ITUWebinars

Quantum information technology (QIT)

Episode #5: Joint symposium on quantum photonic integrated circuits

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QPIC-to-Fibre Coupling

AN OVERVIEW...

Topics

- Introduction to PIC-to-Fibre Coupling
- Types of PIC Coupling
  - Vertical Coupling
  - Edge Coupling
- Comparison of coupling techniques
- Conclusion

PIC-to-Fibre Coupling

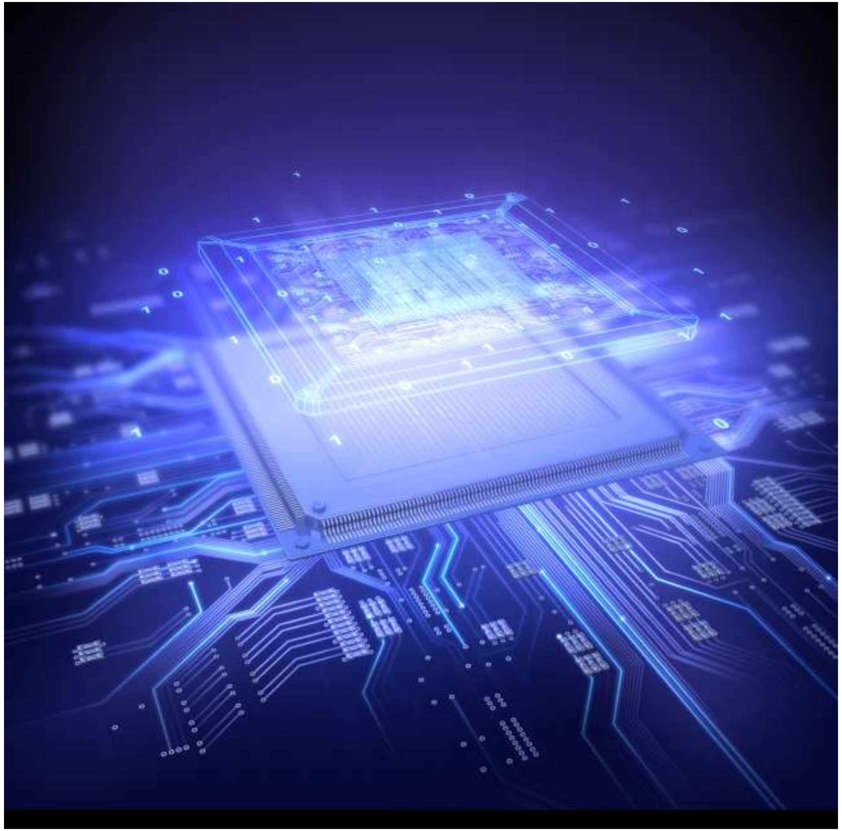
Key Challenges

Photonic Integrated Circuit (PIC)

- A photonic integrated circuit (PIC) or integrated optical circuit is a device that integrates multiple (at least two) photonic functions and as such is similar to an electronic integrated circuit.

- The most commercially utilized material platform for photonic integrated circuits is indium phosphide (InP), which allows for the integration of various optically active and passive functions on the same chip. Other PICs materials may include:
  - Silicon, Silica, Silica Nitrate (SiN) & Polymer (passive function only),
  - Lithium Niobate (LiNbO3), Indium Phosphate (InP) and Gallium Arsenide (GaAs)

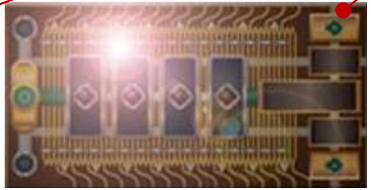
- Quantum Photonic Integrated Circuit (QPIC) are PICs developed for quantum cryptography, communications, and computing requires reducing existing table-top experiments (e.g. quantum light source, quantum number generators, etc)

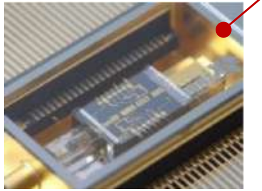


Photonic integrated circuit platforms

	Silicon	InP	SiN	Silica (SiO)	Polymer	$LiNbO_3$
Waveguides	++	++	+++	+++	+	+
Fibre coupling	-	+	++	++	+++	+
Modulators	+	++	---	---	+++/---	+++
Light sources	---	+++	---	---	---	---
Photo detectors	++	+++	-	-	-	-
Footprint	+++	++	-	-	--	---
Wafer size	+++	--	+	+	-	-
Yield	+++	+	++	++	+	-
Hybrid integration	++	-	+	+	+	--
Packaging	++	-	+	+	+	-
Cost	+++	-	+	+	-	---

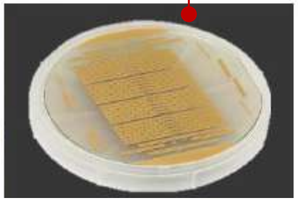

Silicon
(Source: CEA LETI)


Indium Phosphide
(Source: Infinera)

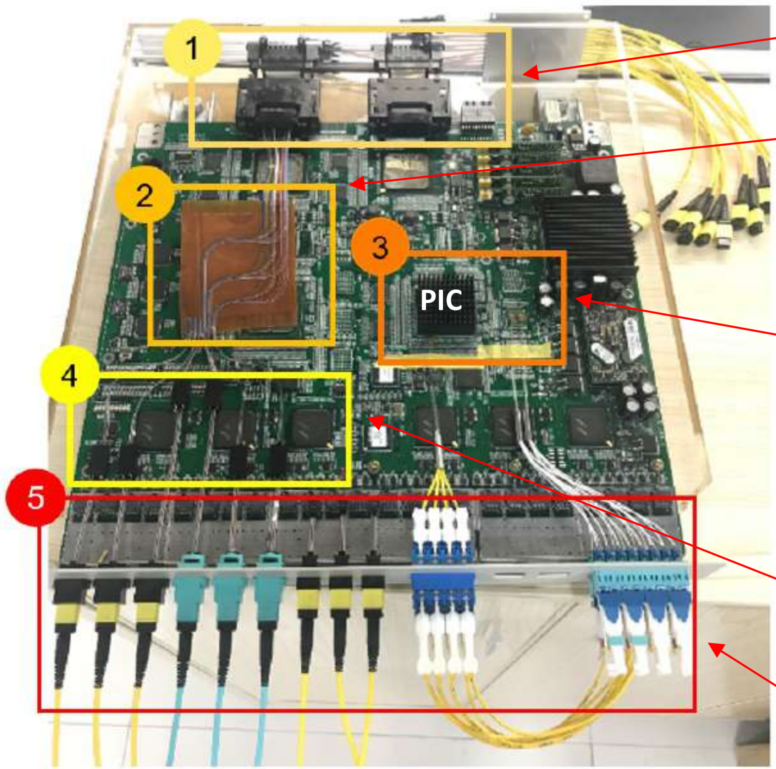

Silicon Nitride
(Source: Lionix)


Silica (Glass)
(Source: Teem Photonics)


Polymer
(Source: Lightwave Logic)


Lithium Niobate $LiNbO_3$

PIC related Optical Interconnect



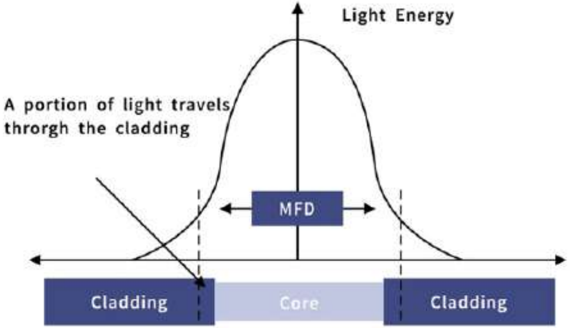
1. Backplane Interconnectors
2. Fibre Routing
   - Fibre Shuffles
   - Fibre Coating/Lamination
3. Photonic Integrated Circuit Coupling
4. On-Board/Mid-Board Interconnect
5. Front Panel /Face Plate

PIC-to-Fibre

- PIC-to-Fibre coupling is essentially the technique to couple the optical signal between the waveguide of the PIC and the core of the optical fibre
- Objective: to match the MFD of the Fibre and the PIC waveguide to achieve highest possible coupling efficiency between the two medium

$$\text{loss (dB)} = -10\log\left\{\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right\}$$

"The mode field diameter (MFD) describes the width of this intensity profile"



Objective of PIC-to-Fibre Coupling

Coupling Efficiency:

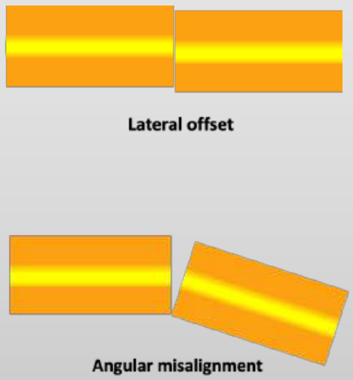
$$\text{loss (dB)} = -10\log\left\{\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right\}$$

Best Coupling efficiency is achieved when

$$MFD_1 = MFD_2$$

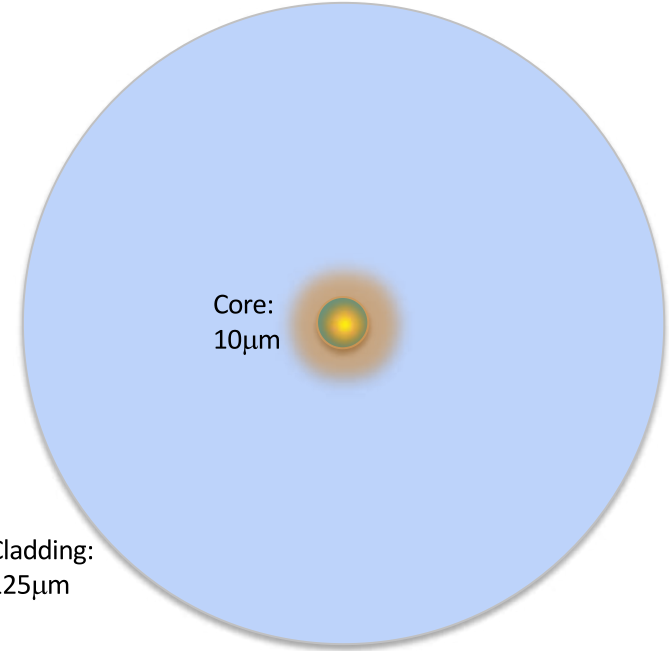
$$Loss\ (dB) = 0$$

Not considered:



Conventional single-mode Fibre

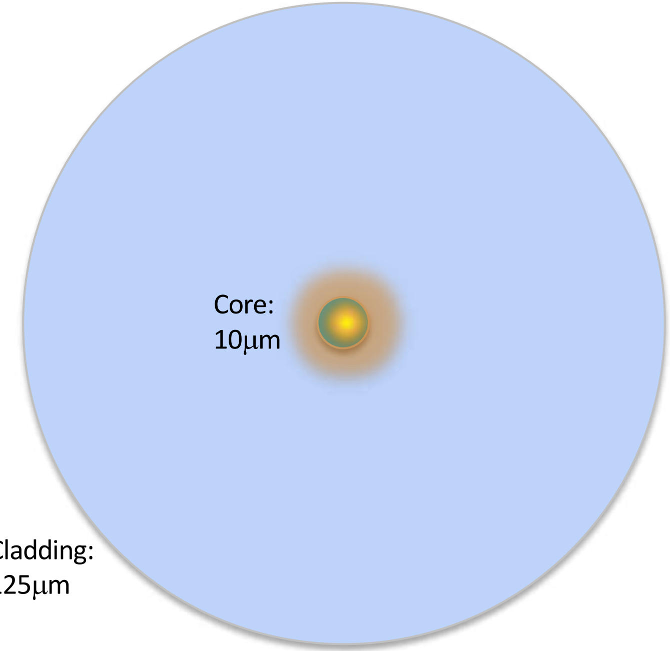
Optical Fibre 1



Typical MFD_1

- 10µm
- Circular

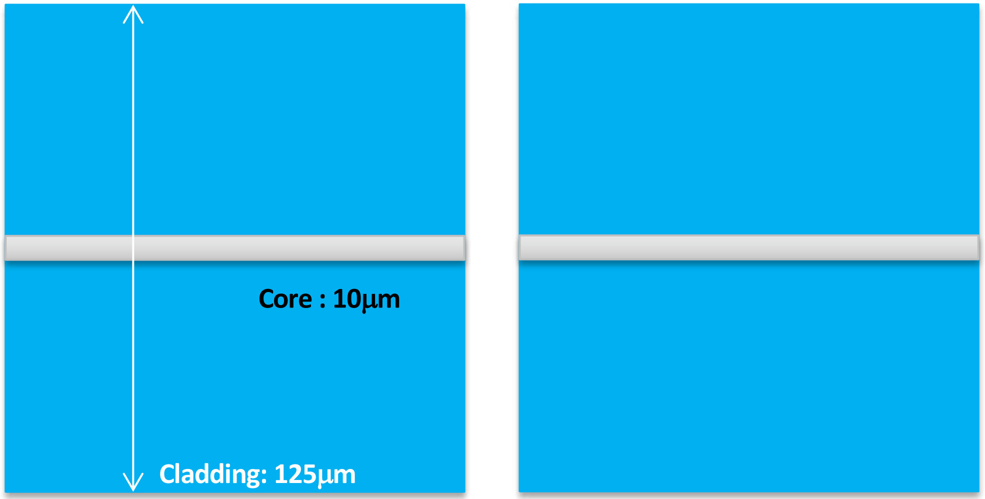
Optical Fibre 2



Typical MFD_2

- 10µm
- Circular

Conventional Fibre-to-Fibre Coupling



Typical MFD_1
- Circular
- 10μm

Typical MFD_2
- Circular
- 10μm

Estimated coupling efficiency high because

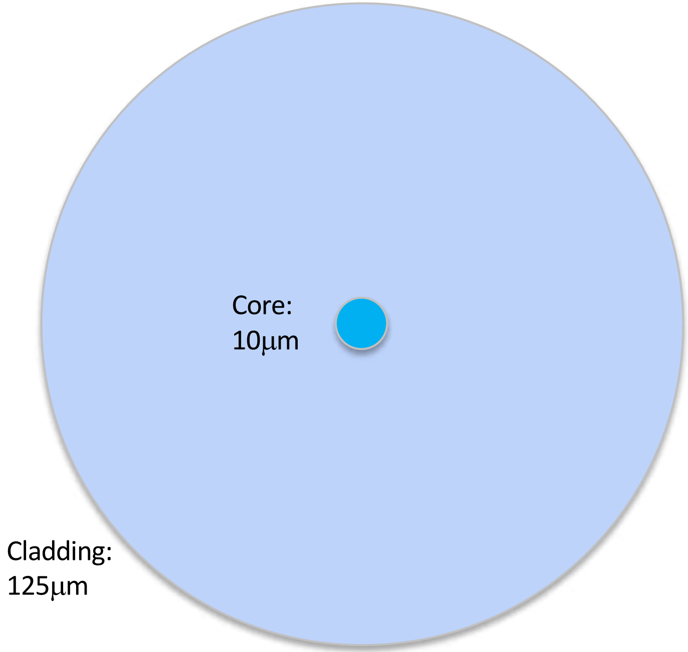
$$MFD_1 \approx MFD_2$$

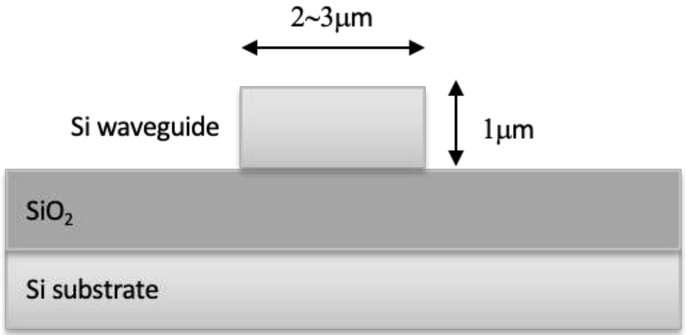
Connector No:	Insertion Loss (dB)		Backreflection (dB)	
	1310nm	1550nm	1310nm	1550nm
001	0.03	0.05	88.6	87.5
002	0.04	0.04	88.9	87.1
003	0.02	0.01	87.3	85.9
004	0.01	0.01	87.5	87.5
005	0.01	0.02	87.5	86.4
006	0.02	0.03	85.4	86.3
007	0.06	0.03	87.3	86.1
008	0.06	0.05	87.5	85.9
009	0.06	0.07	87.9	87.9
010	0.03	0.03	84.7	85.4

Insertion Loss and Back Reflection Readings of QuPC® Connectors

Typically ~1% loss or ~99% coupling efficiency

How about for PIC-to-Fibre Coupling?

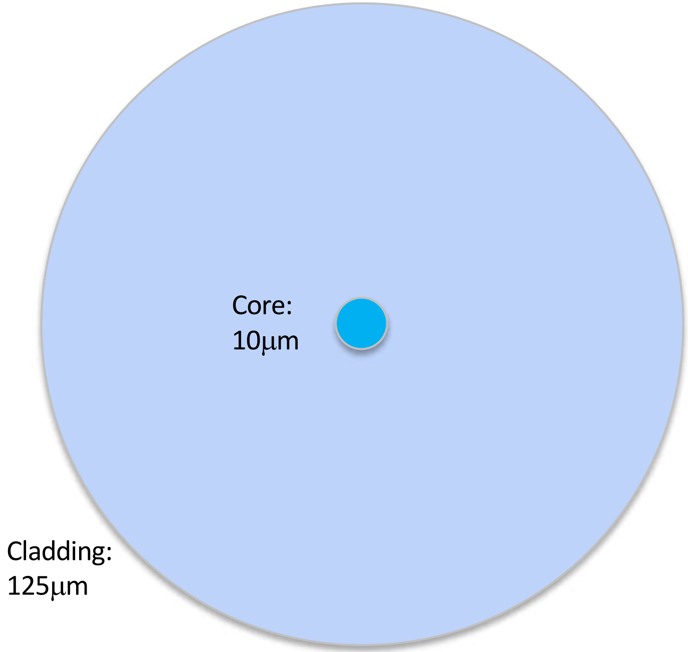


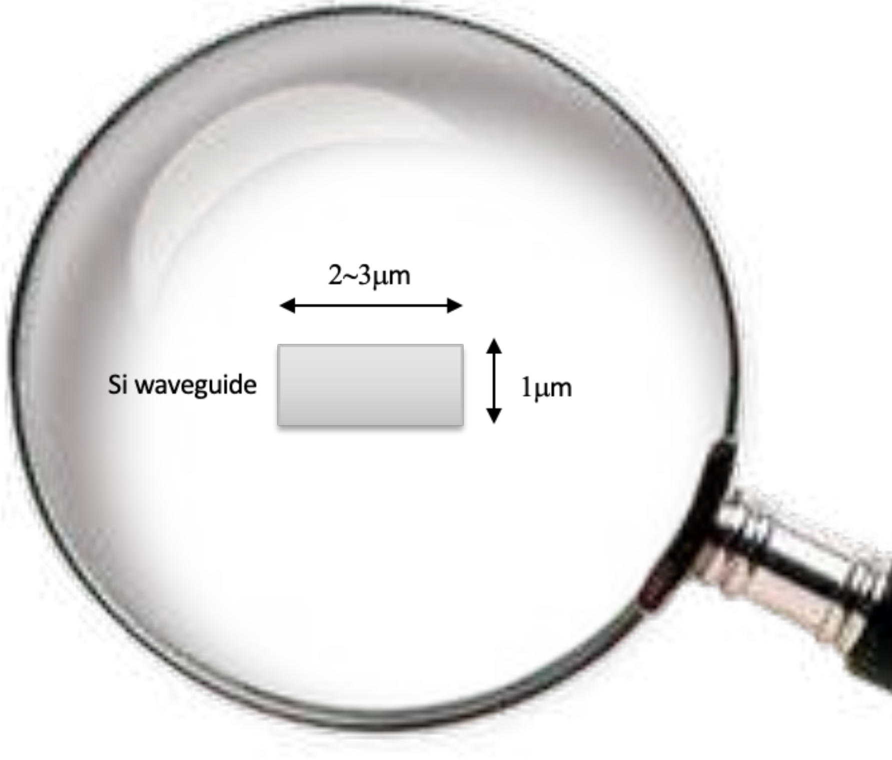


Typical MFD:
- 10µm

Typical MFD:
- <2µm

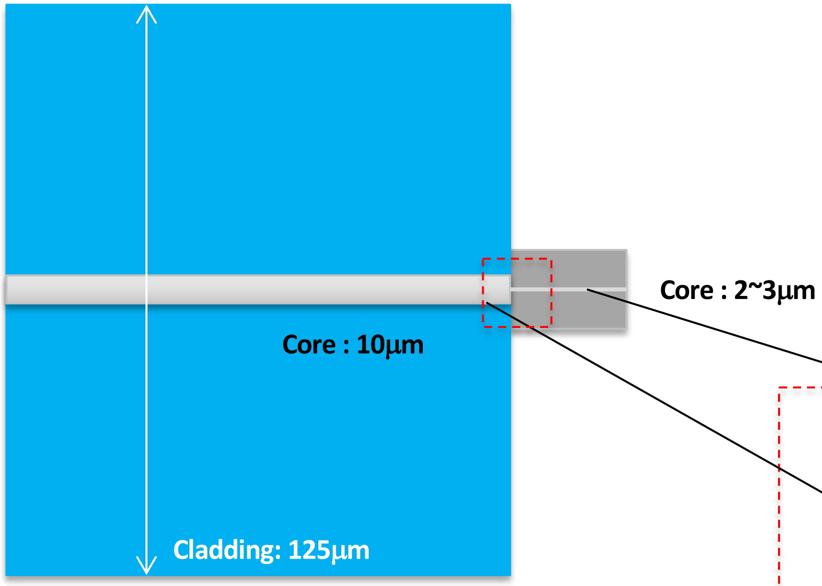
Fibre vs PIC: Dimensional Mismatch





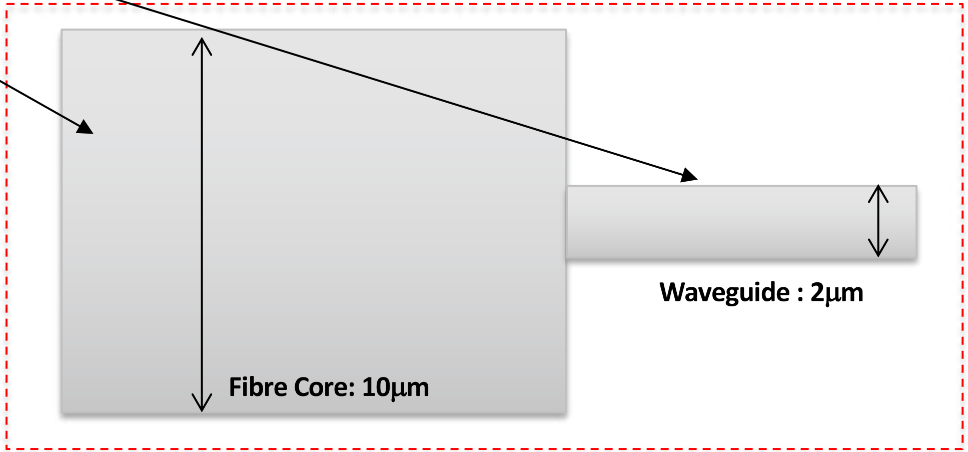
Scale to approximate size

Conventional Fibre vs PIC



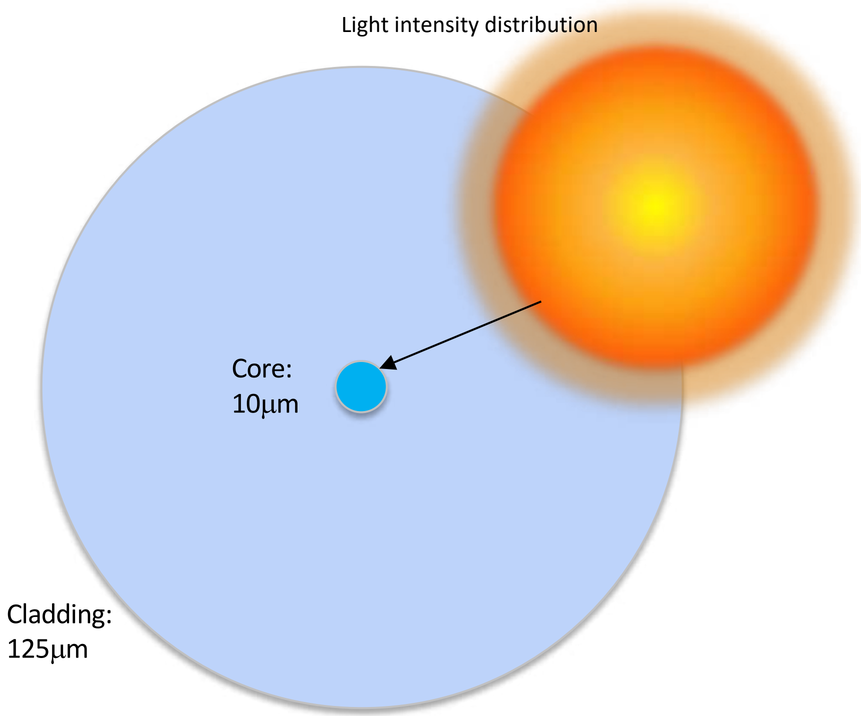
$$\text{loss (dB)} = -10\log\left\{\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right\}$$

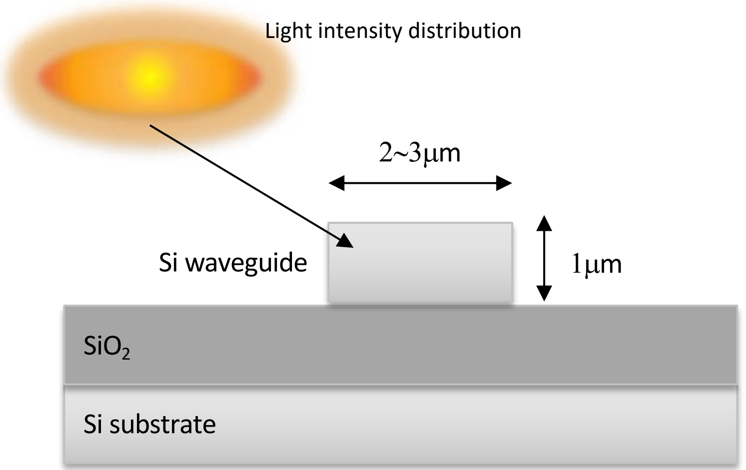
Difference in area is 35 time



$A_{\text{Fibre}} > A_{\text{Waveguide}}$

Fibre vs PIC Waveguide : Light Distribution



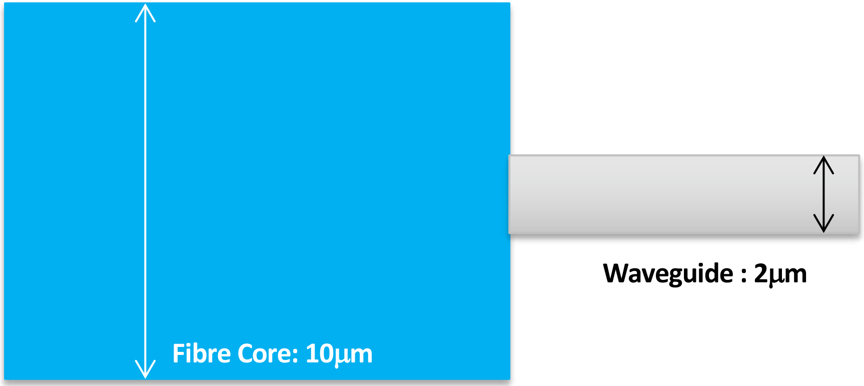


Typical MFD:
- 10µm
- Circular

Typical MFD:
- <2µm
- Elliptical

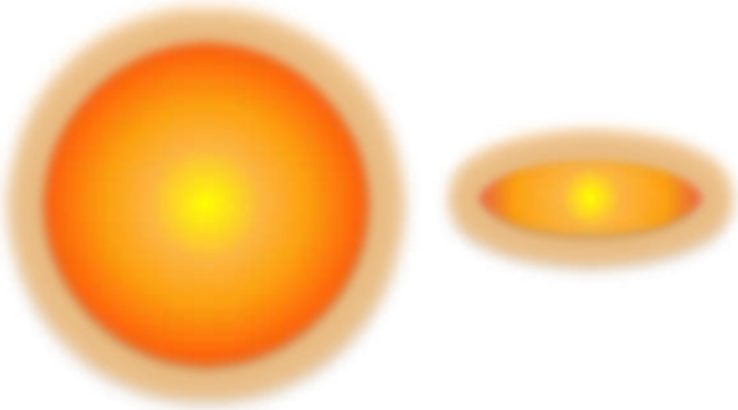
PIC-to-Fibre

- What are the challenges:
  - Match Mode Field Diameter (MFD)
    - Material mismatch between fibre/waveguide (reflective index and numerical aperture)
    - Size/Dimension mismatch between fibre/waveguide
    - Shape/Light Distribution mismatch between fibre/waveguide



Waveguide Size Mismatch

10µm vs 2µm



Light Distribution Mismatch

Circular vs Elliptical

PIC-to-Fibre Coupling

Matching the MFD

Types of PIC-to-Fibre Coupling

Diffraction grating-based coupling

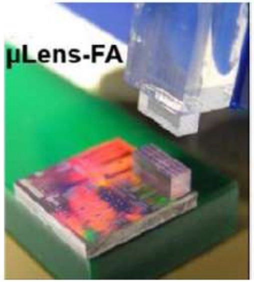
- Vertical fixed coupler or vertical free space coupler

End-fire/Edge coupling

- Active edge coupler or passive edge coupler
- Adiabatic coupling and Photonic Wire-bonding

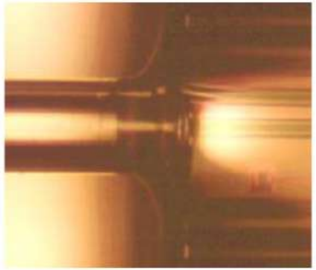
Vertical fixed coupler

Vertical free space coupler

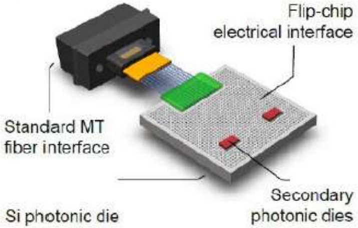


Source: *Tyndall*

Active Edge coupler

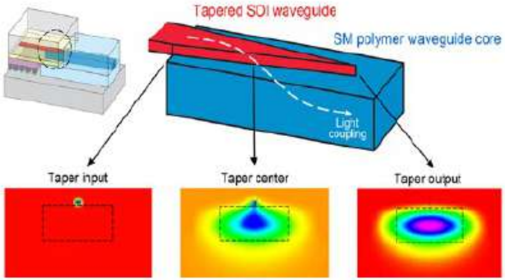


Passive Edge coupler



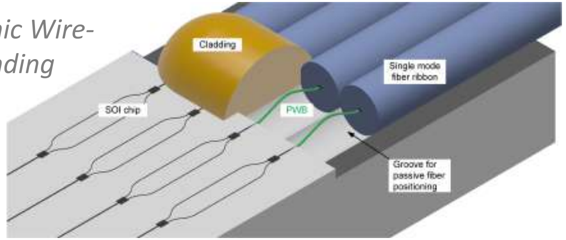
Source: ***IBM***

Adiabatic Coupling



Source: IBM

Photonic Wire-bonding



Source: *Vanguard photonics*

Vertical Grating-Based Coupling

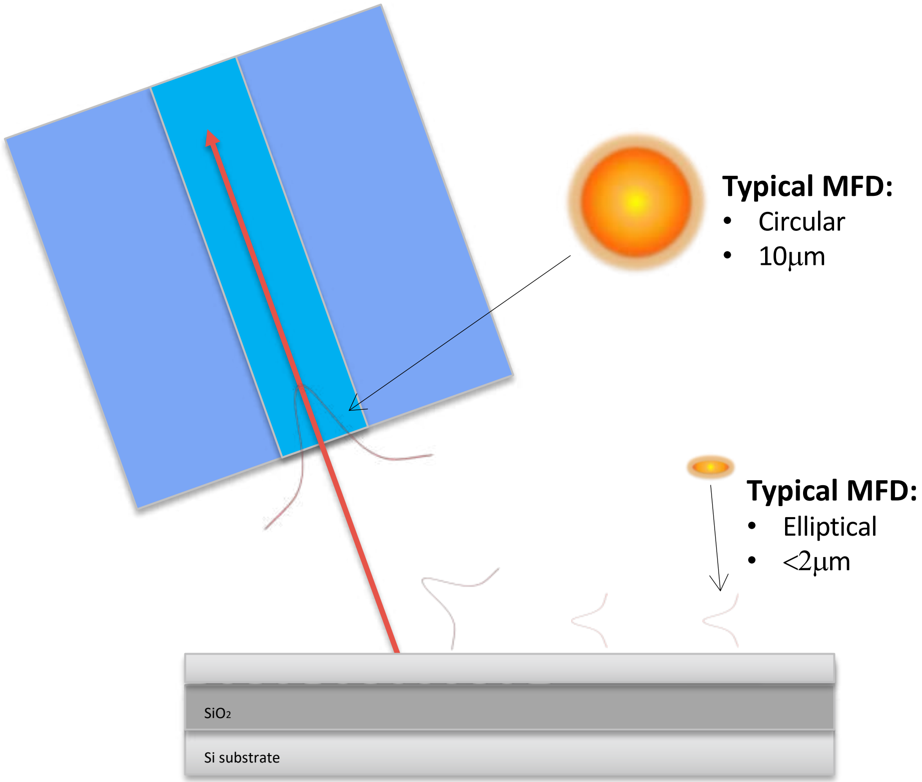
Diffraction Grating-Based Coupling

- Diffraction grating-based optical coupling is solution that provides PIC-to-Fibre coupling **vertically from the surface-normal** direction instead of chip edges.

- **Surface-corrugated grating structures** are usually patterned in the PIC's waveguide layer to create a coherent constructive interference condition that diffractively couples the incident optical beam from the PIC waveguide into optical fibre core, or vice versa.

- The grating is capable of **matching MFD of the fibre and the PIC waveguide** to ensure higher coupling efficiency

- Applicable for both single core and also multicore fibres



Schematic diagram of a diffraction grating-based coupling structure

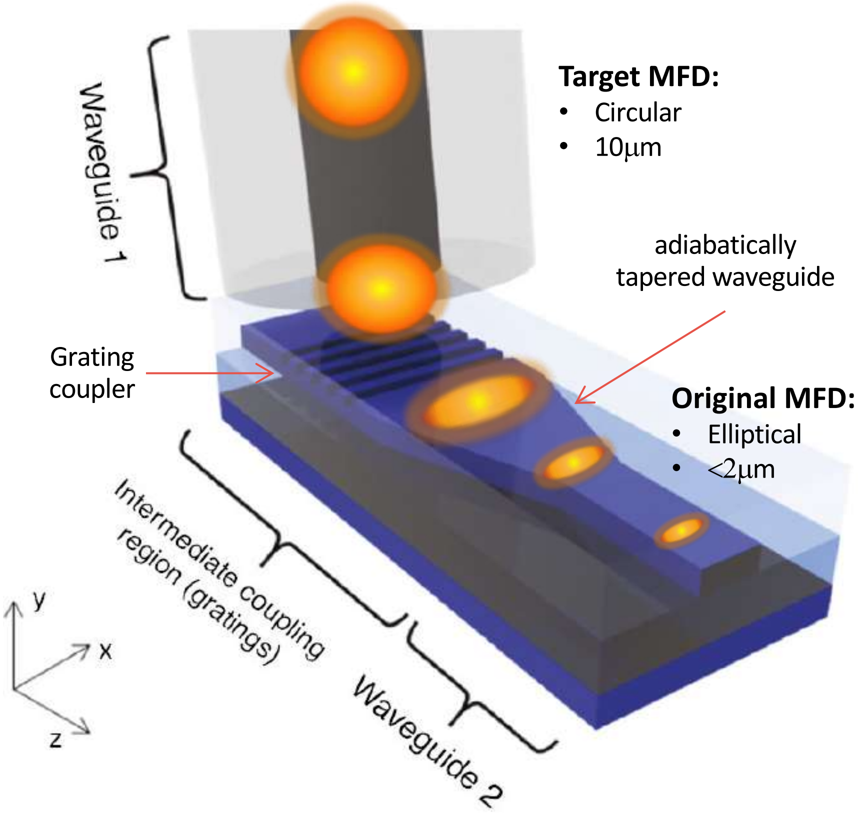
DIFFRACTION GRATING-BASED COUPLING

Principle of operation

- In general, the diffraction grating is composed of diffractive elements placed along the waveguide propagation direction. The efficient fibre-to-chip coupling can be typically achieved using a combination of a tapered waveguide region for horizontal mode size conversion and a grating coupler with a 10µm width similar to the MFD of typical single-mode fibre.

- The waveguide taper region connects to a single-mode waveguide with a grating coupler and transforms the optical field distribution along the width direction perpendicular to the waveguide's propagating axis.

- The grating elements diffract the guided optical beam out of the waveguide plane, and the diffracted optical beam finally couples to the optical fibre's guide mode.



Adapted from : Nanophotonics

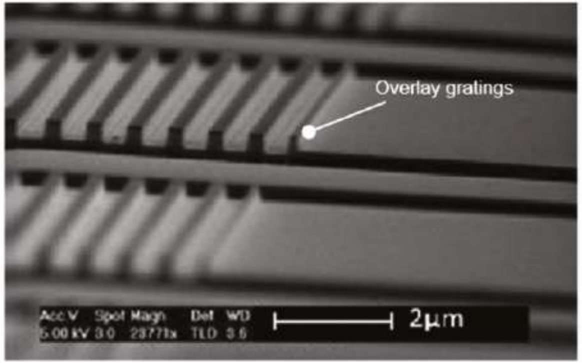
Diffraction Grating-Based Coupling

Grating coupling has three advantages compared to End-Fire Coupling which are:

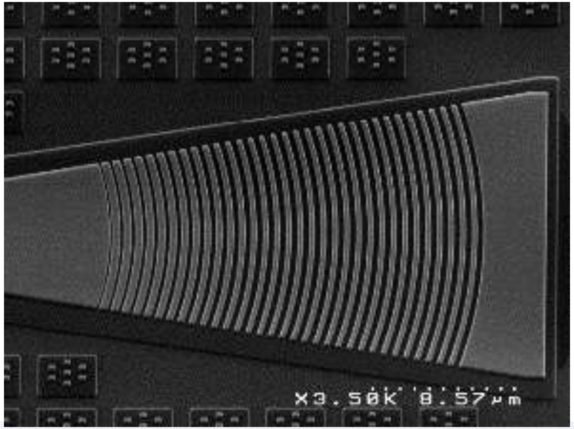
- **Post processing** such as dicing, or polishing is **not required**. This allows in-process wafer-scale optical characterization and testing
- The coupler structures **do not need to be located at the chip edges**, which improves layout design flexibility and optical port scalability
- Alleviated alignment tolerance makes measurement and packaging processes simpler.

The disadvantages of grating-based couplers are:

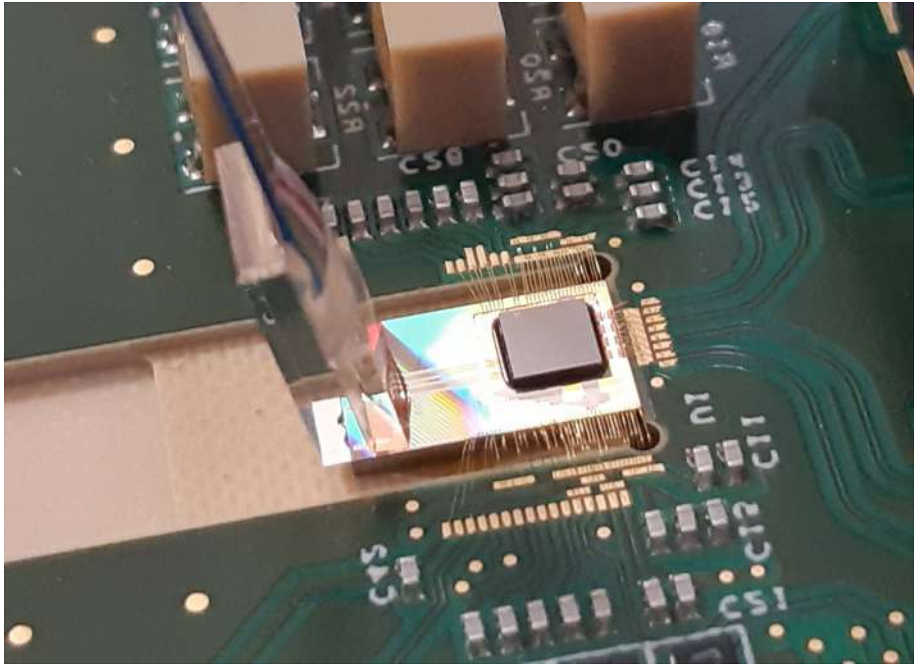
- **Polarization and wavelength dependent**
- **Lower coupling** efficiencies when compared to End-Fire Couplers
- **More complex and costly PIC design** including additional layer for mode conversion



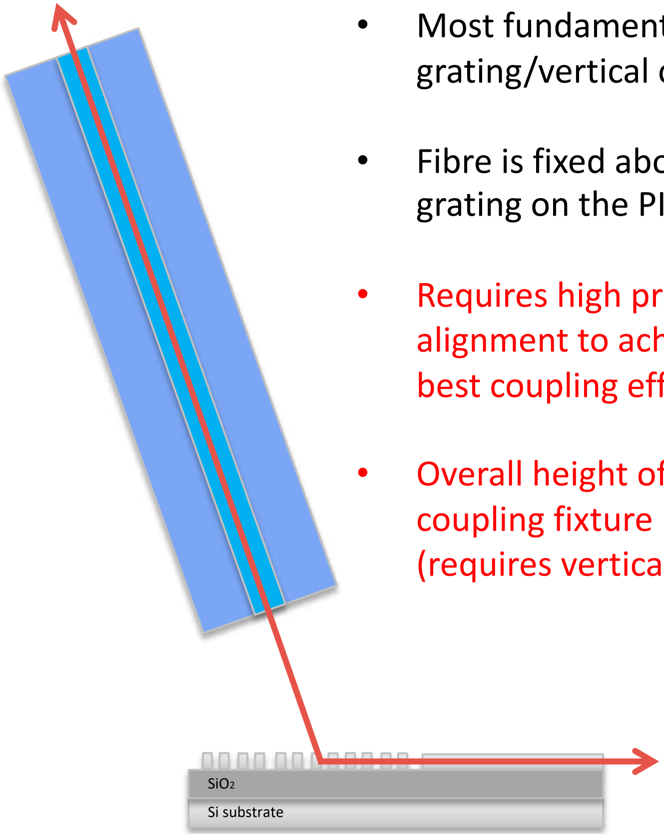
Scanning Electron Microscope (SEM) image of a grating structure.



Variation of Grating Coupling techniques

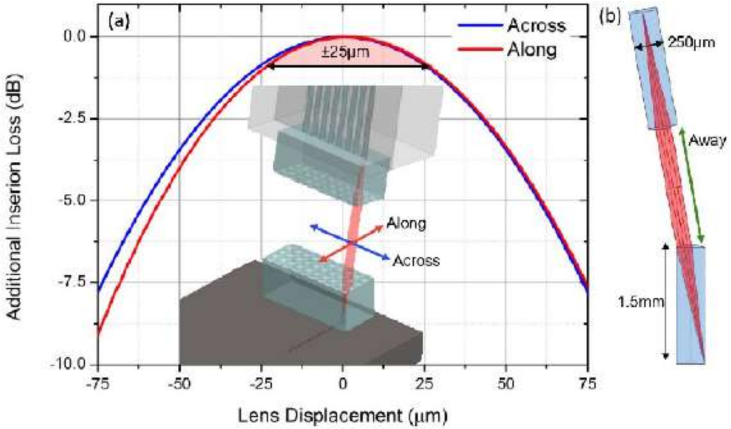


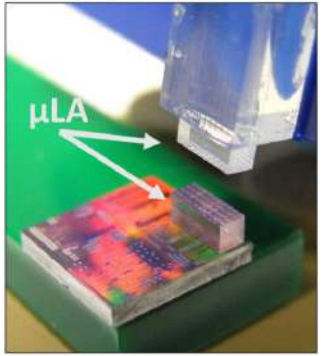
Source: Resolute Photonics



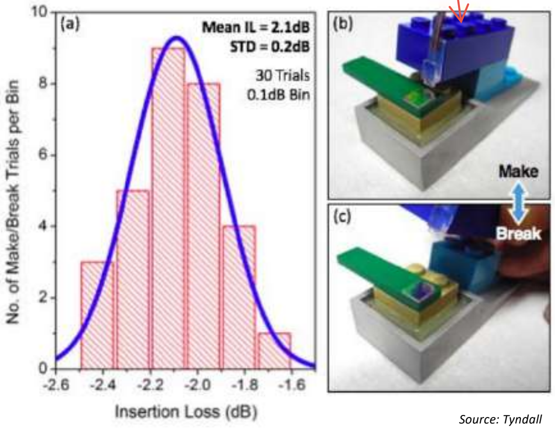
- Most fundamental of grating/vertical coupling
- Fibre is fixed above the grating on the PIC
- Requires high precision alignment to achieve best coupling efficiency
- Overall height of the coupling fixture is high (requires vertical space)

Variation of Grating Coupling techniques

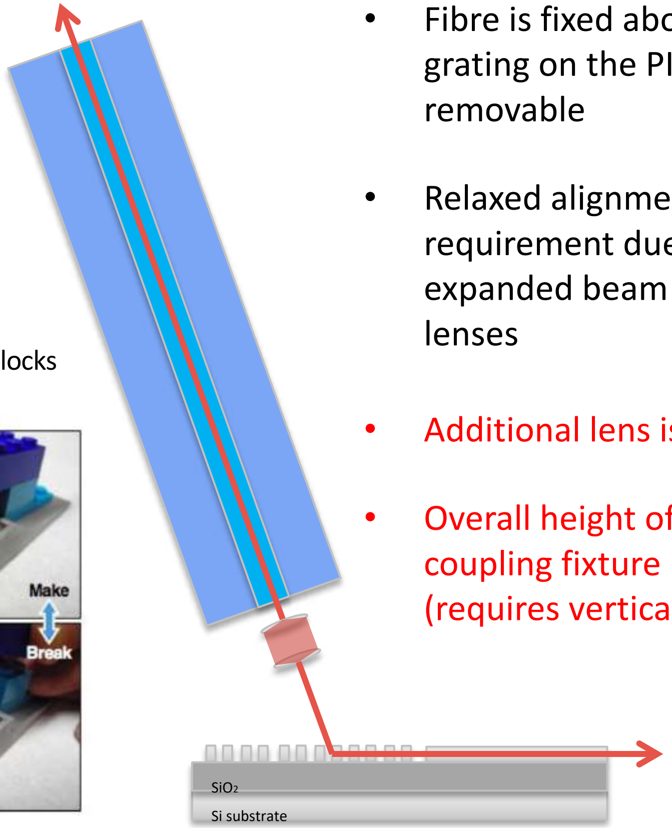




LEGO® Blocks

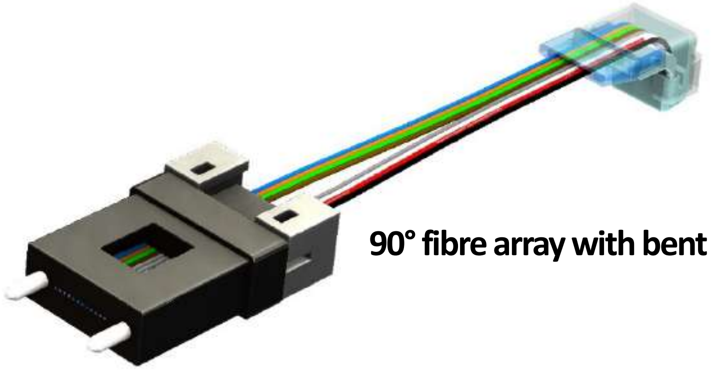


Source: Tyndall

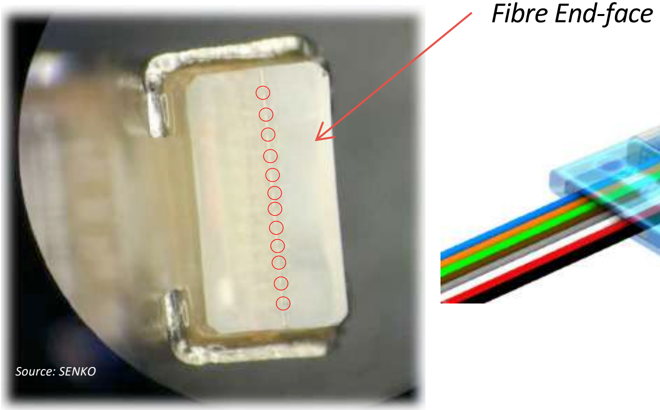


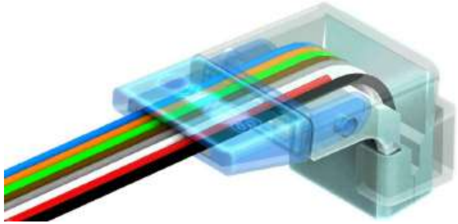
- Fibre is fixed above the grating on the PIC but removable
- Relaxed alignment requirement due to expanded beam micro lenses
- Additional lens is required
- Overall height of the coupling fixture is high (requires vertical space)

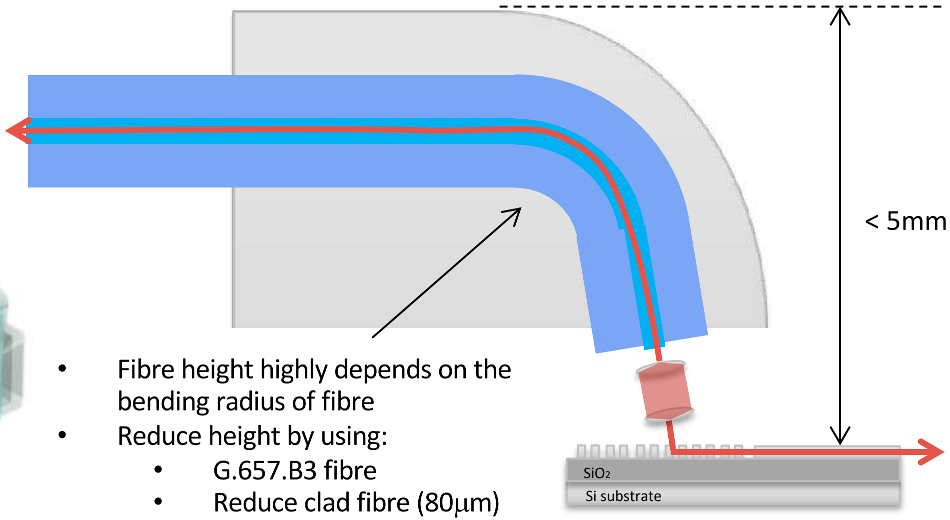
90º Bent Fibre Array



- Fibre is fixed above the grating on the PIC
- Height is significantly reduced to < 5mm
- Lenses can be added to increase alignment tolerance

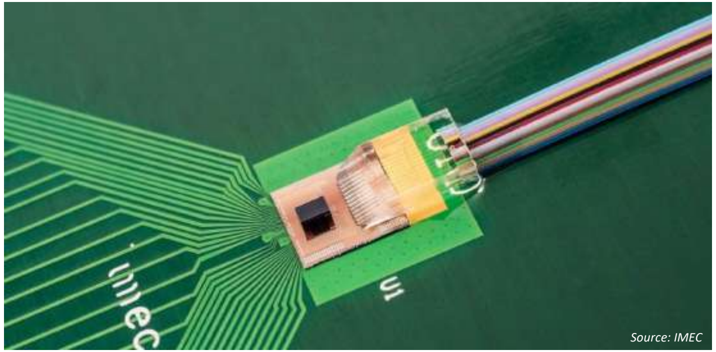




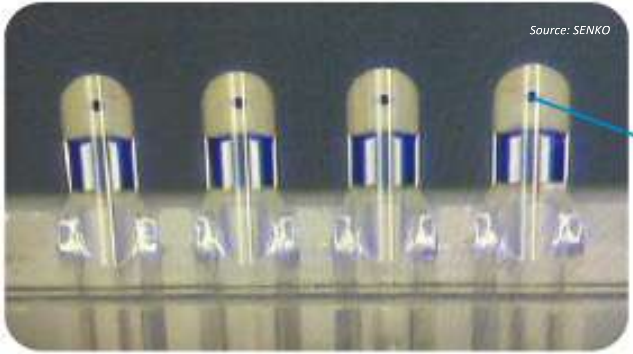


- Fibre height highly depends on the bending radius of fibre
- Reduce height by using:
  - G.657.B3 fibre
  - Reduce clad fibre (80µm) or etched clad fibre

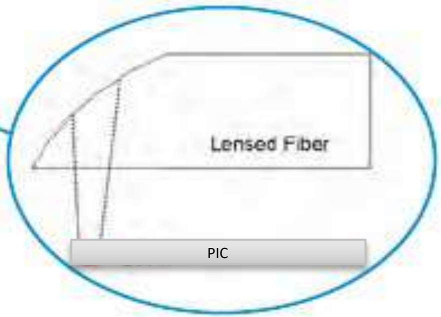
45º Curve Polished/Cleaved Fibre Array



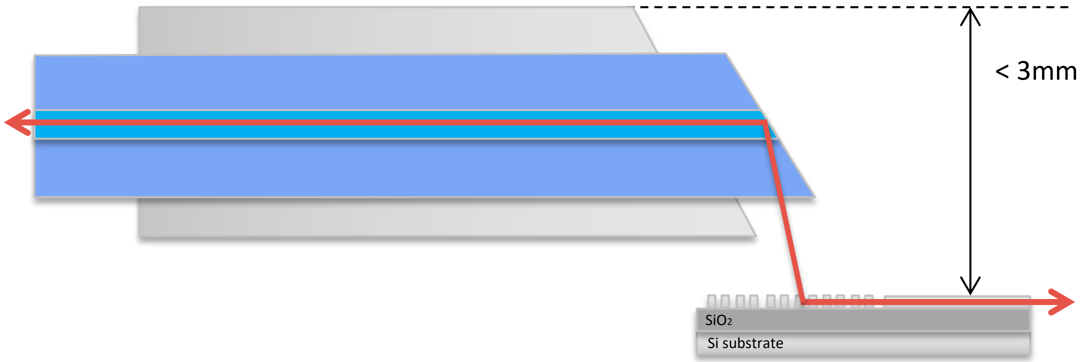
Source: IMEC



Source: SENKO

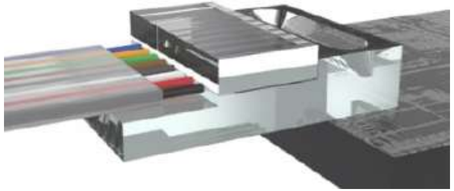


- Fibre is fixed parallel to the PIC which allows the total height to be significantly reduced to <3mm
- Signal is reflected using the polished end-face of the fibre
- A lensed polishing can be performed on fibre end face for better coupling efficiency

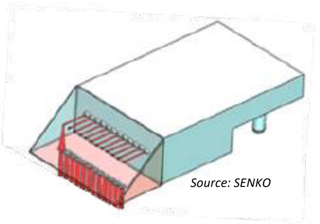


45º Reflective Fibre Array

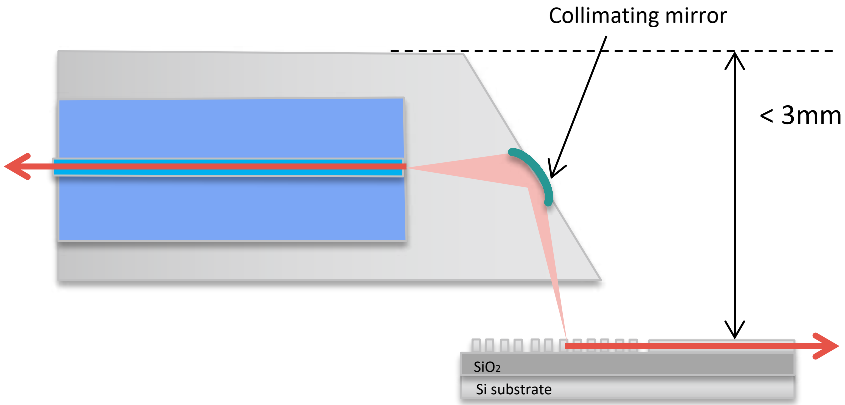
Source: Cudoform

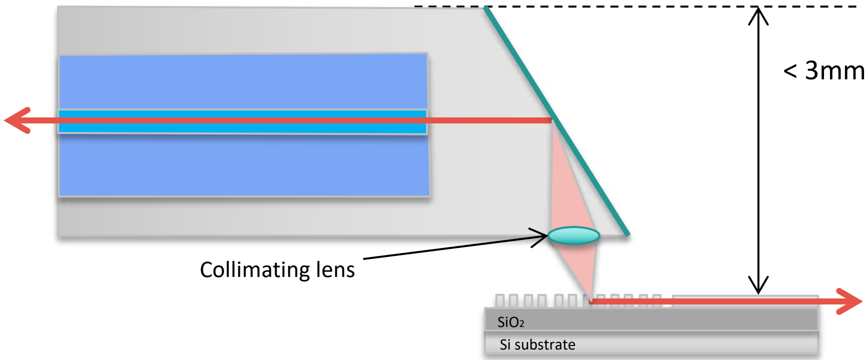


Source: Optoscribe



- Reflective plane at the end of fixture reflects the optical signal between the optical fibre and the PIC
- This approach eases the manufacturing process and potentially allows the coupling fixture to be pluggable
- Lensed structure is also incorporated to increase coupling efficiency

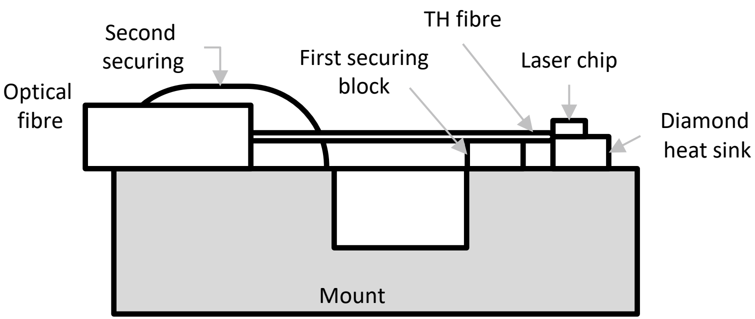


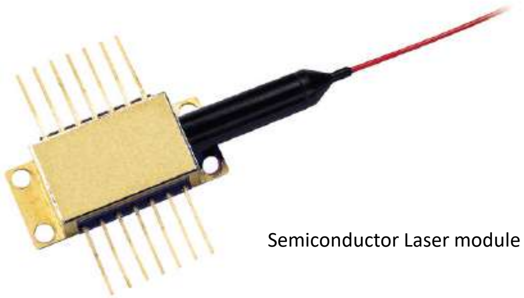


End-Fire/Edge Coupling

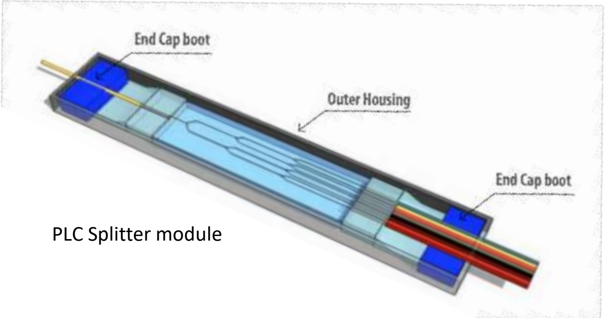
END-FIRE/EDGE COUPLING

End-Fire (also known as Edge Coupling) coupling directly connects two different waveguides and transfer optical signals. This method to couple optical fibre and the integrated waveguide for the PIC is a well-established approach for low-port-count photonic chip packaging (e.g., discrete laser & PLC modules).





Semiconductor Laser module

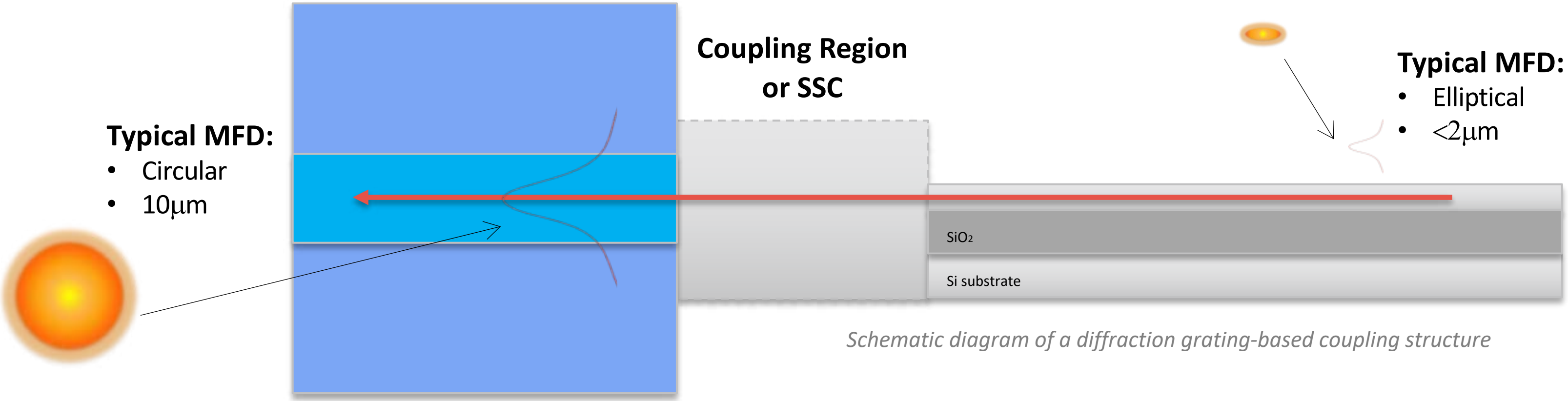


PLC Splitter module

END-FIRE COUPLING – PRINCIPLE OF OPERATION

End-Fire Coupling is advantageous over the grating coupling as it provides a **wide operating wavelength range,** and it is also **polarization-insensitive optical coupling properties**

Nevertheless, it typically requires **precise alignment tolerances**. It is possible to use lenses and other discreet optical components between the fibre and the PIC chip as a Spot Size Converter (SSC) in order to improve optical coupling efficiency.



Schematic diagram of a diffraction grating-based coupling structure

END-FIRE COUPLING – PRINCIPLE OF OPERATION

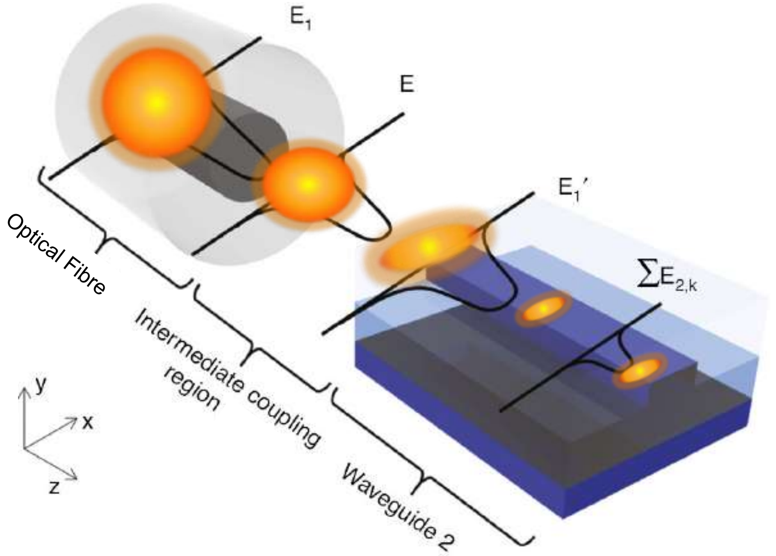
The guided mode of the input waveguide is first radiated through the intermediate coupling region (of a spot size converter) and arrives at the front facet of the second waveguide.

The advantages of end-fire couplers are:

- Polarization independent
- Large operating wavelength range

Disadvantages of End-Fire Coupling are:

- Post processing such as dicing or polishing is required even to testing.
- The coupler structures need to be located at the chip edges and the space on the PIC required to perform the coupling

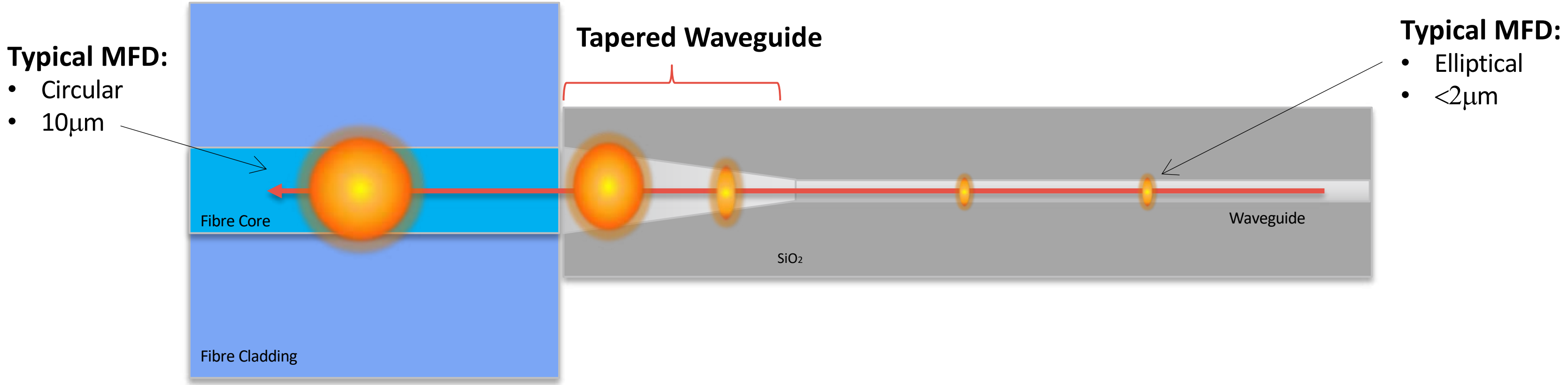


Adapted from : Nanophotonics

END-FIRE COUPLING – TAPERED WAVEGUIDES

Lateral, vertical, and three-dimensional waveguide taper designs have been introduced to enlarge the effective MFD of the integrated waveguides with high-index core materials. This method gradually increases the width and/or height of the integrated waveguide to provide a large terminating facet area up to 100µm^2.

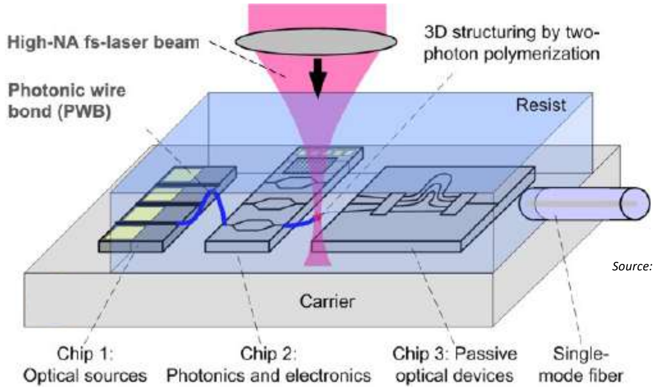
3D tapered SSC is an efficient optical fibre and PIC waveguide coupler where the final waveguide width can be made close to the standard single-mode fibre MFD. Dedicated fabrication steps, such as polishing, thick material deposition, and etching are required. It may also occupy more space when compared to other coupling schemes.



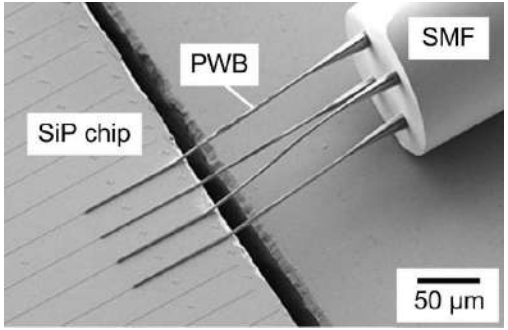
END-FIRE COUPLING – PHOTONIC WIRE BONDING

- The concept of photonic wire bonding, which can be considered as the optical analogue to metal wire bonding in electronics. **Photonic wire bonds (PWB) are single-mode freeform waveguides** that efficiently connect integrated optical chips to each other or to optical fibres.

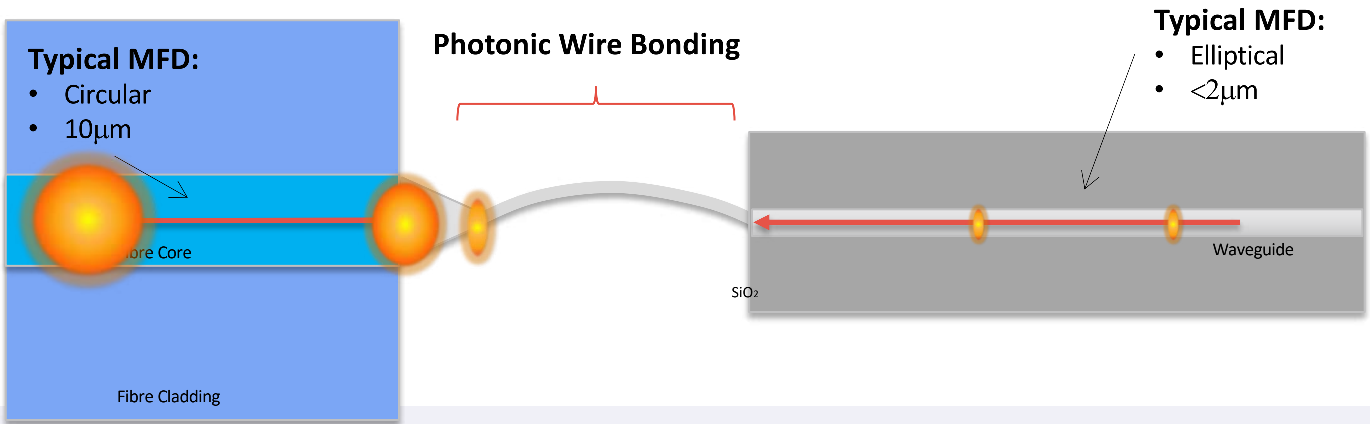
- An additional advantage of PWB is that it is not limited to PIC to fibre but also PIC-to-PIC coupling



Source: Vanguard



Source: Karlsruhe Institute of Technology

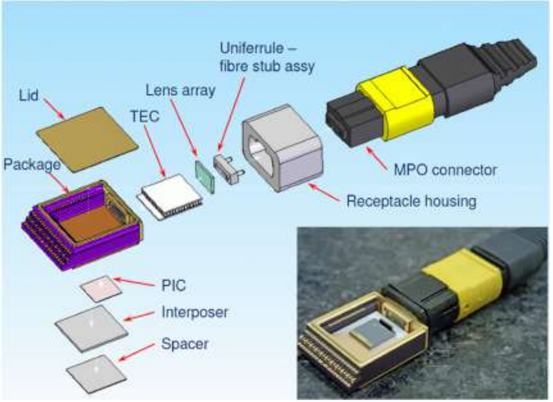


END-FIRE COUPLING – MICRO LENS

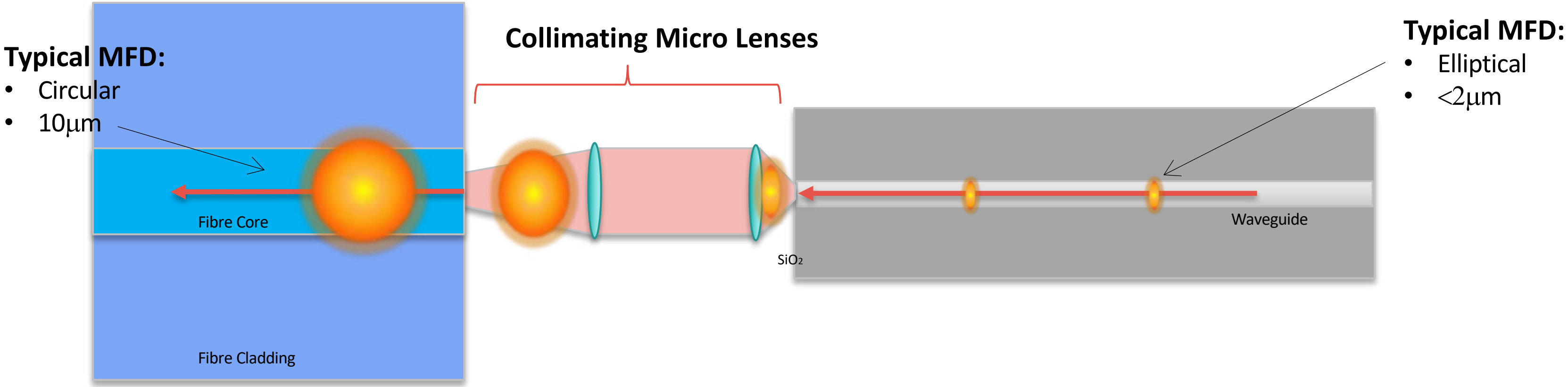
- A typical **geometric microlens** may be a single element with one plane surface and one spherical convex surface to refract the light.

- A different type of microlens has two flat and parallel surfaces and the focusing action is obtained by a variation of refractive index across the lens. These are known as **gradient-index (GRIN) lenses**.

Source: Findlight

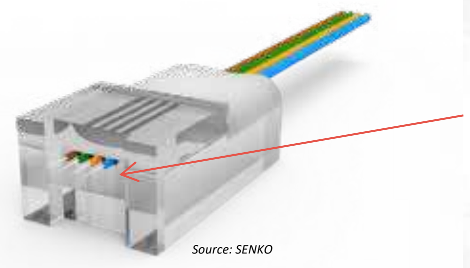


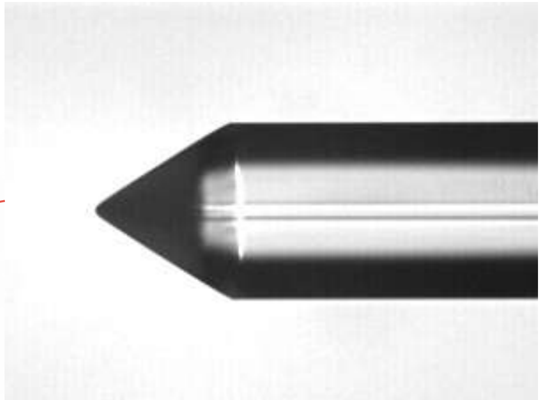
Source: FP7 PARADIGM

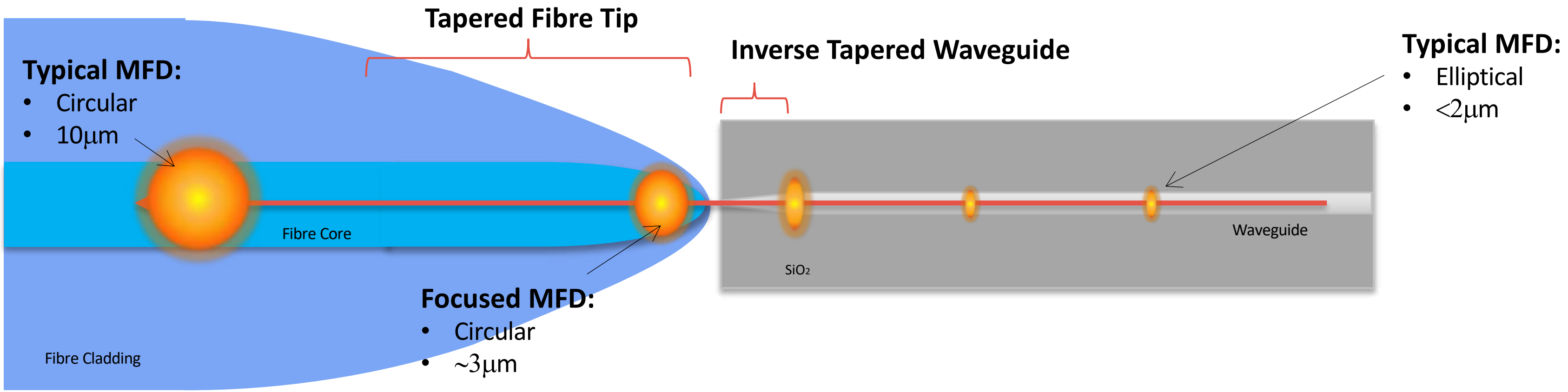


END-FIRE COUPLING – LENSED FIBRE & INVERSE TAPER

- The lensed fibres are produced by glass pulling technology and IR laser shaping. It can be Single-mode (SM), Multimode (MM), and also Polarization maintaining (PM) lensed fibres.
- **Lensed fibre** are usually coupled with an inverse taper section of the waveguide where the width of the waveguide is gradually reduced along the direction of light propagation, down to a small value at the end tip.

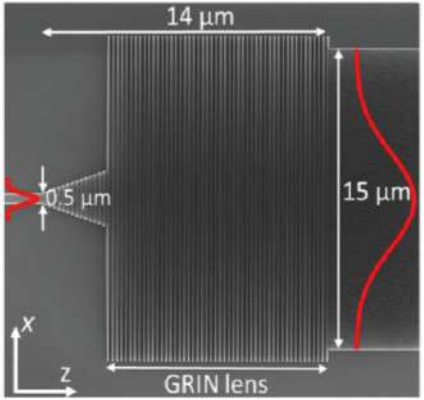




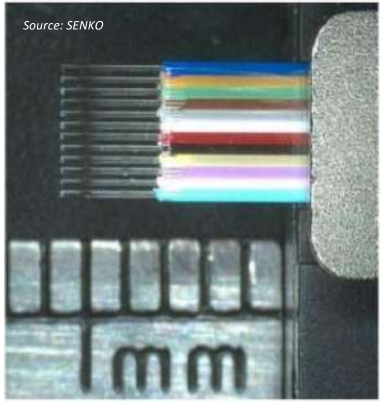


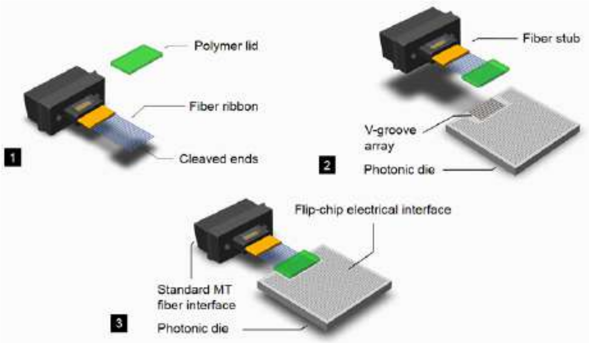
END-FIRE COUPLING – METAMATERIAL

Metamaterial or subwavelength grating based PIC coupling consists of a Si waveguide in which fully etched trenches are periodically formed along the direction of light propagation. The **metamaterial region of the PIC will act as a spot size converter** matching the MFD of the single-mode fibre with the MFD of the PIC.

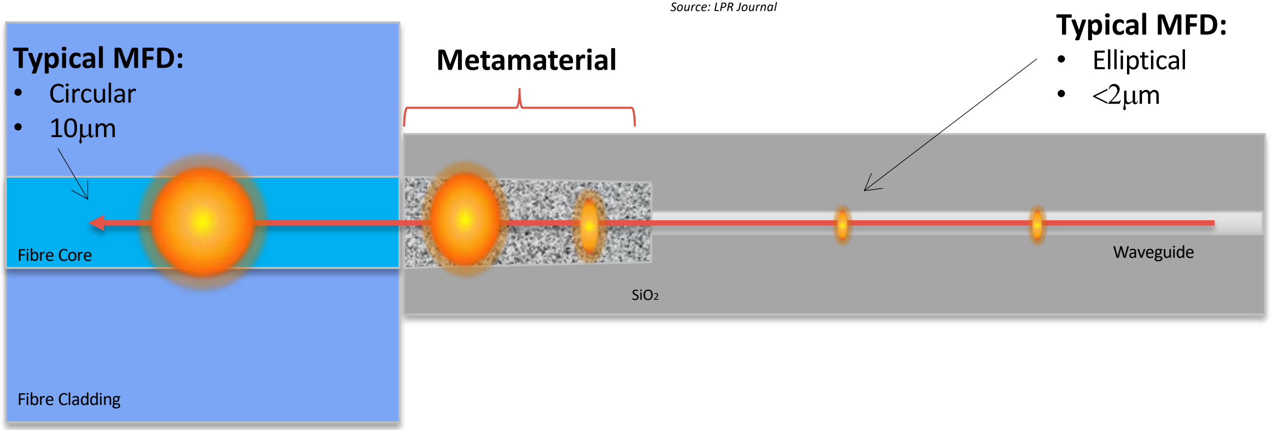


Source: LPR Journal





Source: IBM



Conclusion

Comparison of PIC Coupling Methods

Coupling Type	Advantages	Disadvantages
Grating Vertical Coupling	• Post processing such as dicing, or polishing is not required. This allows in-process wafer-scale optical characterization and testing • The coupler structures do not need to be located at the chip edges, which improves layout design flexibility and optical port scalability • Alleviated alignment tolerance makes measurement and packaging processes simpler.	• Narrow bandwidth window (30nm~40nm) – not suitable for CWDM applications • Polarization sensitive • If using PM fibre-to-chip transmission, assembly more complicated as requires high precision angular alignment, but mitigated if using PM fibre array as part of parallel array unit
Fire-end/ Edge Coupling	• Large bandwidth window (~100nm) – suitable for CWDM applications • Mature technology mainly used for semiconductor laser coupling • Polarisation insensitive	• Requires active coupling and high precision V-groove or U-groove for alignment • No on-wafer testing possible (only vertical grating couplers allow testing of interfaces before dicing) • More complex and costly PIC design including additional layer of typically silicon nitride for mode conversion from main silicon waveguide layer

Conclusion

- Currently there are various methods of PIC-to-Fibre coupling and all variations has its advantages and disadvantages

- Most of PIC-to-Fibre coupling modules are currently bespoke to suit the requirements for PIC manufacturers

- Co-packaged Optics is being driven by the large ICPs for hyperscale data centres and will require cross SDO collaboration to jointly develop international standards for PIC-to-Fibre coupling to accelerate adoption of PICs and Q-PICs

Thank you…

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