元素在合金中的含量

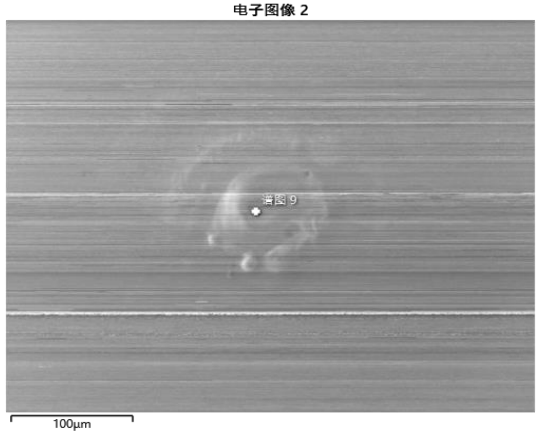




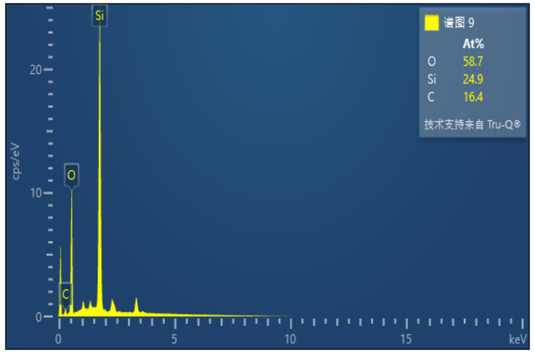
Z	Element	Family	Atomic Fraction (%)	Atomic Error (%)	Mass Fraction (%)	Mass Error (%)	Fit error (%)
32	Ge	K	26.85	3.38	21.33	1.88	0.13
34	Se	K	41.27	7.01	35.65	5.14	0.27
51	Sb	K	23.16	3.85	30.85	4.31	0.27
52	Te	K	8.72	1.44	12.17	1.69	0.29

器件分析：②器件失效点成分分析

- 利用EDS能谱仪对器件失效点进行成分分析

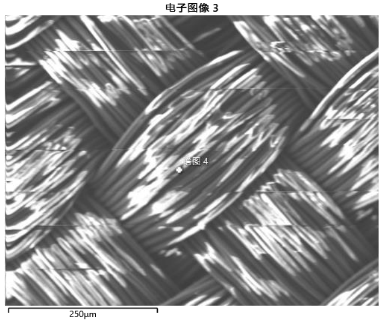


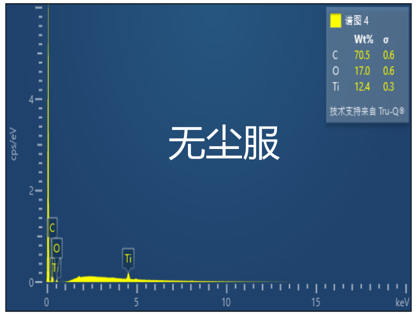
失效区域元素成分测试

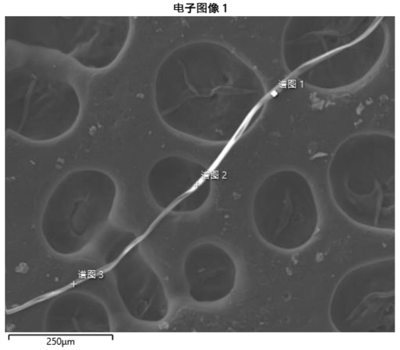


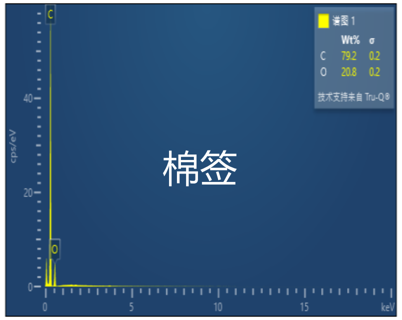
失效点的元素由C、Si和O元素组成，正常样品只含Si和O元素。

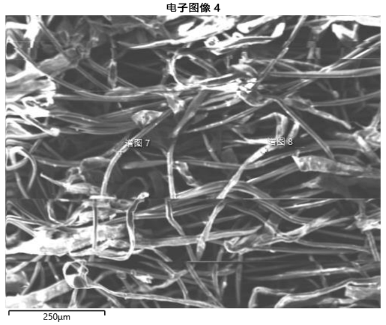
引入C元素的物质？

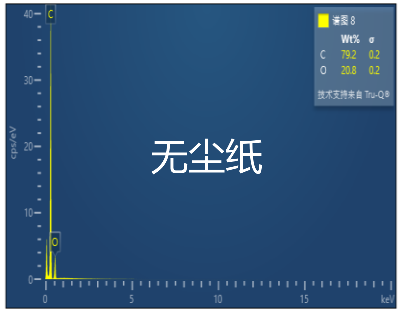










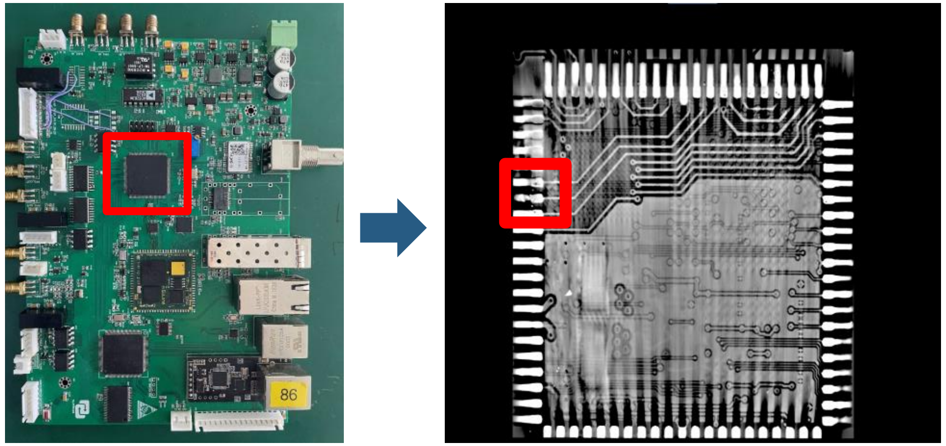


引入C元素的物质可能是棉签和无尘纸，而无尘服中含有钛元素，故将其排除。

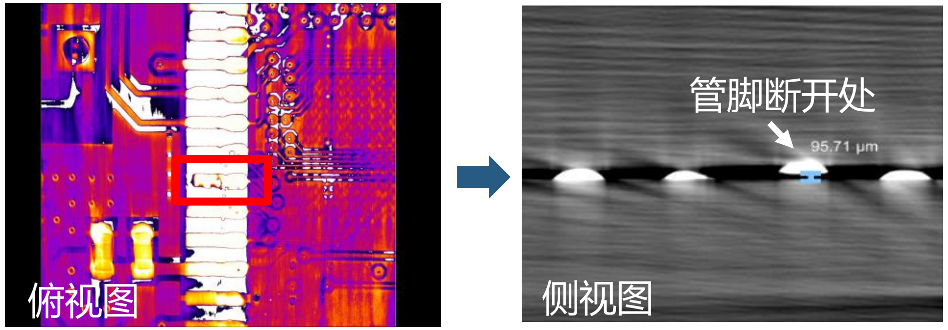
器件分析：③封装管脚失效分析

- 无损分析：无需打开管壳即可3D透视成像

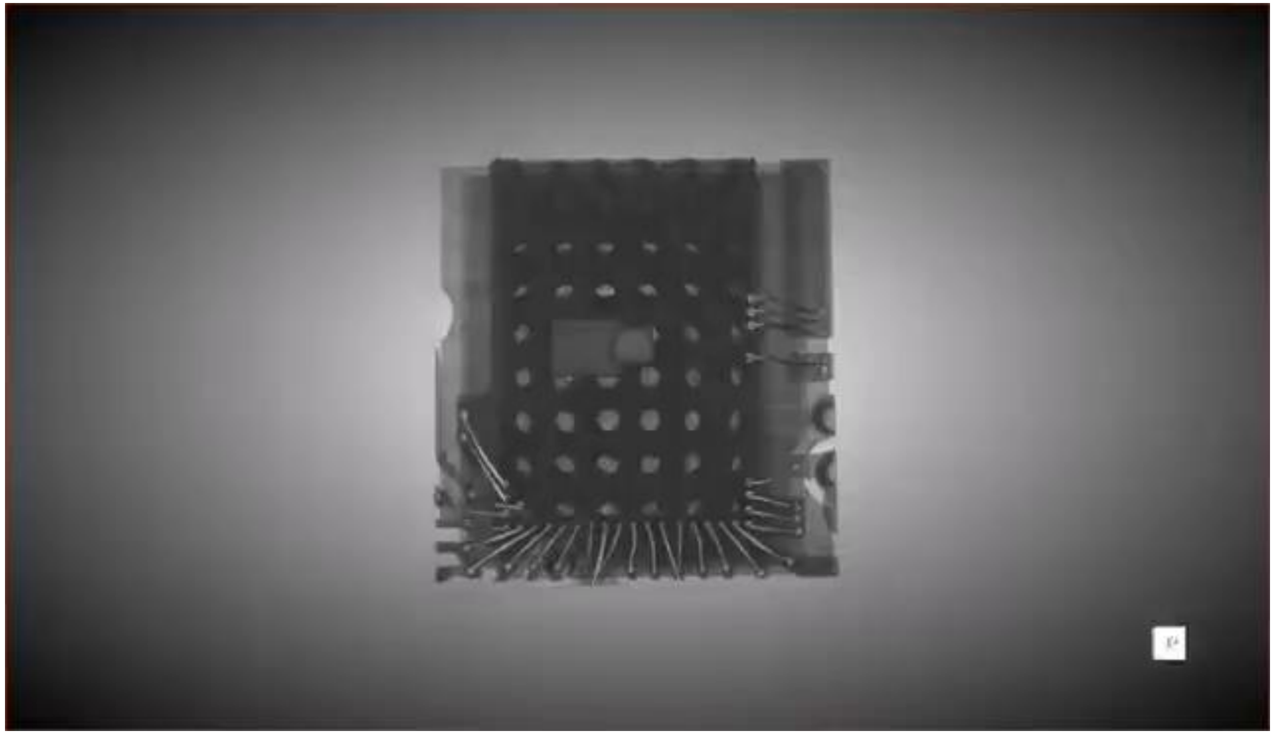
  - 利用X-RAY显微镜对失效芯片进行整体扫描



  - 对断开管脚放大扫描



芯片管脚信号无法接收：左侧管脚7与PCB断开

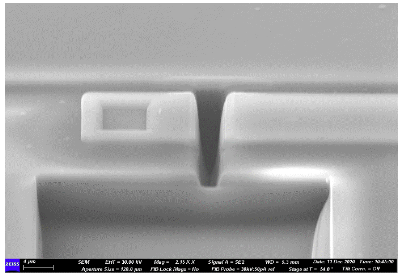


电路修复

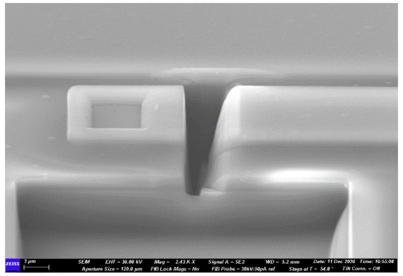
设计和工艺原因引起电路问题

- 电路短路 → 金属导线切割
- 电路断路 → 金属导线连接

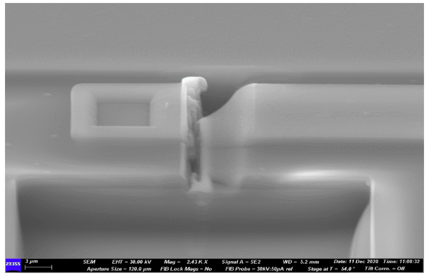
FIB-SEM双束聚焦离子束电子显微镜



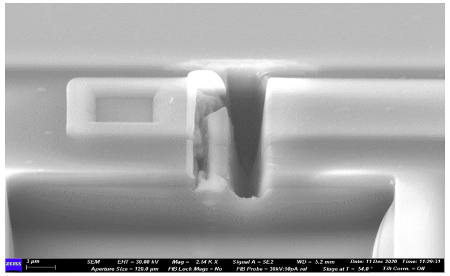
大束流粗切



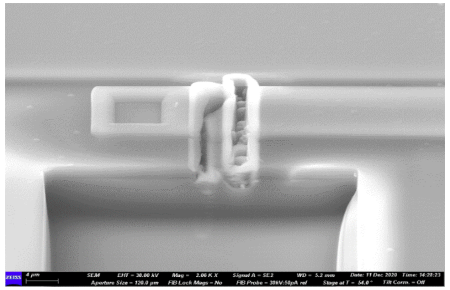
单边精抛



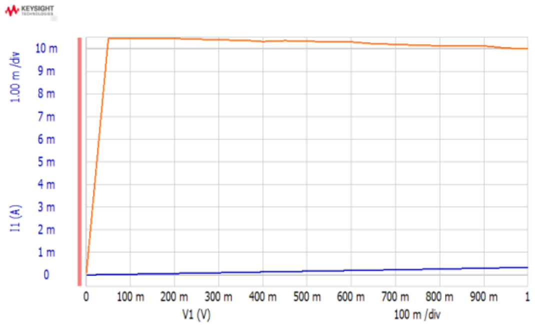
单边沉积二氧化硅



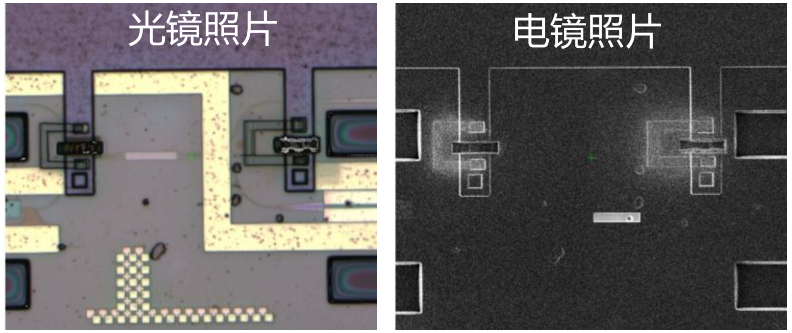
另外一边精抛



另外一边沉积二氧化硅



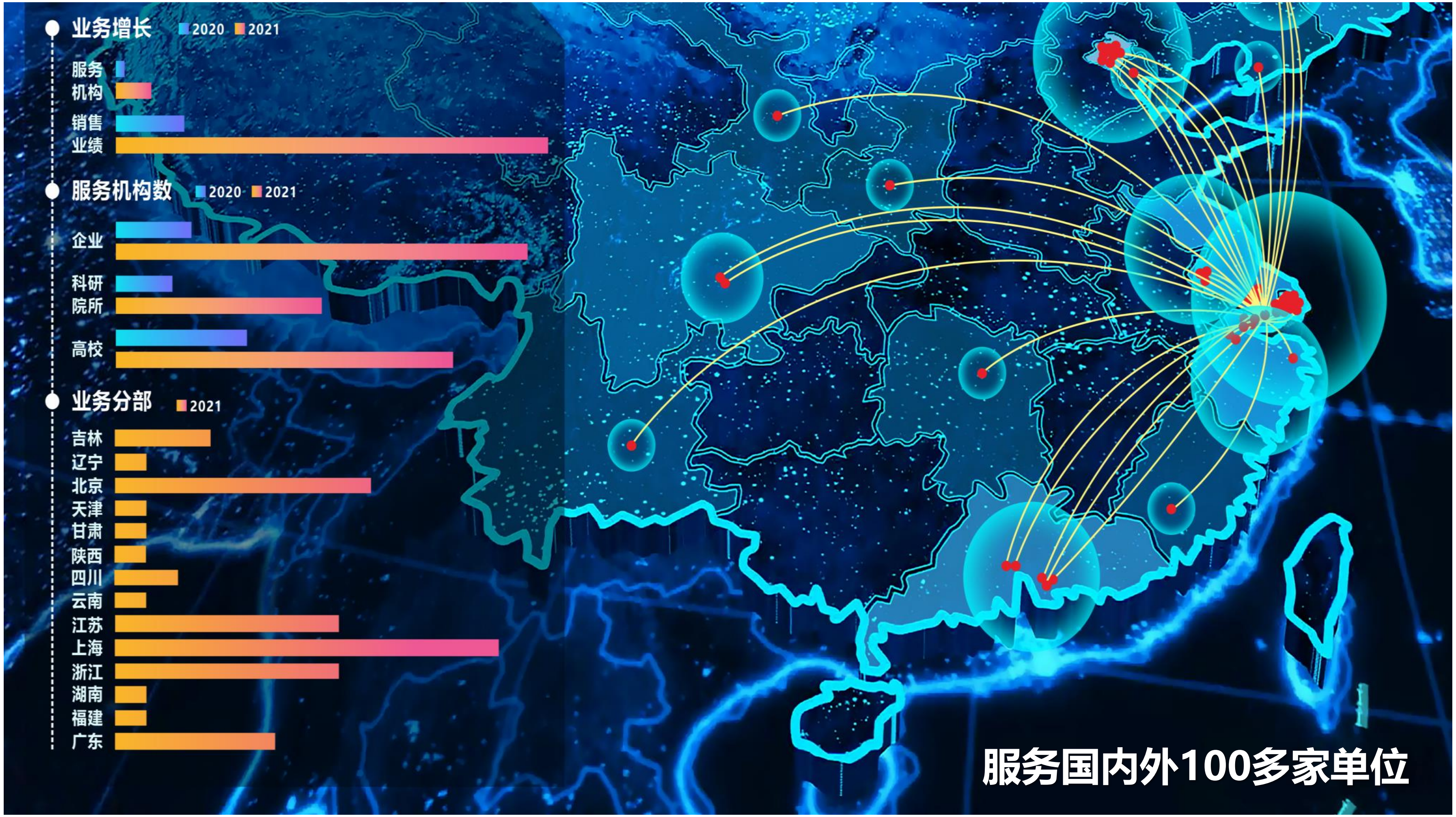
IV测试判断是否切断



利用沉积完成电路修复

- 通过光电镜联动，可以精确定位到切割位置

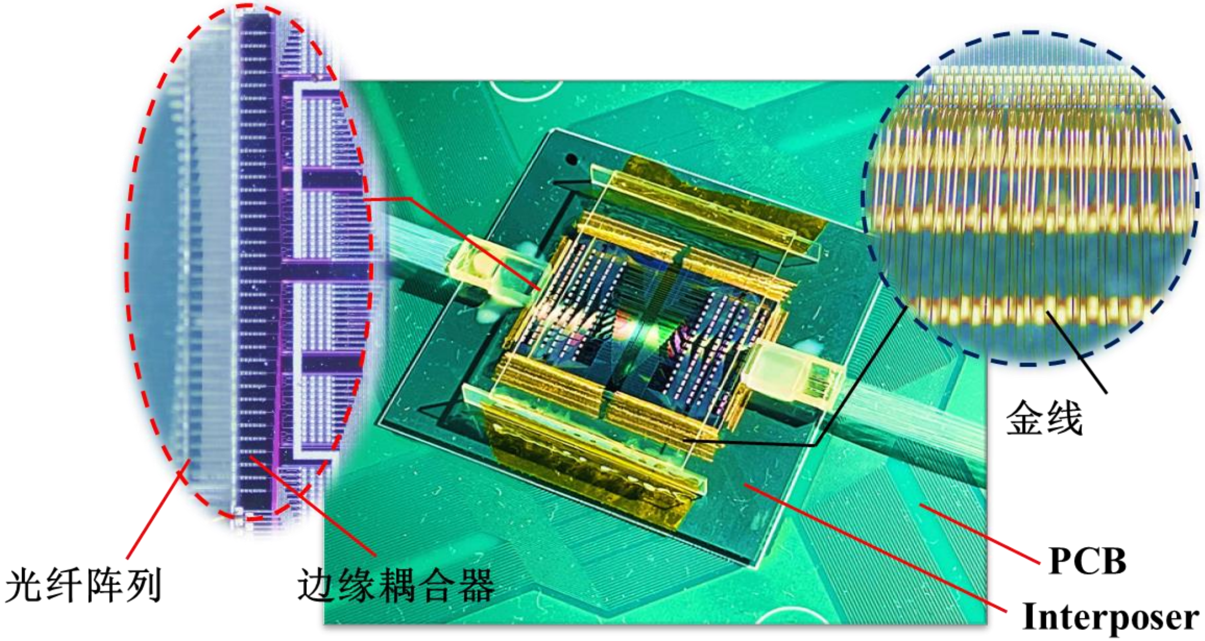
合作单位



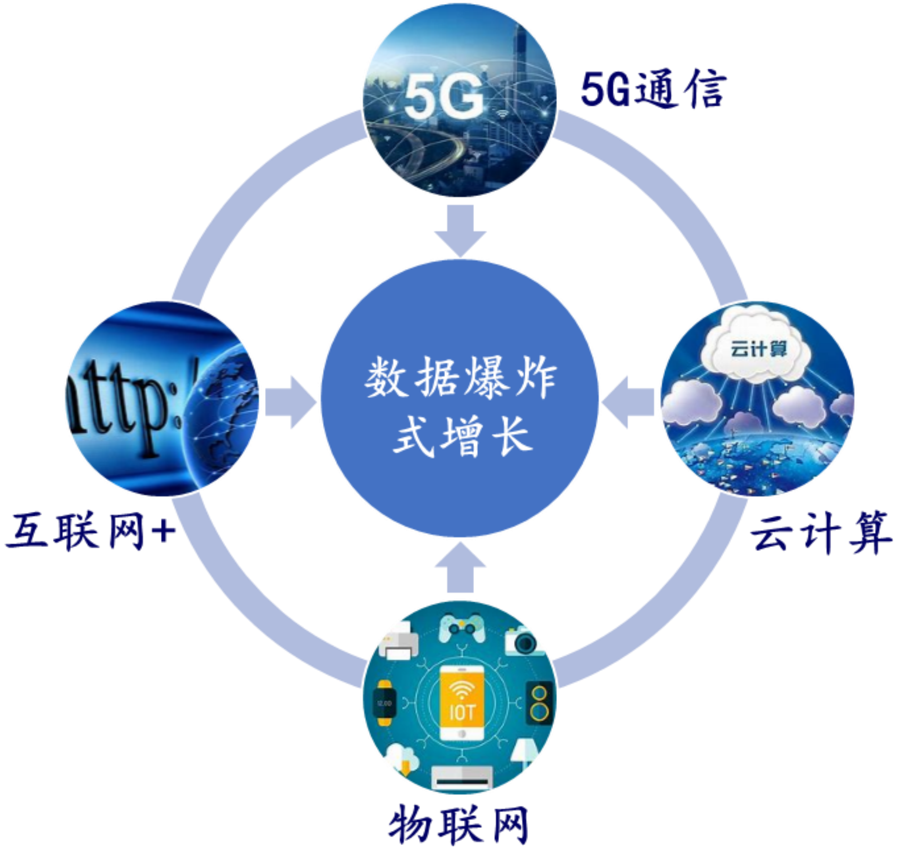
服务国内外100多家单位

光电子芯片封装实例

封装实例一：32×32光交换芯片



光交换重要性



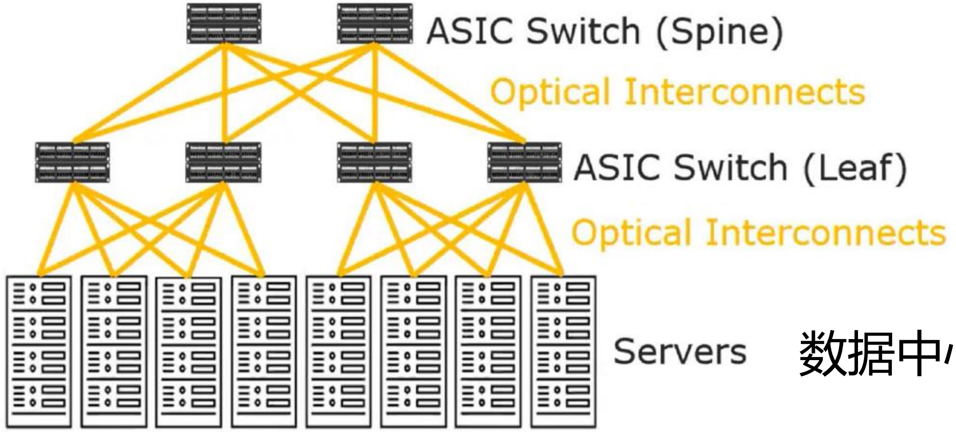
吞吐量将高达Tb/s甚至Pb/s级别

通信网络

交换节点

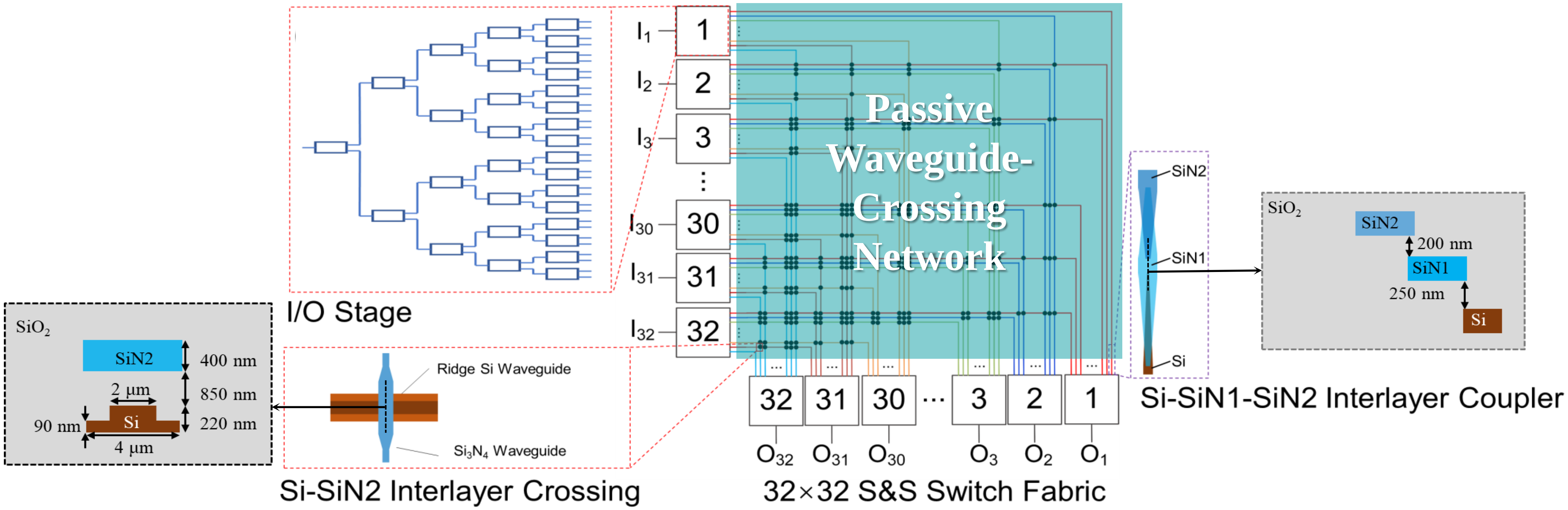
数据中心

CPU/存储器



数据中心网络架构

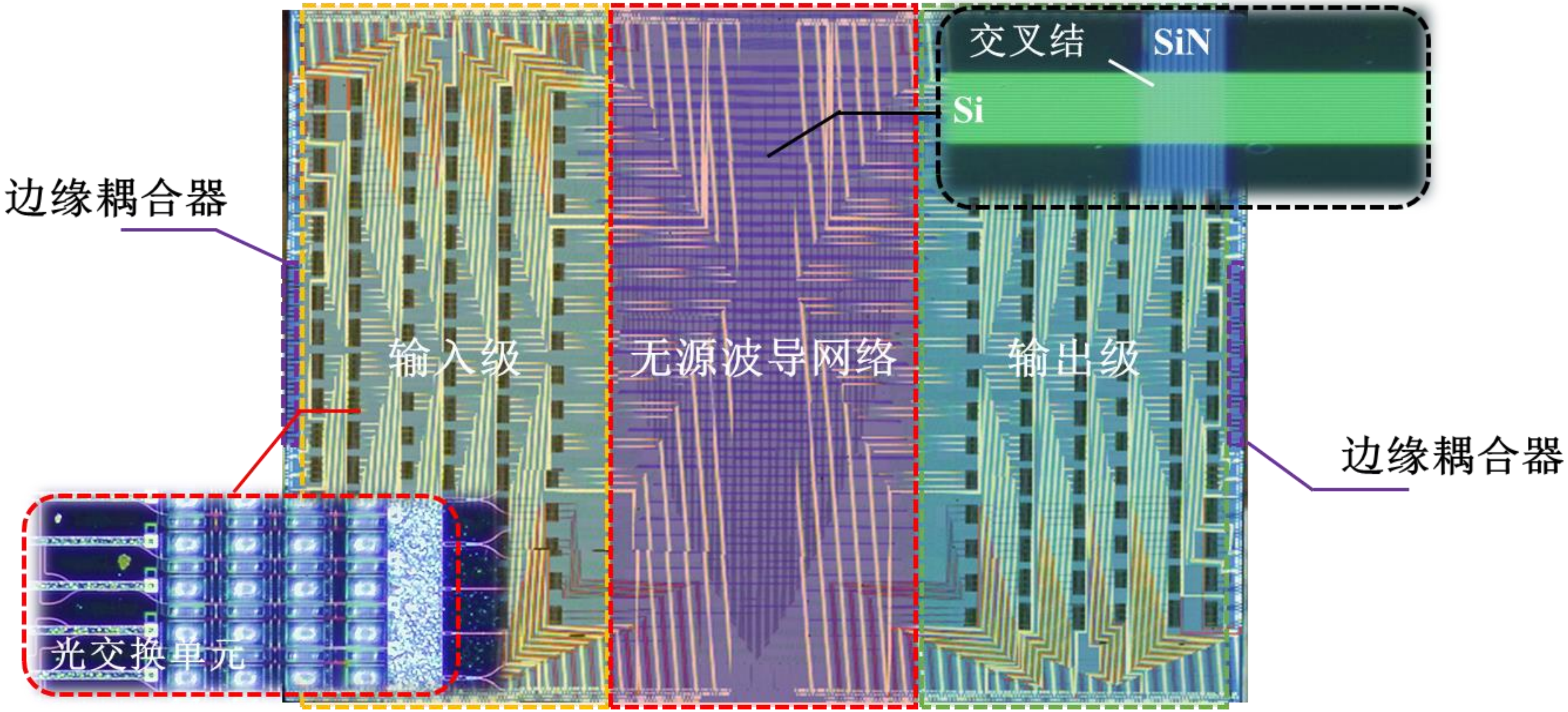
32×32光交换芯片



Switch & Select (S&S)拓扑结构：严格无阻塞、低串扰

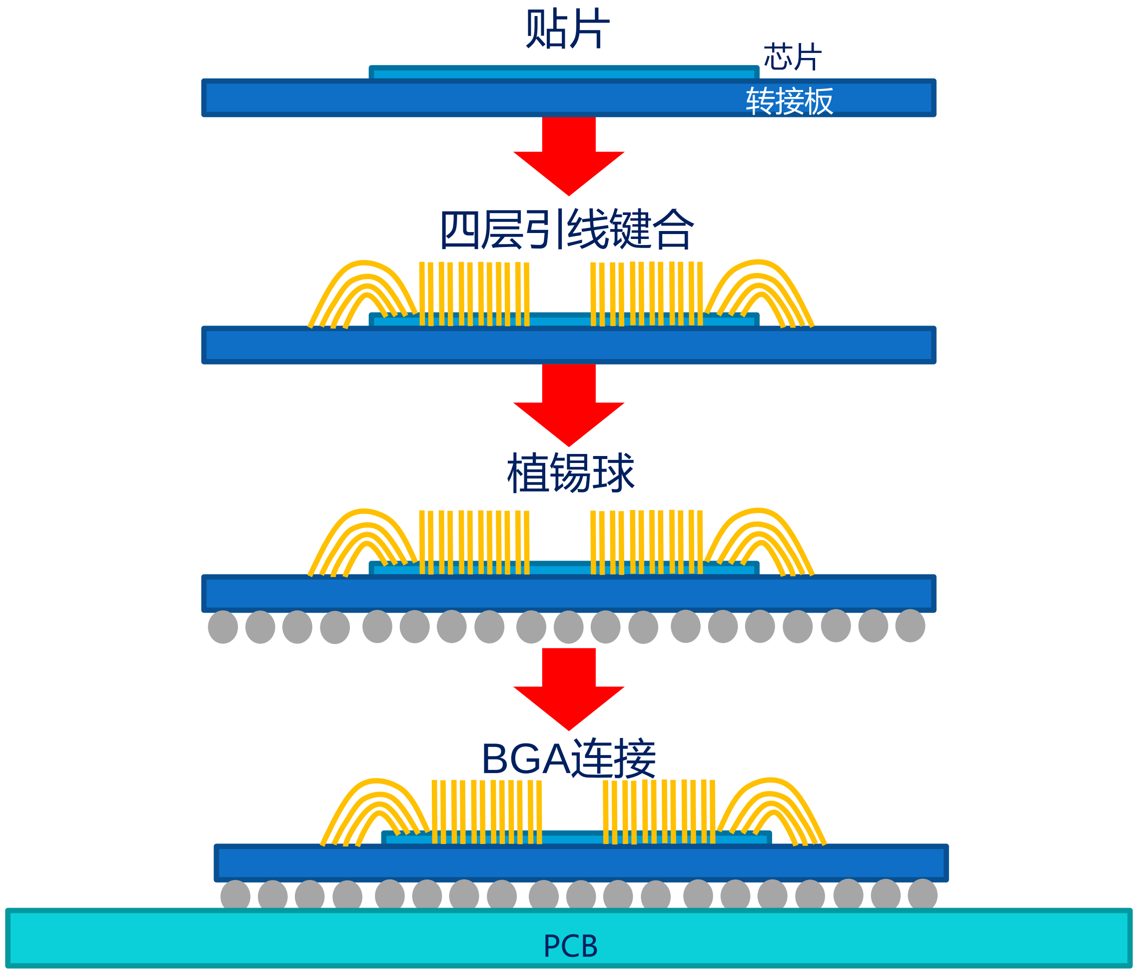
- 输入/输出级：各32 组1×32 二叉树型光开关，共**1984个** MZI 交换单元
- 无源波导交叉网络：共**246,016** 个交叉结, **2048** 个层间耦合器
- 单条链路包括10 个MZIs, 2个层间耦合器, 至少 **0且至多961** 波导交叉结
- 任意一种路由状态，需调控MZI不超过**320**个

芯片照片



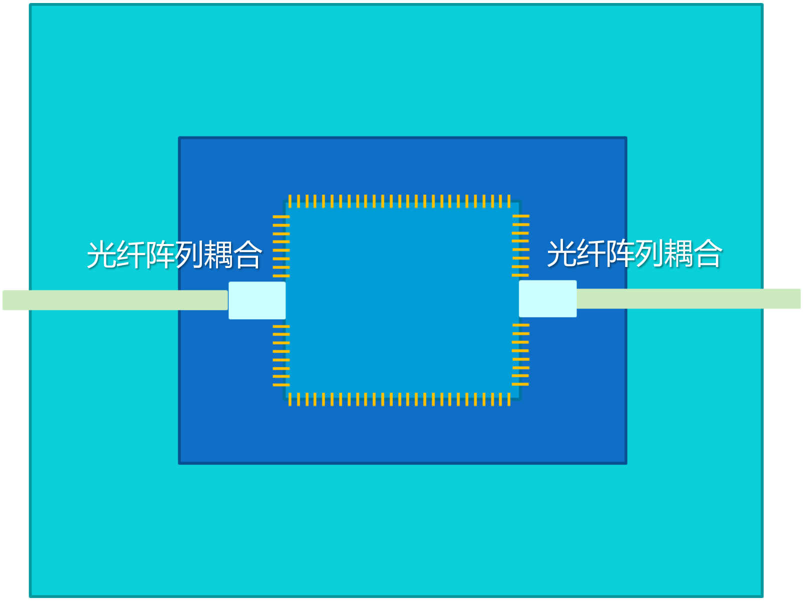
- 芯片面积：18.3 mm×24.8 mm
- 2000多个电学端口
- 72个光学端口

封装流程



电学封装

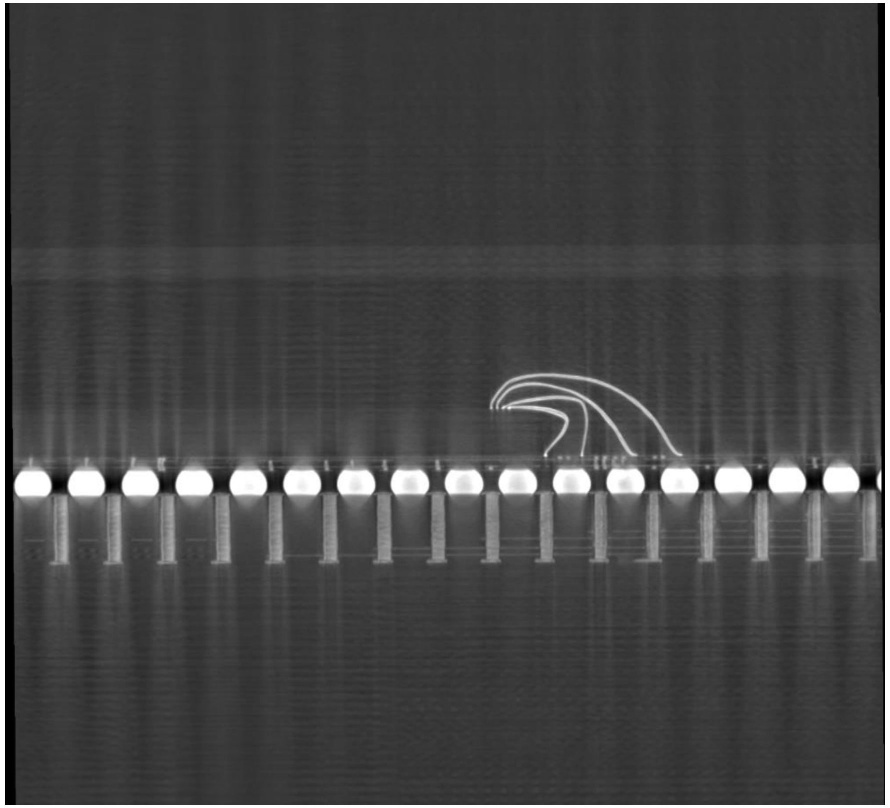
- 先光后电
- 考虑工艺兼容性



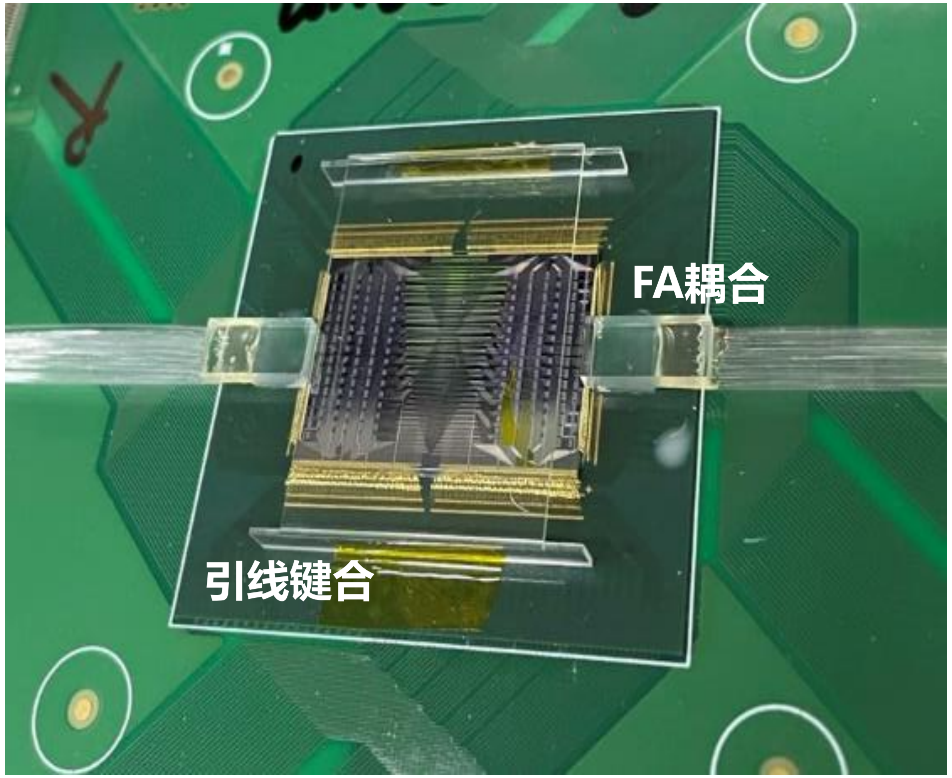
光学封装

封装后照片

- **3D-Xray分析**

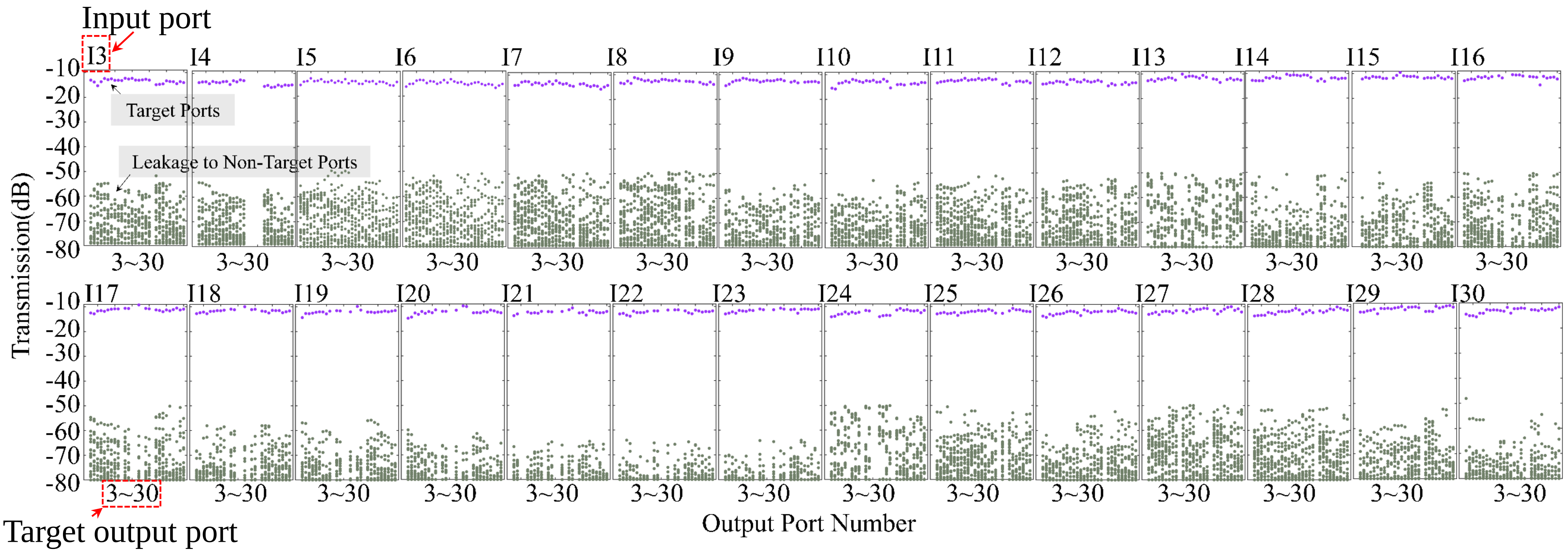


- **芯片照片：**



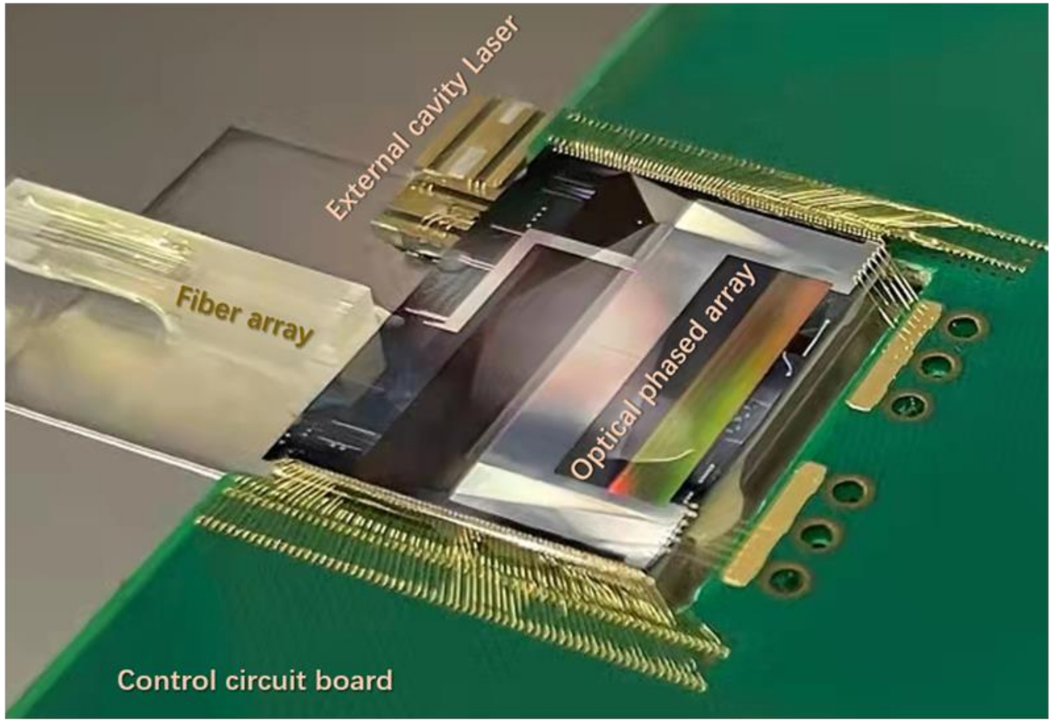
- 光学封装: SMF光纤阵列端面耦合(~3 dB/facet)

芯片测试结果: 插损和串扰



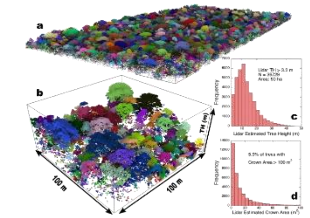
- 光纤-光纤插损: 9.61~14.51 dB (~6 dB 耦合损耗)，平均损耗：11.76 dB
- 消光比： >35 dB @1580 nm

封装实例二：混合集成LiDAR发射芯片

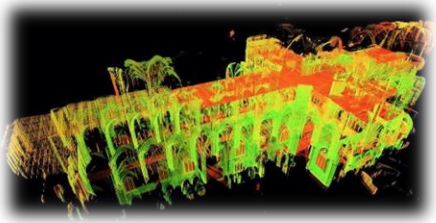


激光雷达应用

遥感测量



Environmental Surveillance



Architecture Preservation

Digital Twins

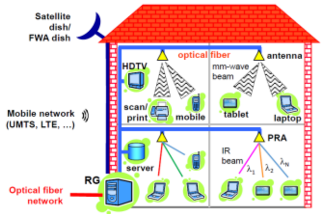
自动导航

Space Rendezvous

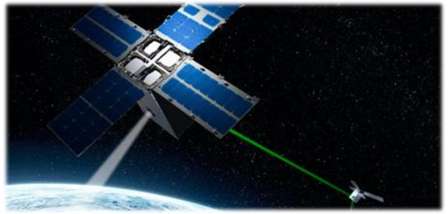
Automotive Lidar

Obstacle Sensing

空间通信



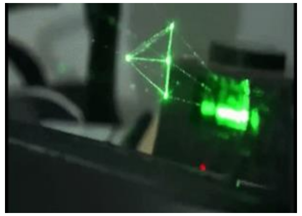
Indoor LiFi



Free Space Communication

Laser Guided Ordnance

成像识别



Laser Hologram

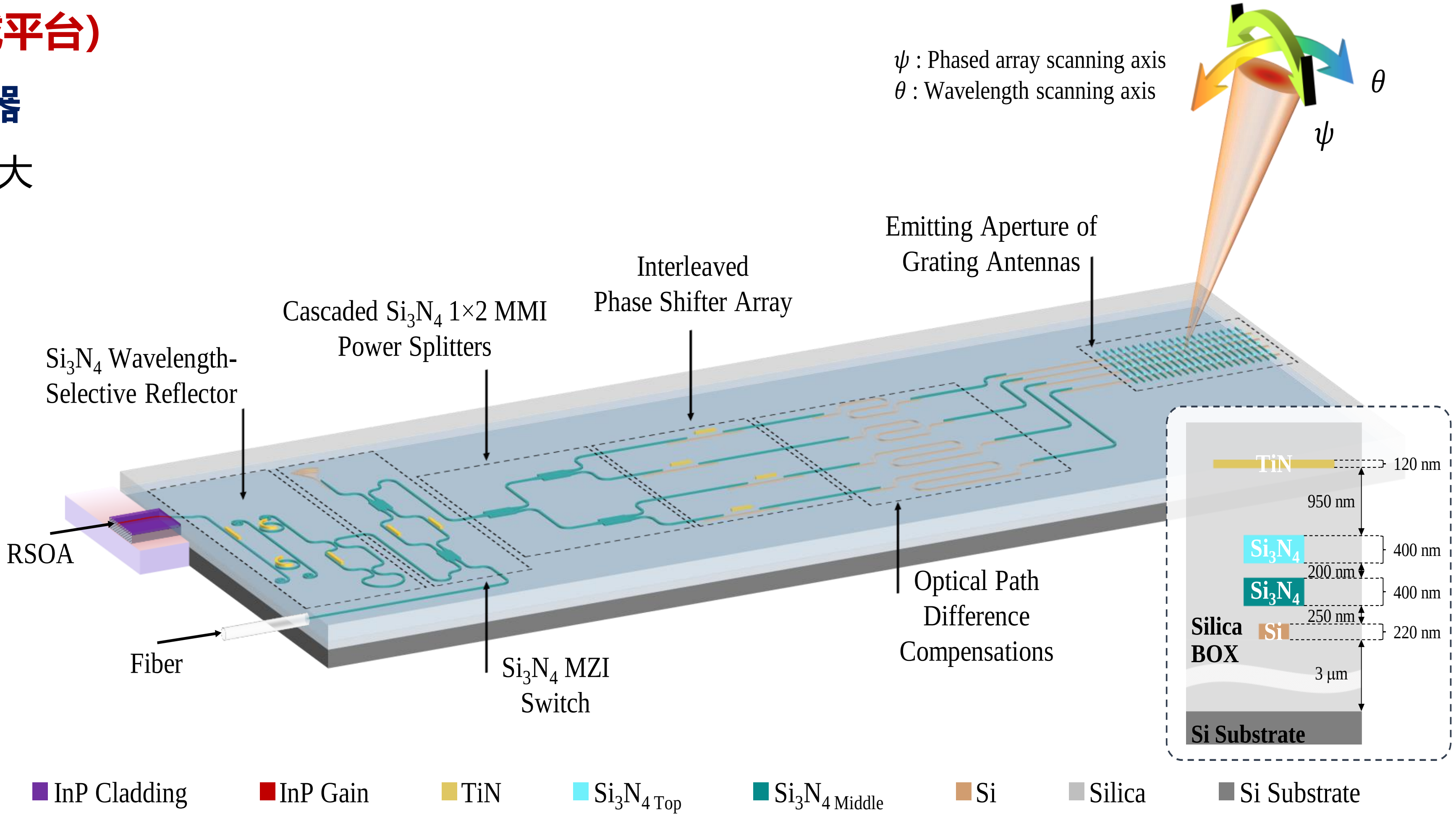
Facial Recognition

VR/AR

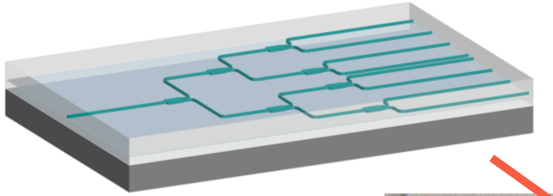
混合集成LiDAR发射芯片

芯片结构（Si-Si$_3$N$_4$三维集成平台）

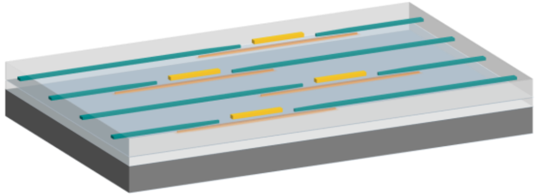
- **III-V/Si 窄线宽可调激光器**
  - Vernier微环：可调范围大
  - Si$_3$N$_4$微环：低损耗
- **256通道二维OPA**
  - Si$_3$N$_4$分路器：大功率
  - Si移相器：低功耗
  - Si-Si$_3$N$_4$发射天线：间距线性增加



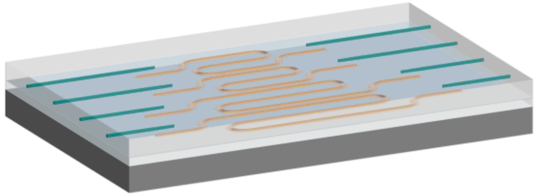
芯片结构



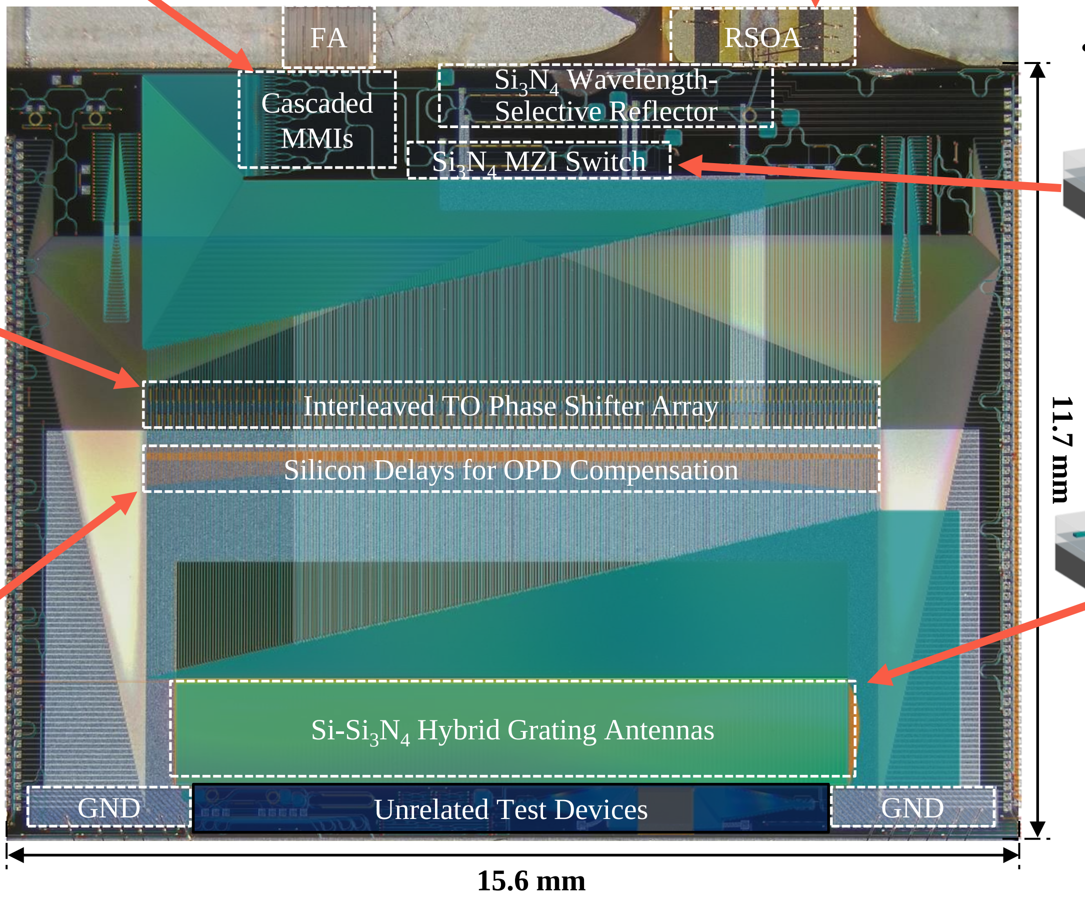
Si_3N_4 MMI$_{1\times2}$
- Unit size @ 7 μm x 100 μm
- Unit insertion loss = 0.04 dB
- 8 stages for 256 channel power splitting

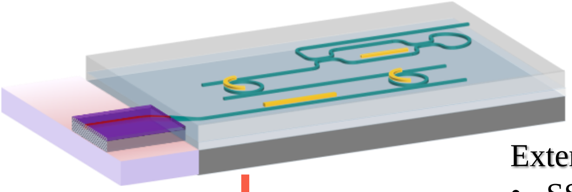


TO Phase Shifters
- Inter-channel Pitch = 44 μm
- Efficiency @ 22 mW/π
- Response time < 60 μs

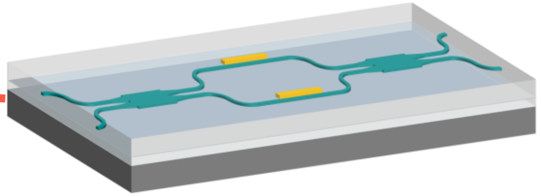


Si Delay Lines
- Euler-bend effective radius = 4.6 μm
- Si-SiN inter-layer transitions IL @ 0.06 dB

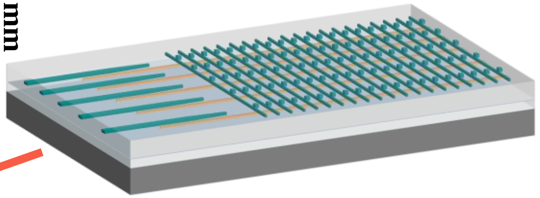




External Cavity Laser
- SSC tilted @ 17.87° for isolation of reflection
- Typical ring resistance = 2.7 kΩ

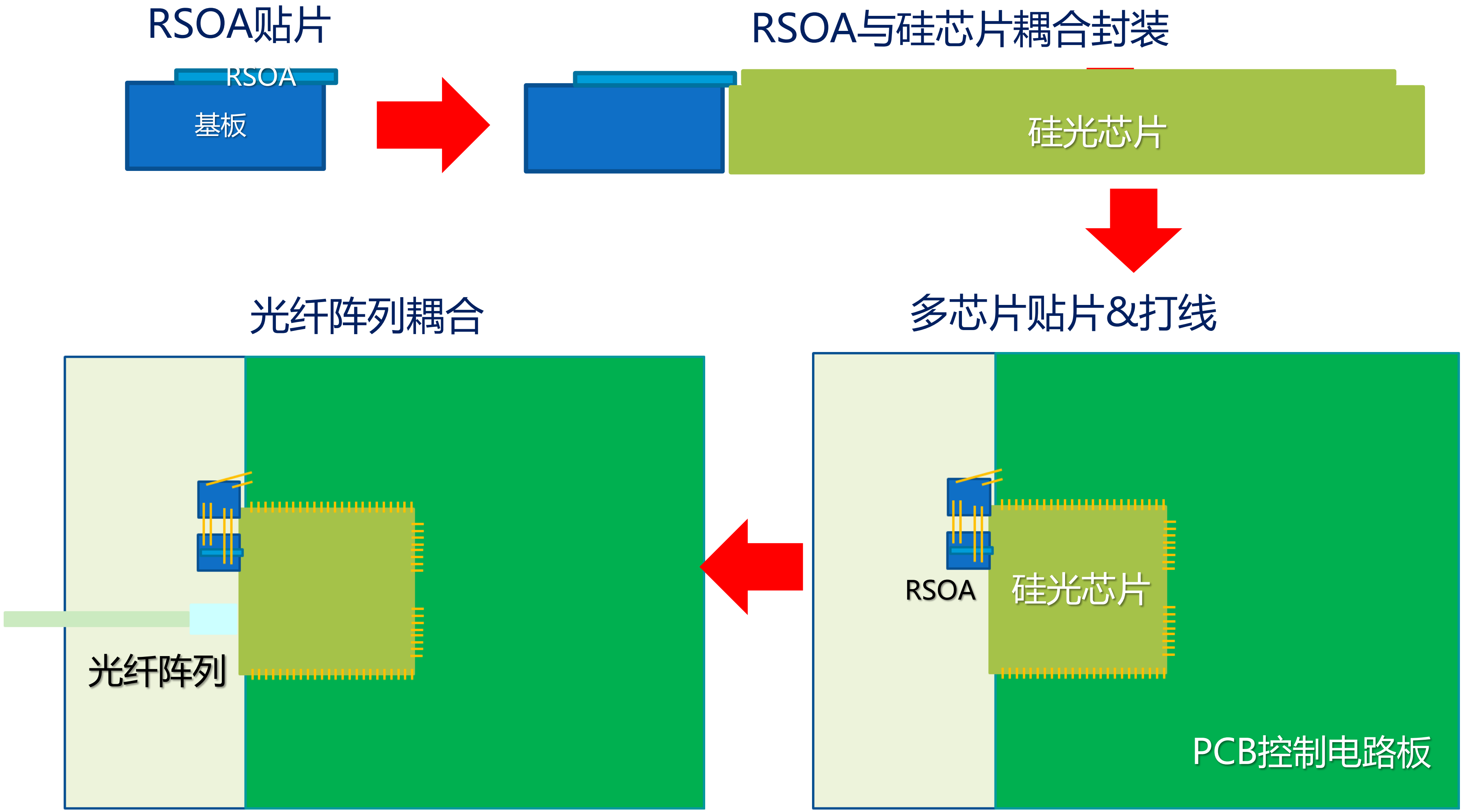


Si_3N_4 MZI Switch
- Passive Loss < 0.35 dB
- Efficiency @ 300 mW/ π



Grating Emitters
- Fixed grating strength
- Grating period = 0.7 μm
- \# of gratings = 14700 @ 10.3 mm

封装流程



RSOA贴片

RSOA

基板

RSOA与硅芯片耦合封装

硅光芯片

多芯片贴片&打线

RSOA

硅光芯片

PCB控制电路板

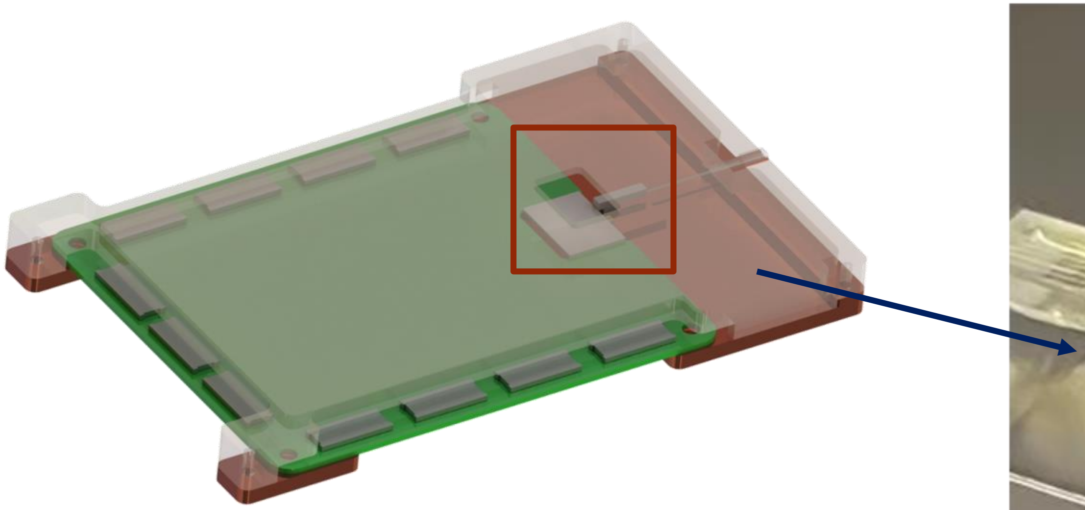
光纤阵列耦合

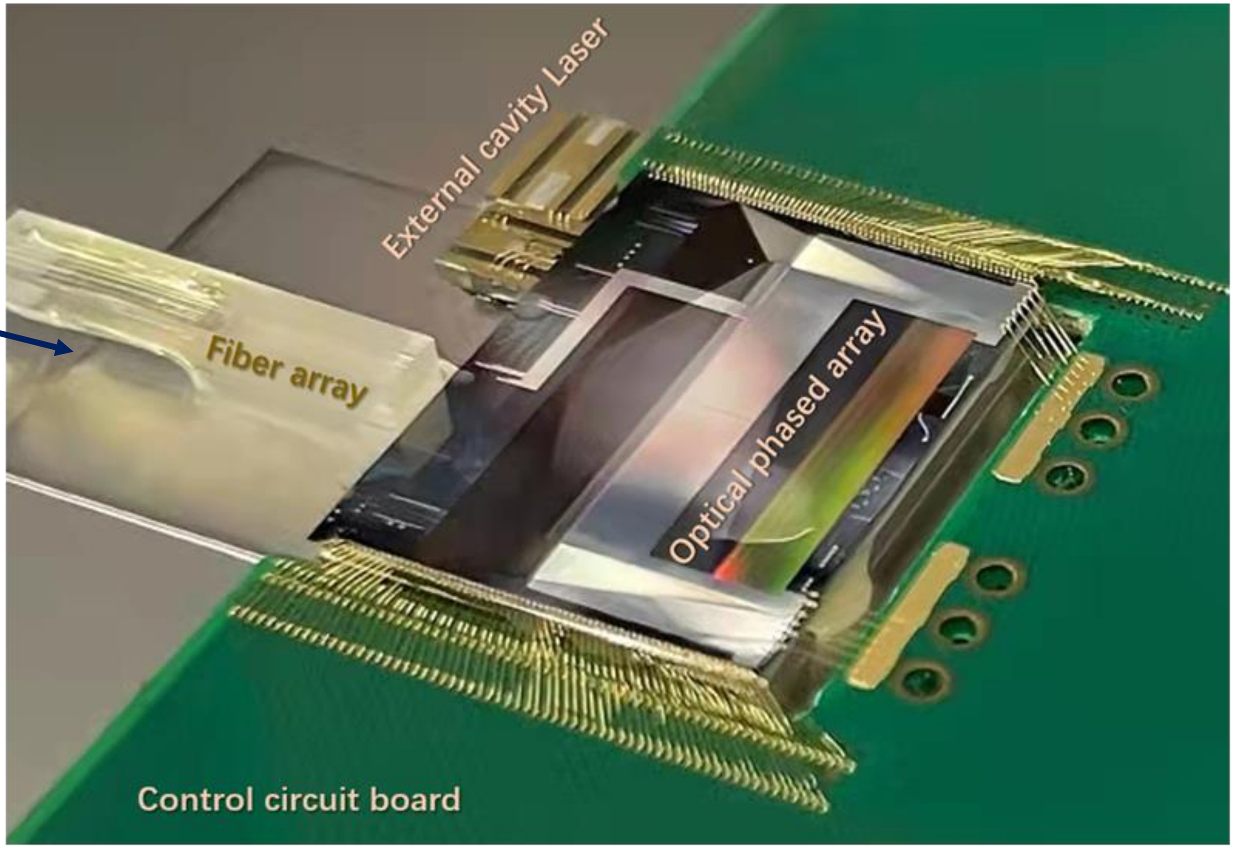
光纤阵列

- 多芯片耦合
- 电学封装
- 光学耦合

封装后照片

模块结构

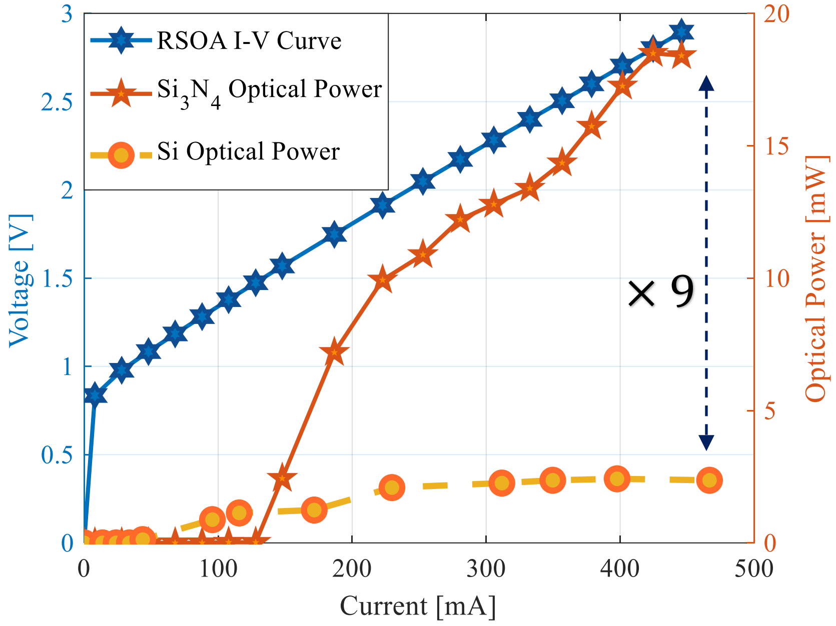




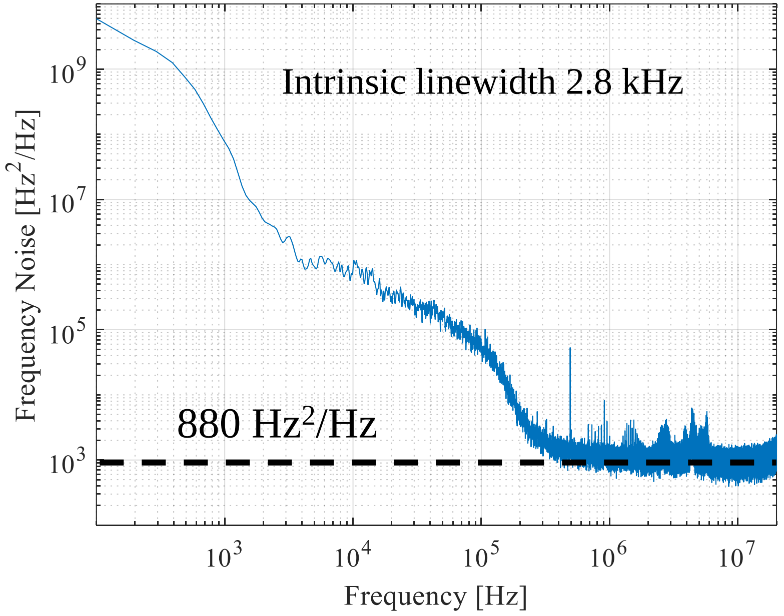
- FA耦合损耗：~4 dB
- RSOA耦合损耗：~2 dB

芯片测试结果: 激光器

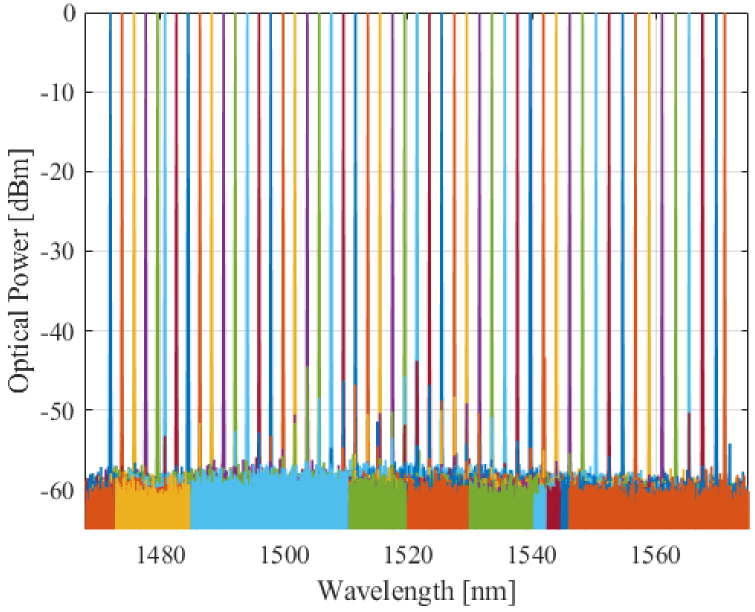
- **L-I-V**



- **线宽**



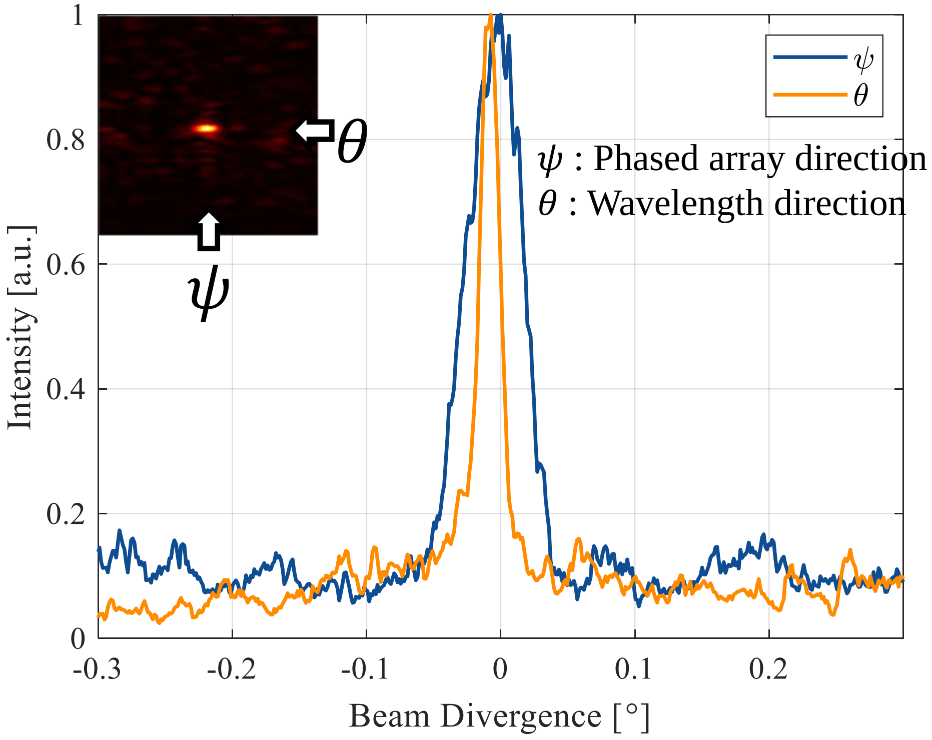
- **光谱**



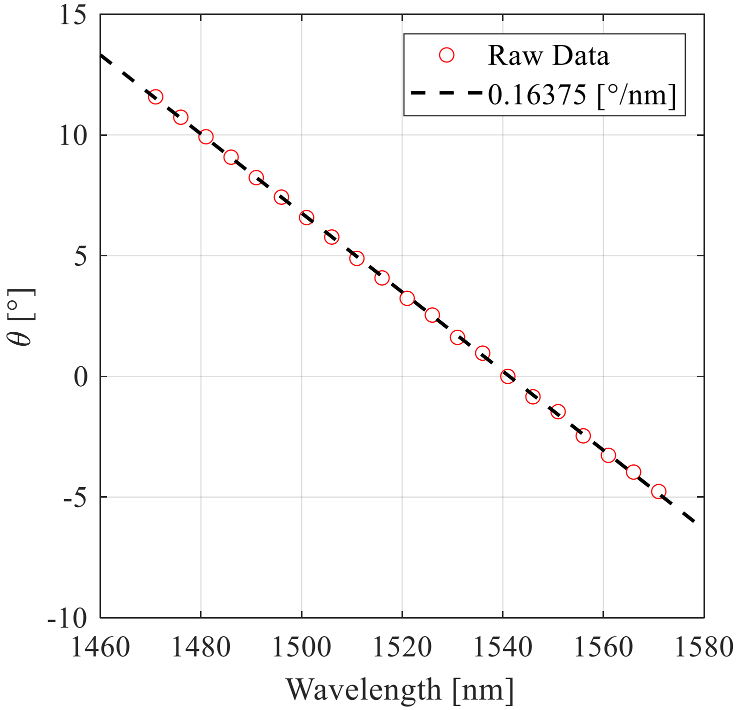
- 片上出光功率：~18 mW，是Si基激光器的9倍
- 本证线宽：2.8 kHz@1549 nm, 200mA
- 波长范围：1471~1571 nm
- SMSR：≥ 42.6 dB @150 mA

芯片测试结果: OPA

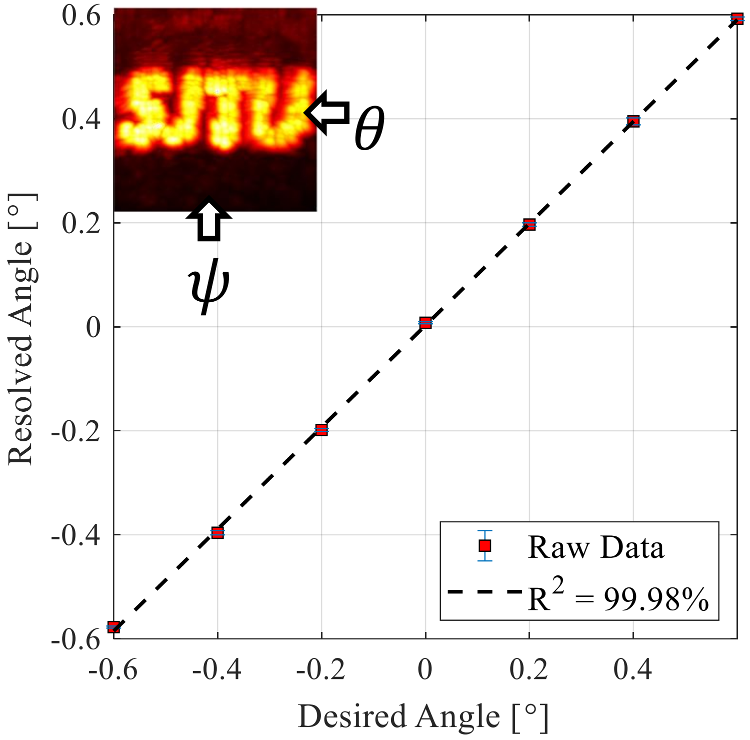
- **波束质量**



- **波长扫描**



- **相位扫描**



- 波束发散角： 0.05°×0.018°， SLSR： 8 dB
- 波长扫描范围：~16° (0.163°/nm)
- 角度扫描范围：150°，扫描误差：<0.011°

谢 谢！

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