Optical Input / Output Considerations for Photonic Integrated Circuit Coupling & Packaging

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1. Why Should I Care about Probing & Packaging?
   ➢ When should I care about probing & packaging?
2. What are my Probing/Package Requirements?
   ➢ Self assessment for out- or in-sourcing
3. Optical I/O Considerations & Options
4. Packaging Service Providers and Exemplary Services
Bias Disclosure: Surface Coupling

Surface Coupling

Edge Coupling

Vertical Grating Couplers

Waveguide Facet
Why Should I Care about Probing & Packaging?

1. Proper testing of your PIC demands it
2. May want to get off lab bench/probe station and test in real world
   ➢ Even if not your initial goal
3. 80:20 electronic vs. 20:80 photonic chip:package costs (?)
4. Achilles’ Heel: [Definition: Weakness in spite of overall strength, leading to downfall]
   ➢ “Can you package my 2 μm MFD channels on 127 μm pitch?”
   ➢ Packaging can be a strong asset and need not be painful
   ➢ Start discussing it when you purchase your design software
     • Perhaps as a prerequisite – can software model optical coupling?
     • Certainly at earliest stage of design
Basic Probing / Packaging Requirements

Map out your testing:

1. How will I systematically and granularly verify my design?
   • Electrical
   • Optical
   ➢ Independently verify electrical and optical, e.g. pure optical alignment / measurements uncomplicated by detector or modulator verification

2. Do you want to do wafer-level probing?
   ➢ Consider addition of taps and vertical grating couplers (VGCs)
   ➢ Erasable VGCs: M. Milosevic, "Towards autonomous testing of photonic integrated circuits," Proc. SPIE 10108, Silicon Photonics XII, 1010817 (2017/02/20)
Electrical, Layout and Fixturing Considerations

- Electrical design
  - Single-end vs differential RF
  - Minimize RF line lengths
  - Electrical I/O design: Wire bonds vs. Flip-chip (solder bump, Cu pillar)
    - Copper pillar offers: Higher I/O density, improved electromigration resistance, improved thermal conductivity, simplified underbump metallization and underfill
    - Often a progression of designs
  - Die bonding electrical needs, e.g. grounding

- Layout considerations
  - Die Size: L x W x H
  - Minimize conflicts between electrical and optical I/O
    - Keep die edges unmixed: electrical OR optical
    - Use opposite edges for optical when 2 edges are needed
    - Clearance between optical and electrical probe “pads” for simultaneous probing

- Test fixturing that considers test needs, e.g. compatible connectors
Thermal Management & Application-Specific Considerations

• **Thermal Design**
  • Especially relevant when PIC contains: laser, resonators, AWGs, WDM components, amplifiers or components that generate heat or are temperature-sensitive
• **Thermal modeling**
• **Thermoelectric cooler (TEC) and feedback/control**
  • On-chip temperature measurement
  • Thermistors with feedback to TEC
• **Die bonding requirements**

• **Application-specific packaging needs**
  • Package design and environmental needs: form factor / testing:
    • Testing requirements: Telcordia to biocompatible (e.g. sterilizable) to hermeticity to vacuum-compatible to cryogenic, etc.
Optical Considerations

- Spectral range / fiber needs
- Number of channels
- Polarization sensitivity: PM channels
- Edge vs. surface coupling
  - Surface coupling may be desirable for wafer level testing even when edge coupling packaged device
- Mode Field Diameter (Spot Size) at die interface: waveguide facet or VGC
  - VGC diffraction angle
    - Experimentally verified mode field dimensions preferred
- Pigtailed vs. pluggable
- Active alignment design / equipment needs
  - Alignment channels / taps / fiducials
  - On-chip detector / source
- Package materials needs – stability
- Hermiticity needs
- Package process sequence

- Optical performance expectations
  (transmission losses, polarization and temperature sensitivity)
# PIC Optical Coupling: Edge vs. Surface

- **Die to fiber:** Submicron to ~ 10 μm spot size (1550 nm) conversion needed

## Edge Coupler vs. Vertical Grating Coupler (VGC)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Edge Coupler</th>
<th>VGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>100s of nm</td>
<td>30 nm (1 dB) typ.</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>2 dB typ.</td>
<td>3-4 dB typ.</td>
</tr>
<tr>
<td>Fiber-to-die</td>
<td></td>
<td>Deceptive</td>
</tr>
<tr>
<td>Mode Field Diameter [Alignment Tolerances]</td>
<td>1-2 μm typ. [0.1-0.2 μm] (Inverted taper)</td>
<td>6-10 μm typ. [0.6 - 1 μm]</td>
</tr>
<tr>
<td>Arrays / # of Channels</td>
<td>1-dimensional / 10s</td>
<td>2-dimensional / 100s</td>
</tr>
<tr>
<td>Edge preparation</td>
<td>Yes: etch (ledge), polish</td>
<td>No (also enhanced stability)</td>
</tr>
<tr>
<td>Wafer-level Probing (KGD, Foundry vs. BE)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Polarization Maintaining</td>
<td>Yes</td>
<td>No 2D PM fiber couplers yet</td>
</tr>
<tr>
<td>Polarization Handling</td>
<td>On-chip PM splitters</td>
<td>Polarization diversity VGCs (IL penalty)</td>
</tr>
</tbody>
</table>


**Other considerations include:** IP, Overall package design, thermal management.....
Optical Coupling Technologies

Free Space Optics
- Lens
- Lensed Fiber
- Micro-Optic for Arrayed Lenses
- Planar Fiber Coupling (TIR)
- Tyndall National Institute

Interposers
- Interposer Chip
- PLC Connections

Photonic Wire Bonds
- Karlsruhe Institute of Technology

Passive Alignment
- Adiabatic Coupling

Fiber and Fiber Arrays
- High NA fiber
- Multicore Fiber
- V-Groove Arrays
- Pitch Reducing Optical Fiber Array (PROFA)

Interposer Chip
- PLC Connections

Photonic Wire Bonds
- Karlsruhe Institute of Technology

EU FP7 Initiative PHASTFlex

Wafer-level “PhotonicBump”
- Teramount Ltd.
PhotonicPlug

- Provide passively aligned optical I/O via standard pick & place equipment: +/- 6 µm placement accuracy
  - PhotonicBump via wafer-level process
  - PhotonicPlug via standard pick & place equipment
  - Fiber array: SM, 250 µm spacing
  - Performance (standard flip chip equipment, 1500 UPM): < 0.5 dB coupling loss
  - Introduction: 2H 2018 (working with customers now)
• Dual, concentric core design and choice of glass refractive indices ($n_1$, $n_2$) enable device to be compatible with standard fibers (on left).
• Light is confined within secondary core, tailored ($n_2$, $n_3$) to be compatible with reduced mode field diameter (MFD) of coupled to waveguide
• The central core ($n_1$) effectively “vanishes” relative to light traveling through tapered region.
“Vanishing Core” Fiber Concept

Vanishing Core

Secondary Core

Tailored NA

Waveguide

Fiber

Cladding (Ø ≈ 125 µm)

n_1 - n_2 < n_2 - n_3 - reduced MFD
n_1 - n_2 > n_2 - n_3 - expanded MFD
n_1 - n_2 = n_2 - n_3 - preserved MFD

Endface for PM coupling

Configurable output geometry for polarization control and mode shape adaptation

Pitch Reducing Optical Fiber Array (PROFA)

Conventional single-lens focusing:
if \( p_1 > p_2 \) then \( \text{MFD}_1 > \text{MFD}_2 \)

PROFA:
if \( p_1 > p_2 \) then
\( \text{MFD}_1 > \text{MFD}_2 \) \ OR \( \text{MFD}_1 < \text{MFD}_2 \) \ OR \( \text{MFD}_1 = \text{MFD}_2 \)
PROFA Products – PROFA1D

- 1-6 Channel Optical Couplers (linear)
- MFD ~ 2 μm (1/e^2 intensity) @ 1550 nm
- 12 um channel pitch, ≤ 0.2 μm position tolerance
- Insertion loss (IL) < 1 dB
- Crosstalk < -40 dB
- No air gap within optical path
- PM aligned and coupled: typical PER ≥ 20 dB
  - Slow axis ↔ TE
  - Fast axis ↔ TM
PROFA Products – PROFA2D

- 1-61 Channel Optical Couplers (2D)
  - MFD ~ 4-10 μm (1/e² intensity) @ 1550 nm
  - Channel spacing ~ 35-50 μm – optimal: 37 μm
  - ≤ 0.4-1 μm position tolerance
  - Insertion Loss (IL) < 1 dB
  - No air gap within optical path
  - Crosstalk < -35 dB
# PROFA1D vs. PROFA2D

<table>
<thead>
<tr>
<th>Comparison</th>
<th>PROFA1D</th>
<th>PROFA2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical for coupling to</td>
<td>Edge</td>
<td>Surface</td>
</tr>
<tr>
<td>Mode field size (µm)</td>
<td>~ 2</td>
<td>~ 4-10</td>
</tr>
<tr>
<td>Array Lattice</td>
<td>Linear</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Channel spacing (µm)</td>
<td>12</td>
<td>35-50 (37 optimal)</td>
</tr>
<tr>
<td>Channels currently available</td>
<td>1-6</td>
<td>1-61</td>
</tr>
<tr>
<td>Singlemode (SM) / Polarization Maintaining (PM) availability</td>
<td>SM / PM</td>
<td>SM</td>
</tr>
<tr>
<td>Typical coupling loss (fiber-to-chip, dB)</td>
<td>2</td>
<td>3-4</td>
</tr>
<tr>
<td>Alignment accuracy required (µm)</td>
<td>≤ 0.2</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Price per channel (Qty:1)*</td>
<td>~ USD 400</td>
<td>~ USD 30</td>
</tr>
</tbody>
</table>

* Pricing can be reduced significantly in quantity and depending on configuration
Face Coupling: 37 Channels, 1 Port

Pitch Reducing Optical Fiber Array


- Coupling loss 3 dB (1 dB on top of VGC coupling loss)
- 0.7 dB standard deviation across all 37 channels
Currently Available Configurations:
• Channel pitch: 35 – 45 µm
• MFD: 6 – 10 µm
• NA: 0.1 – 0.21

Insertion Loss < 0.9 dB
Crosstalk < - 48 dB
The World’s First Open Access Photonic Packaging Pilot Line
PIXAPP (Advanced Training Programme)

**First Course**

**January 2017**

- PIC Design for Packaging
- Package Design (optical, electrical, thermal, mechanical)
- PIC Fabrication Fundamentals (lab based training)
- PIC Packaging Processes (lab based training)
- Application Examples (telecom, medical, sensors)
PIXAPP (The Packaging Technologies)

- Photonic Integrated Circuit (PIC)
- Mechanical Package
- Thermal Management
- Electrical Packaging
- Source Integration
- Electronic Integration
- Fibre Optics
- Micro Optics
PIXAPP Optical I/O Offerings

• Fibers: UV cure and laser weld attachment for both edge and grating coupled PICs
• Micro optics: Wafer scale integration of micro optics on Si-PIC grating couplers for fiber-free coupling
• Photonic Wirebonds: KIT (Germany) is partner
Freedom Photonics Overview and Products

- Developer and manufacturer of photonic integrated circuit based products (InP, GaAs, Si-dielectric, Si Photonics)
  - Fast turn-around small lot wafer fabrication at Nanotech cleanroom facility

- Products and product development:
  - 1310, 1550 and 1650nm Monolithic tunable lasers
  - Monolithic tunable transmitters
  - High power, high speed photodetectors

- Optical I/O Offerings: Collimating micro-optics to couple into fiber
  - Flexibility in shaping the beam for the fiber
• Multichannel transceiver prototype (16 Tx/16 Rx) with expected 1,600 Gb/s aggregate bandwidth (50 Gb/s/channel)

• Coupling loss < 3.5 dB per VGC

• Crosstalk < -30 dB


Tailorable Mode Field Size and Density: 1.5 µm x 2 Channels

19 µm spacing, dual channel array coupled to an InP Multi-Wavelength Coherent Receiver (Alcatel-Lucent)

Tailorable Mode Field Size and Density: 2 µm x 10 Channels

Doany et al., IEEE J. of Lightwave Technology 29, 475 (2011)
PIC Development Package - Edge

- Two single-channel PROFA1Ds
- Two I/O ports
- Open package design for electrical probing
- Cryogenically stable package

Work done with OpSIS
http://opsisfoundry.org/
1550 nm PANDA fiber coupled to 220 x 200 nm Si waveguide

< 2 dB coupling loss
< -20 dB polarization crosstalk

Work done with OpSIS
http://opsisfoundry.org/
FTNIR Spectrometer – Oil & Gas Industry
Hermetic Butterfly Package – PROFA1D

• Single-channel PROFA1D
• 1550 nm PANDA fiber coupled to Si waveguide

Work done with Luxmux Technology Corporation
http://www.luxmux.com/
Conclusion

• Plan for coupling and packaging at the earliest design stage

• Internally review coupling/packaging needs
  ➢ Designguide@chiralphotonics.com
  ➢ Form an informed optical I/O opinion

• Engage with packaging house(s) early