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Quantum Fiber Optic Interconnect for Quantum Networks

SCV EPS Chapter meeting

(11 November 2021)

Quantum Fiber Optic Interconnect for Quantum Networks

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Presentation Topics

- Quantum Key Distribution (QKD)
- Key Challenges of QKD deployment
- Ultra Low-Loss Optical Interconnect requirements for QKD
  - Fiber-to-Fiber
  - Fiber-to-QPIC
- Summary

Introduction to Quantum Key Distribution (QKD)

Recent Netowrk Trends driving Data Growth

2005

From mid 2000s to early 2010's the focus of the industry has been FTTH with various high profile national projects such as the HSBB in Malaysia, NG-NBN in Singapore, NBN in Australia & also the UFB in NZ

2010

Beginning from mid 2010s to 2020, Hyperscale DCs for Cloud services has dominated the growth of the industry with mass adoption of optics in place of conventional copper for DC Interconnect

2015

It is forecasted that the next phase of growth will be from mass deep fibre deployment to cater for the connectivity that will provide the connectivity to 5G cell sites (both outdoor and in-building)

2020

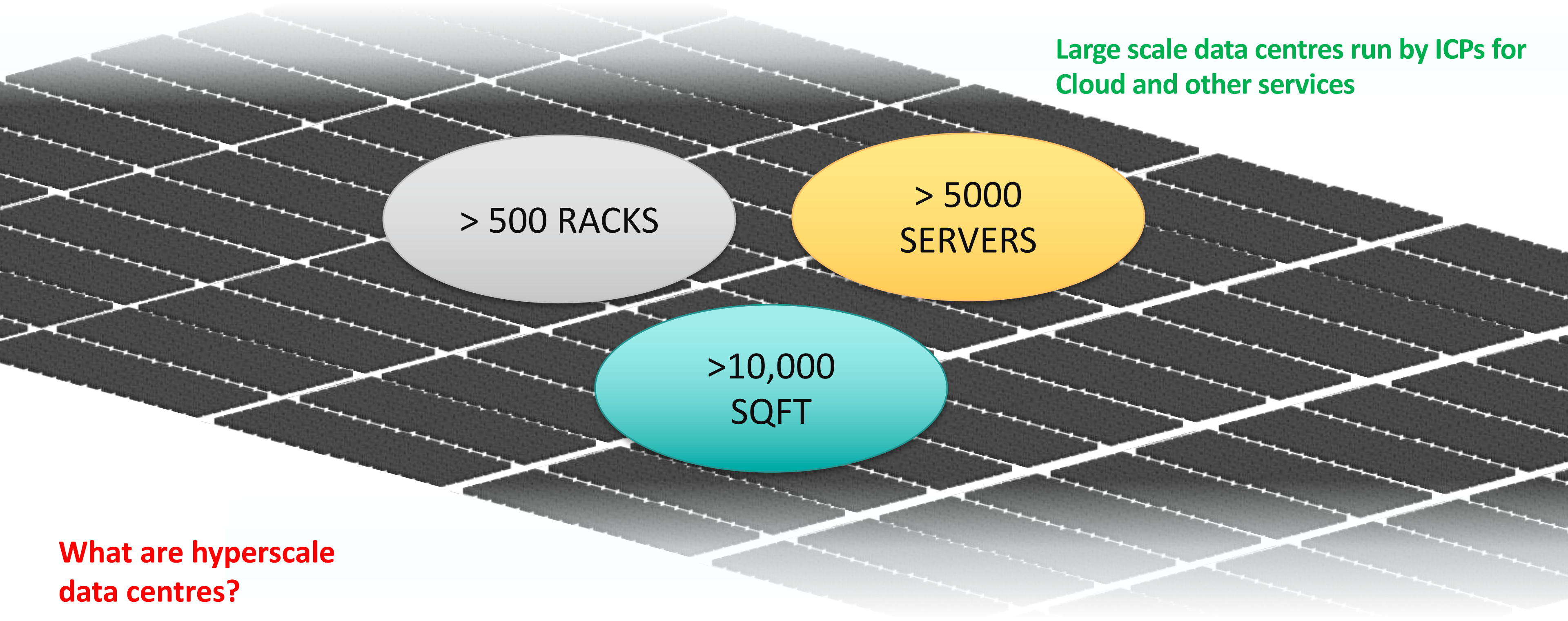
The adoption of AI in various industries has seen massive data transfer for analytics and machine learning. Networks are required to collect, route, and process this vast amount of data at real-time speeds.

Source: Team Analysist

The Rise of Cloud/Hyperscale Data Centres

What is a Hyperscale Data Centre?

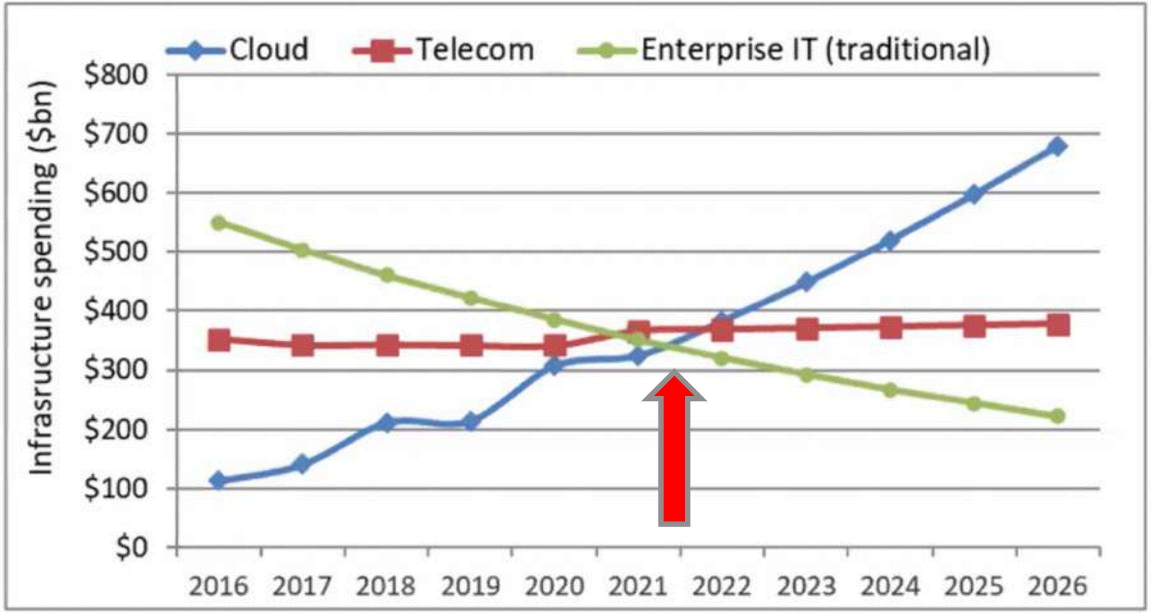
Large scale data centres run by ICPs for Cloud and other services



What are hyperscale data centres?

Projected growth of infrastructure spending by segment

5



Cloud nearly matches telecom spend in 2020, as we forecasted seven years ago.

2020 spending rise (+6% vs. 2019):

- Led primarily by Cloud (+43%)
- In lieu of Telecom (flat) and Enterprise (-25%)
- Cloud had the highest CAGR from 2016-2020, (+29%) vs Telecom (-1%), and Enterprise (-9%)

Note: Spending includes company reported 'capital expenditures' or 'purchases of property, plant, and equipment'.
It includes data center equipment (servers, storage, transport, etc.) as well as real estate, office building construction, and other items.

LIGHTCOUNTING

Highlights from Mega Datacenter Optics Report I July 2021

Source: *LightCounting*

Next Evolution of the Cloud

Quantum Computers

High performance computers increasingly complemented with **Quantum Computer** pods

Advanced computing

Artificial Intelligence
Neural networks (neuromorphic)
World-scale simulation

Future hyperscale data centres and exascale computers may increasingly incorporate quantum computer and communication nodes to complement their capabilities including for example the provision of "**Quantum As A Service**".

These quantum nodes will be interconnected by special quantum networks

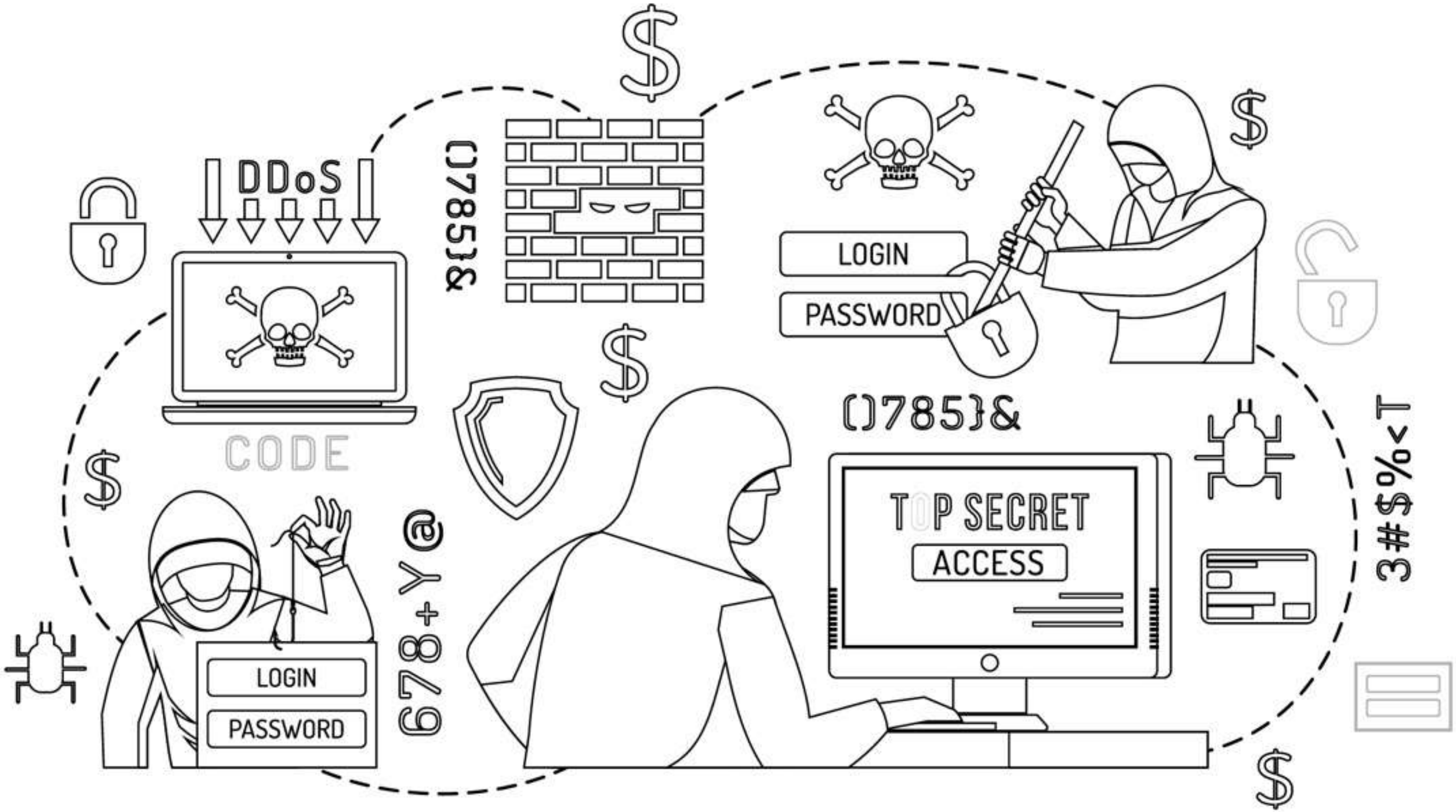
Quantum Communication

Quantum Key Distribution uses the principles of quantum superposition and entanglement to determine if data has been transferred securely

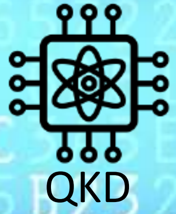
Security

Unhackable databases and smart contracting using **Blockchain** servers. Required for Medical, Financial, Cryptocurrencies

The need for a Secure Communications Networks



What is Quantum Cryptography?



Quantum cryptography : any attempt to intercept quantum particles along a quantum communication channel will irreversibly change the state of the quantum particles and will be detectable by the parties exchanging information.

How does QKD work?

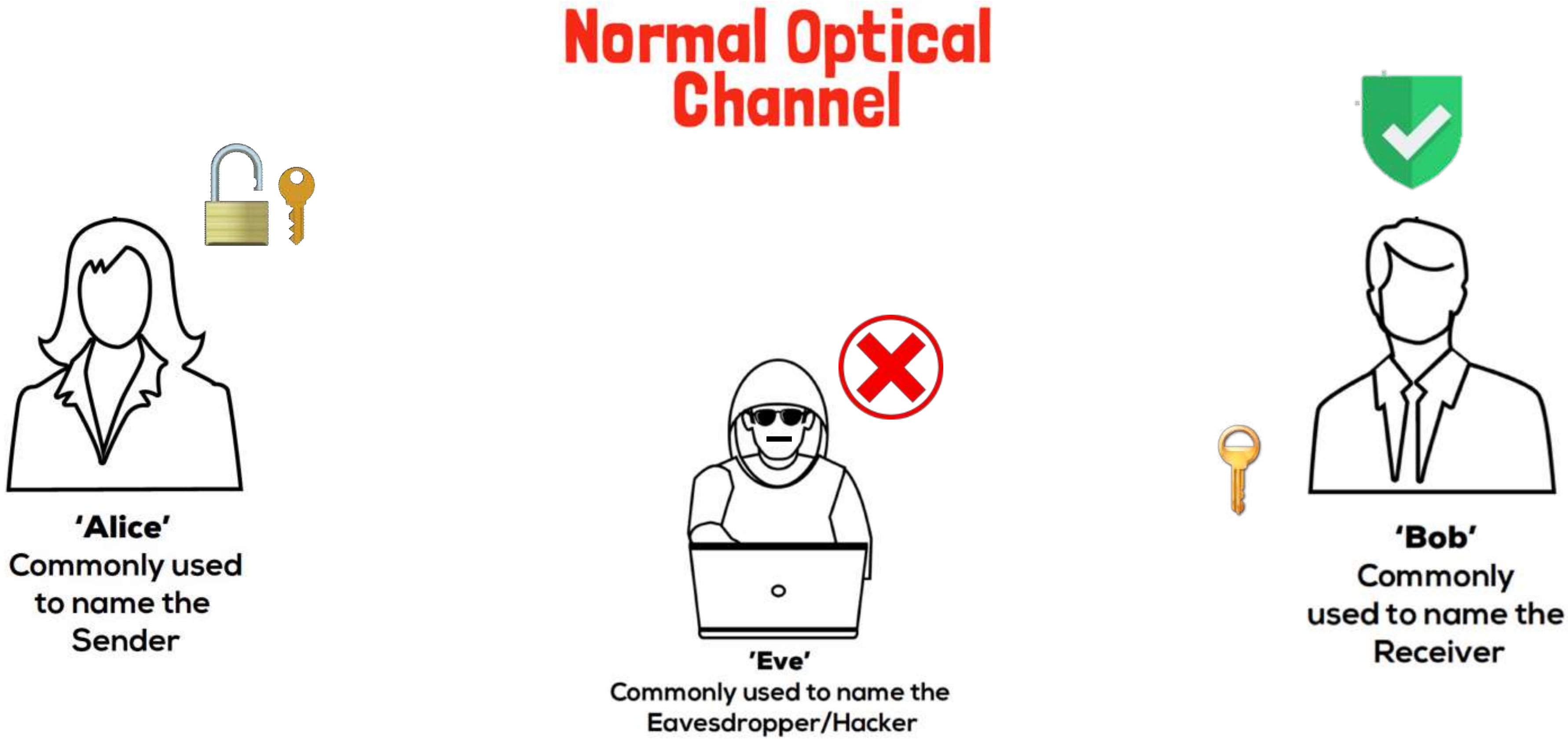
Normal Optical Channel

'Alice'
Commonly used to name the Sender

'Eve'
Commonly used to name the Eavesdropper/Hacker

'Bob'
Commonly used to name the Receiver

How does QKD work?

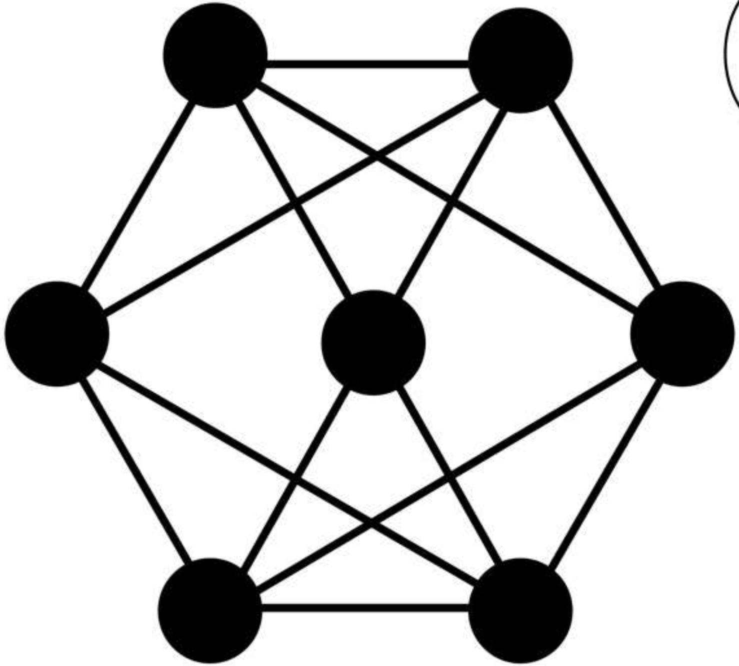


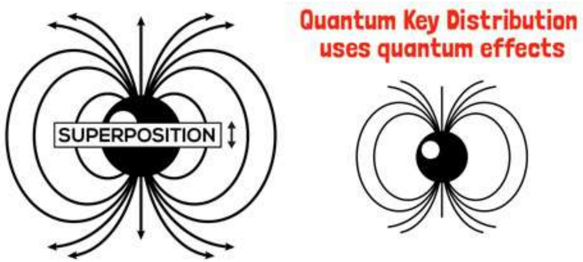
How does QKD work?

Normal Optical Channel

How does QKD work?

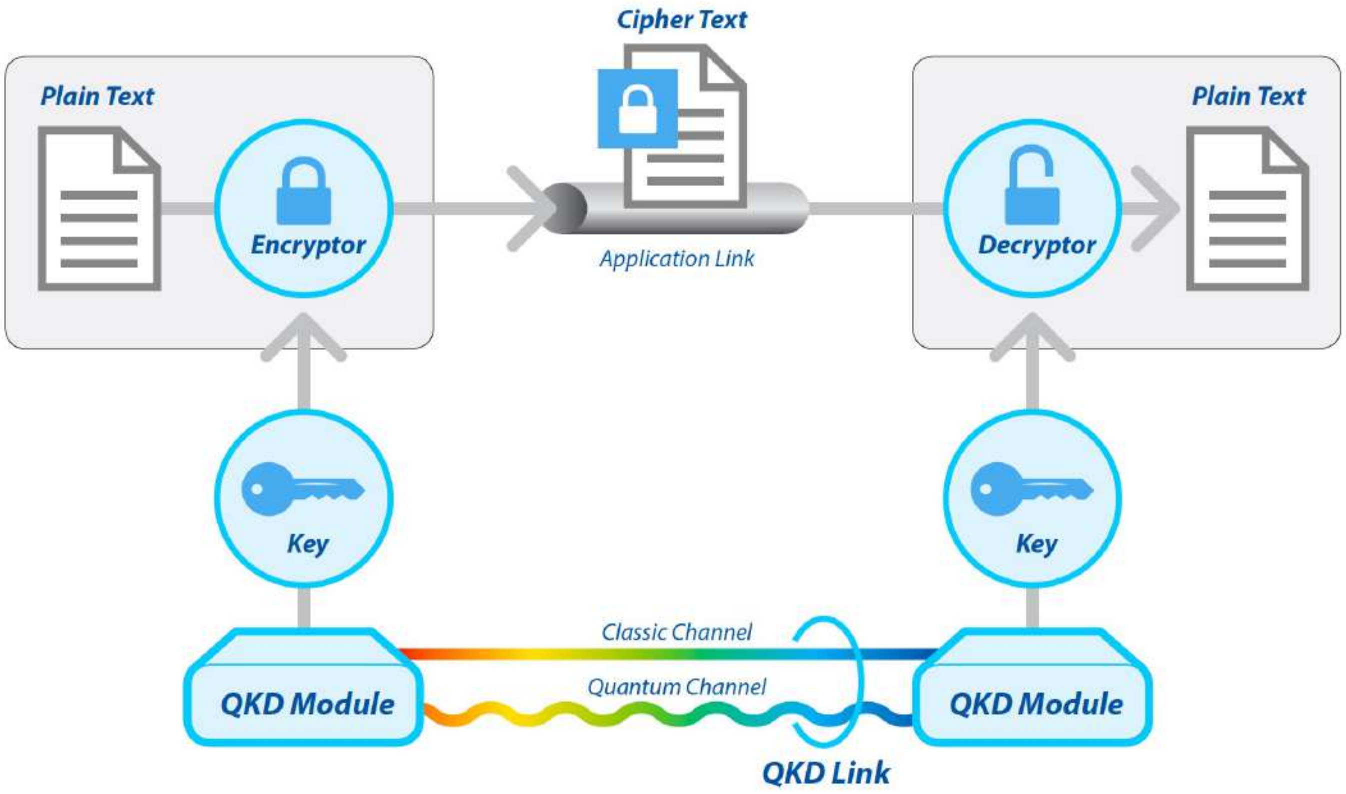
Quantum Key Distribution





- take advantage of quantum effects, such as superposition or entanglement
- a particle, such as a single photon, can be many things at once, until it is measured or observed for the first time

How does QKD work?



How does QKD work?

Quantum channel

'Alice'
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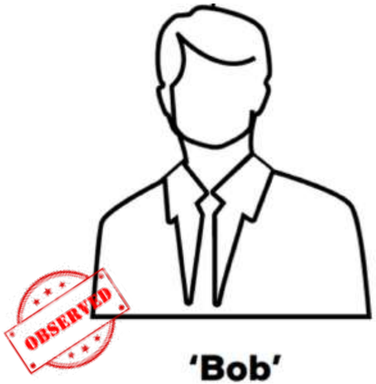
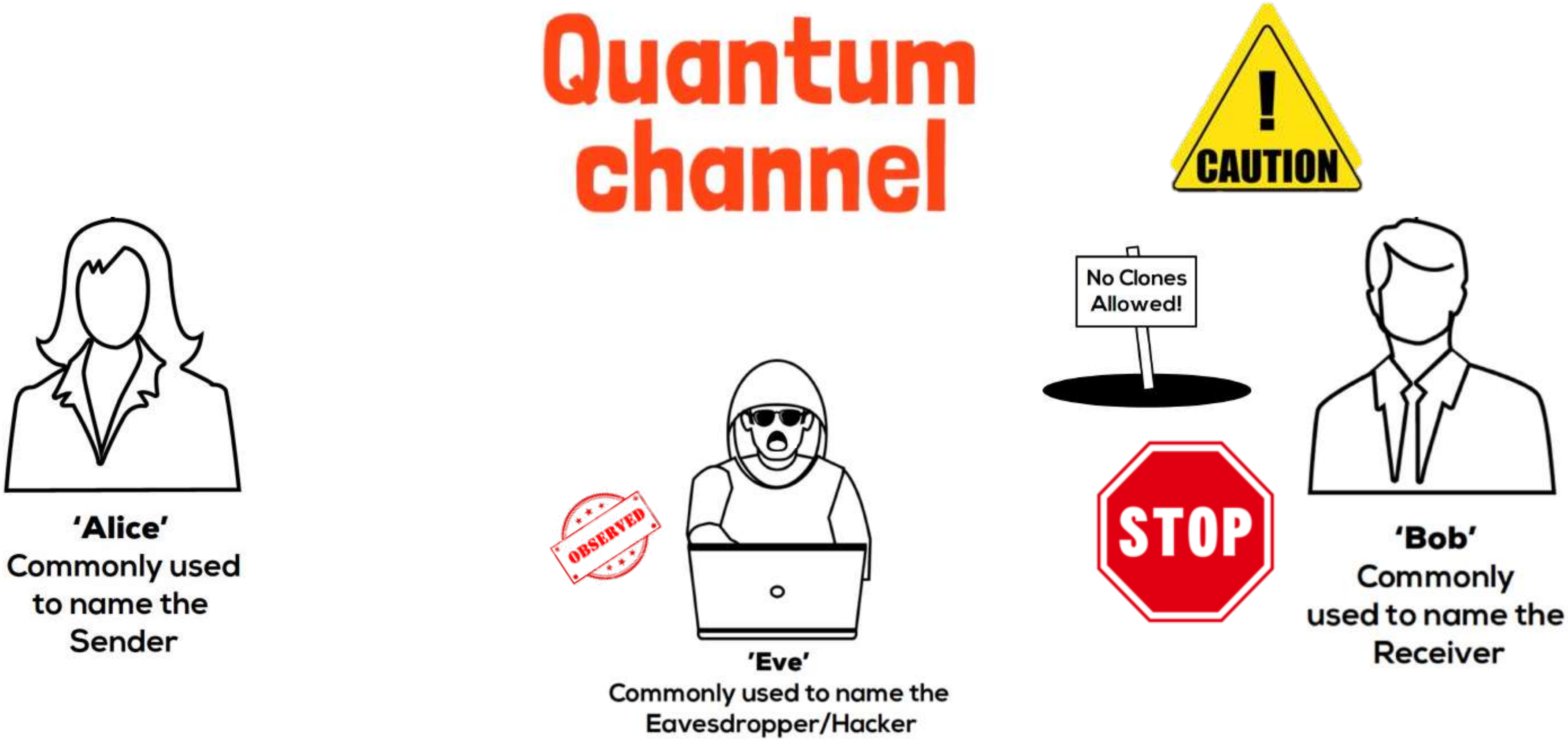
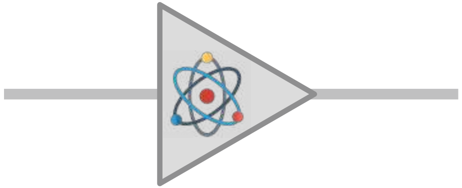


'Bob'
Commonly used to name the Receiver

How does QKD work?

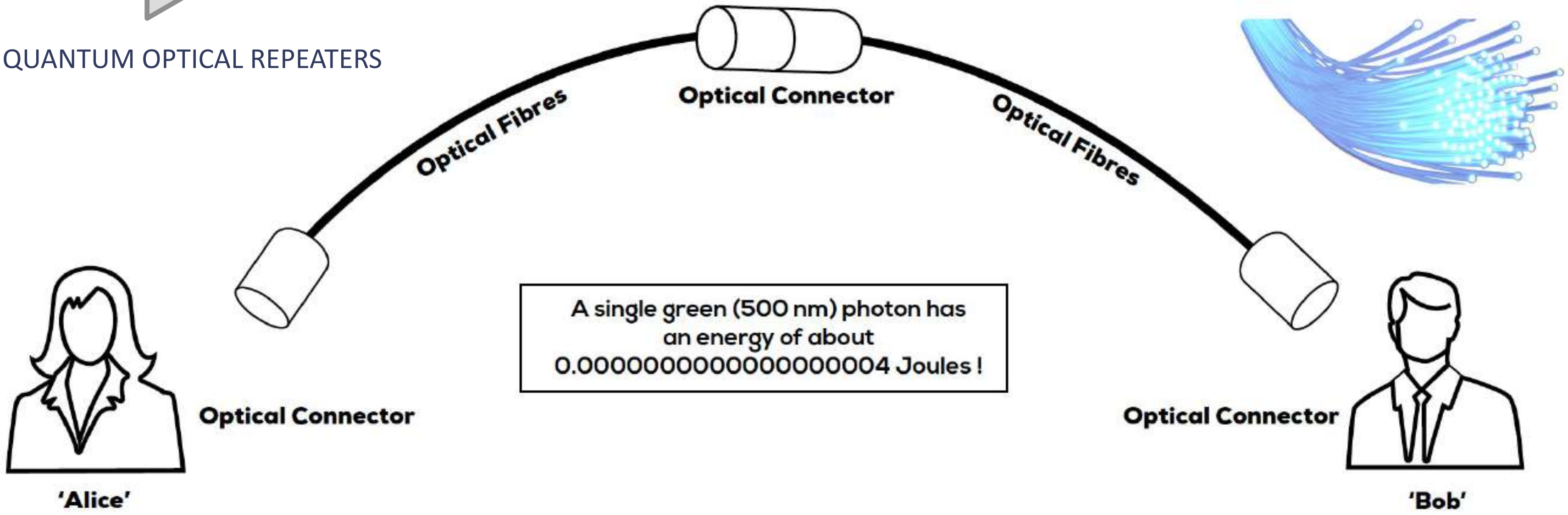


Inherent challenges of a QKD Link



QUANTUM OPTICAL REPEATERS

ULTRA LOW LOSS PASSIVE COMPONENTS



Overview on quantum standards activities

ISO/IEC JTC1

SC7 formed SG1 to investigate quantum standards
SC27 focusses on security and privacy in ICT systems

ITU -T

SG 17 – Quantum security
SG 13 – QKD
FG-QIT4N – Quantum information technology for networks

IEEE

P7130 Standards for QC Definitions
P1913 for Software Quantum Communications
P7131 for QC performance metrics & Performance Benchmarking

CEN / CENELEC

FGQT – Focus Group on Quantum Technologies

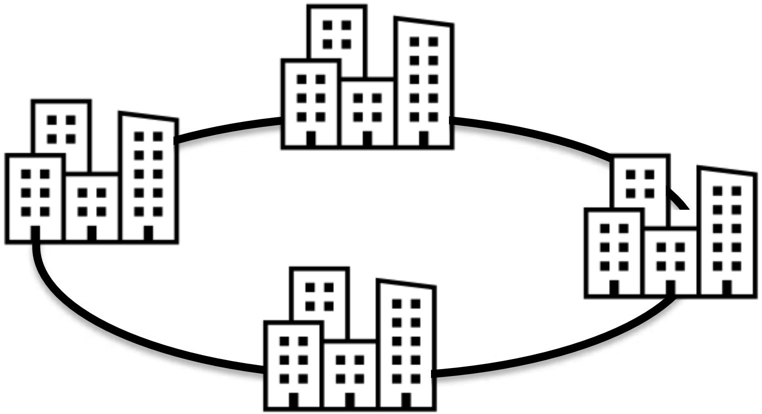
ETSI

ISG QKD – Quantum key distribution
TC Cyber WG QSC – Quantum Safe Cryptography

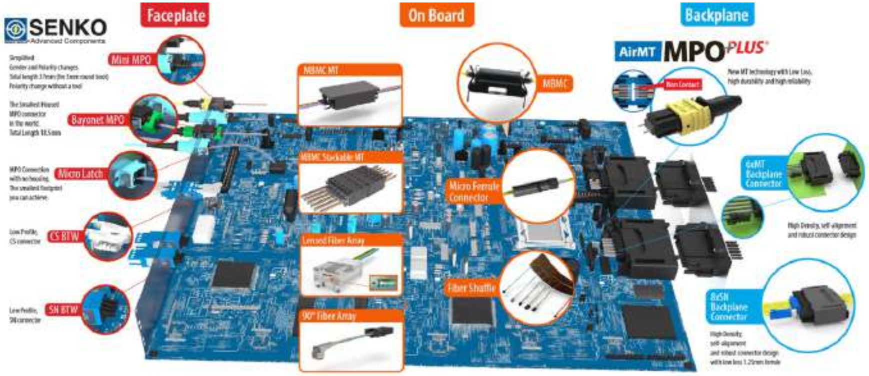
IEC SMB/SWG 10

WP on Quantum Information Technologies

Optical QKD Interconnections



Metro & Local Area Networks

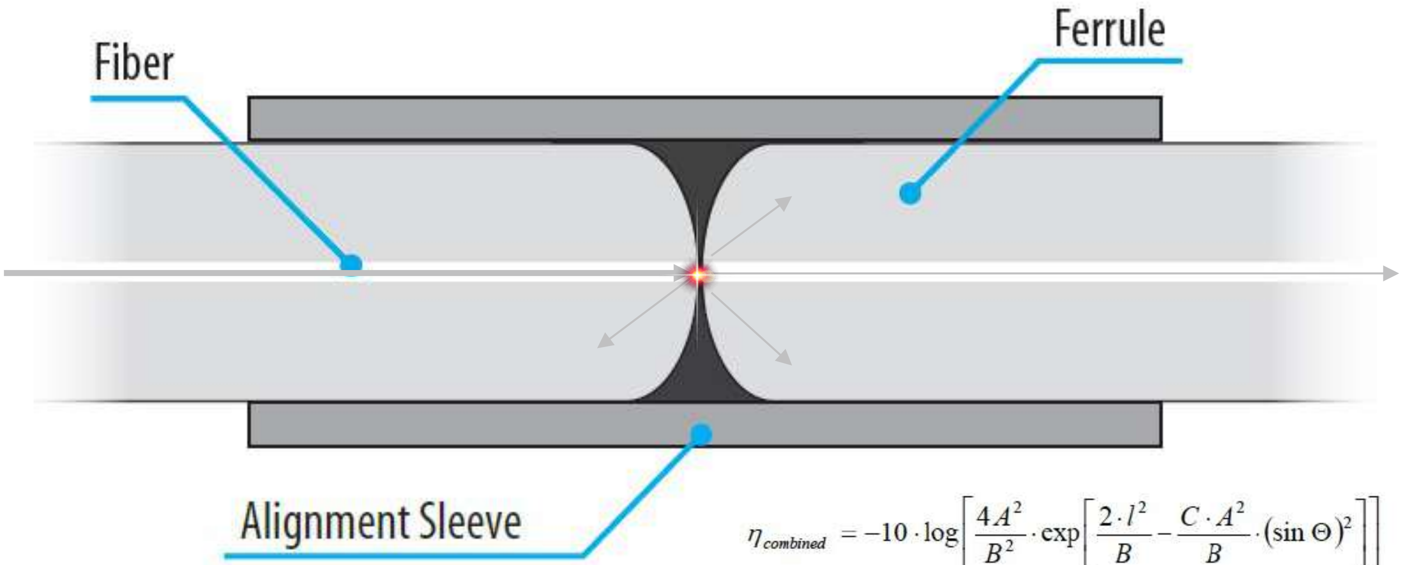


Photonics Integration

QuPC® Optical Connectors

Metro & Local Area Networks

What affects IL and RL in connectors?



$$\eta_{combined} = -10 \cdot \log\left[\frac{4A^2}{B^2} \cdot \exp\left[\frac{2 \cdot l^2}{B} - \frac{C \cdot A^2}{B} \cdot (\sin\Theta)^2\right]\right]$$

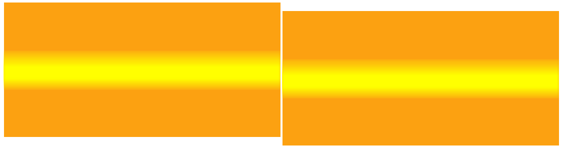
Where:

$$A = \omega_1 \cdot \omega_2 ; B = \omega_1^2 + \omega_2^2 ; C = 2\pi^2 \cdot \frac{n_0^2}{\lambda^2}$$

l =	lateral misalignment between fibre cores	n_0 =	refractive index of the fibre core
Θ =	pointing error between the fibres	ω_1 =	mode-field radius of transmitting fibre
Λ =	wavelength (in vacuum)	ω_2 =	mode-field radius of receiving fibre

Equation for Eccentricity vs IL (as stipulated in EN 50733-8-3 & IEC 61300-3-34 Standards)

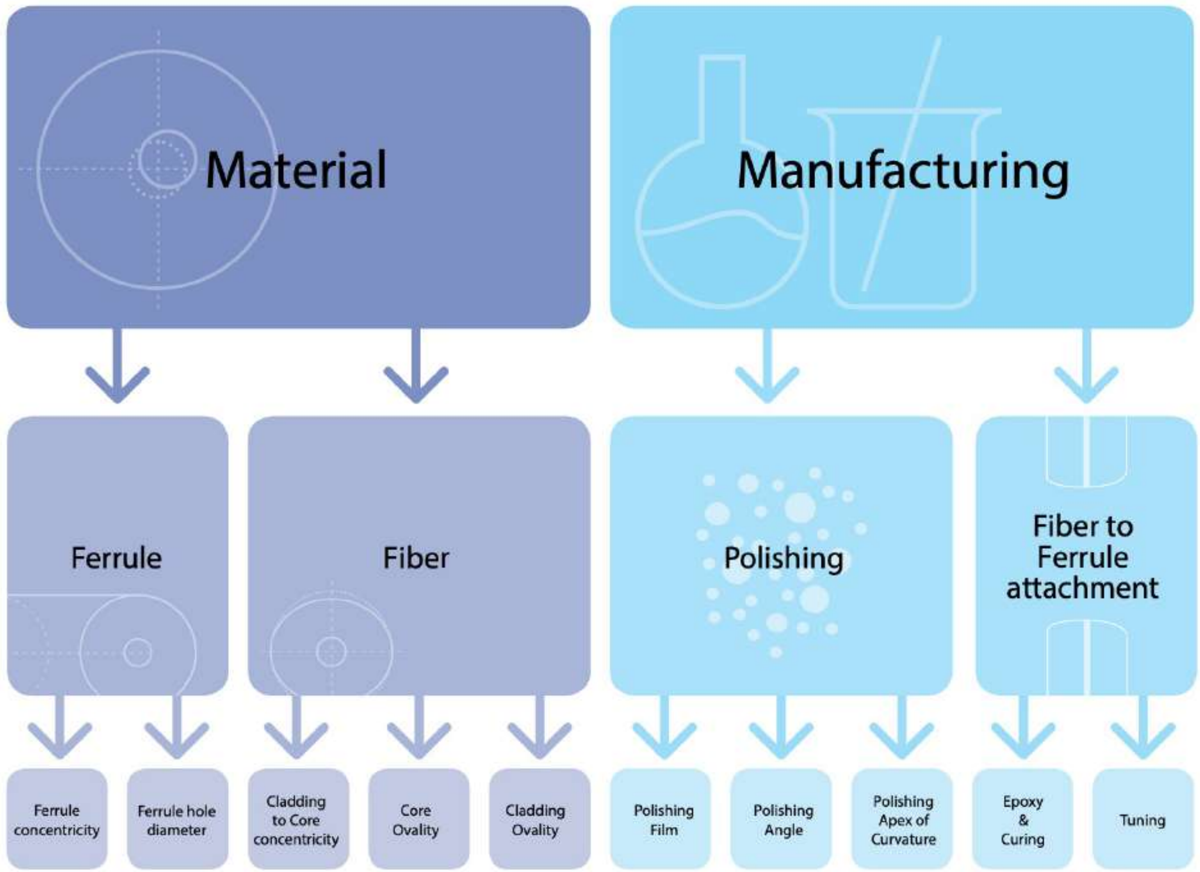
What affects IL and RL in connectors?



Lateral offset

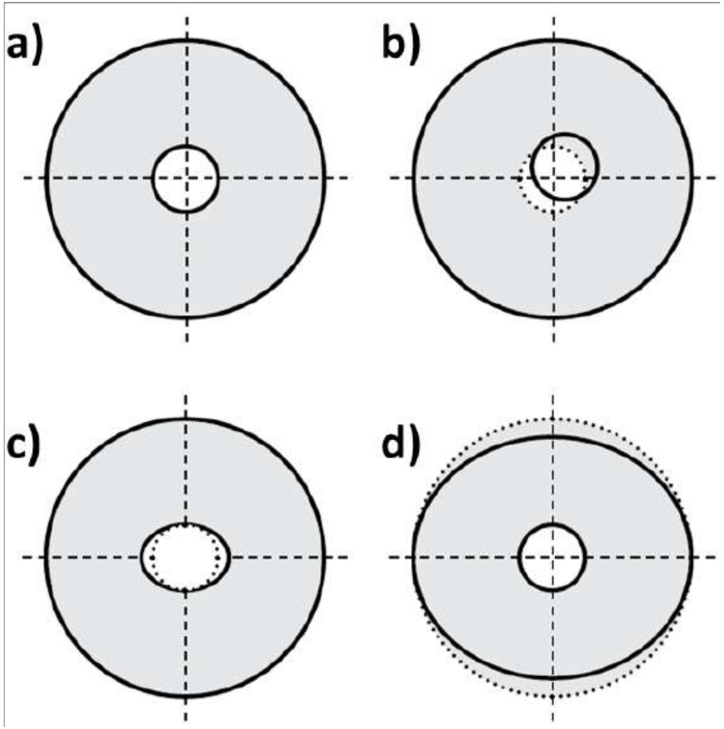
Angular misalignment

How to improve IL and RL in connectors?



How to improve IL and RL in connectors

a) Ideal fiber with perfectly circular core and cladding and the centres of core and cladding aligned,



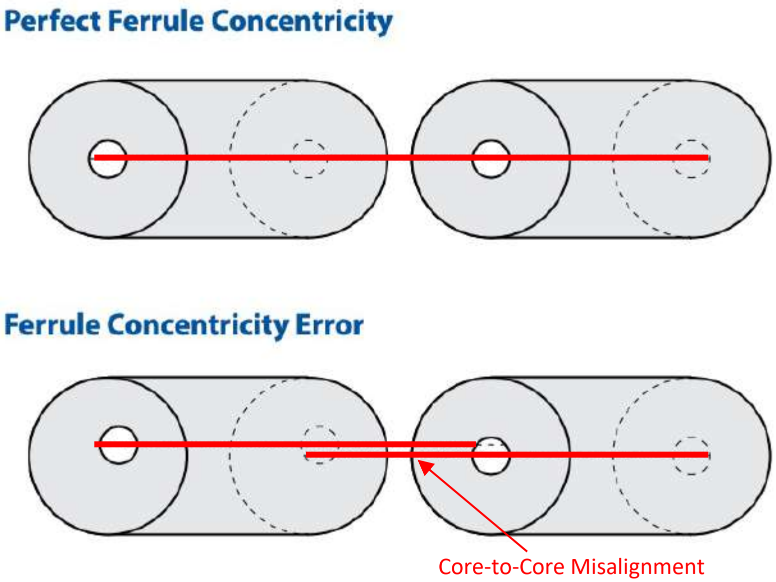
b) fiber with perfectly circular core and cladding, but where the geometric centre of the core is offset to the centre of the cladding

c) fiber where cladding is circular, but fiber exhibits slight ovality

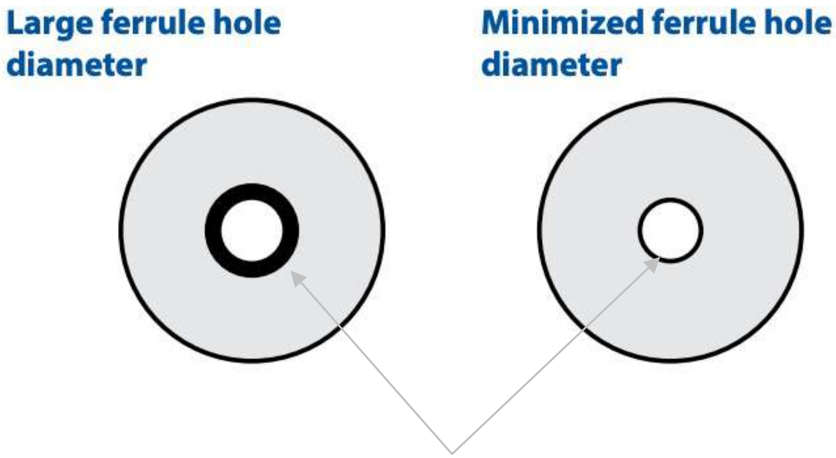
d) fiber where core is circular, but cladding exhibits slight ovality

Examples of Core and Cladding Concentricity and Ovality

How to improve IL and RL in connectors

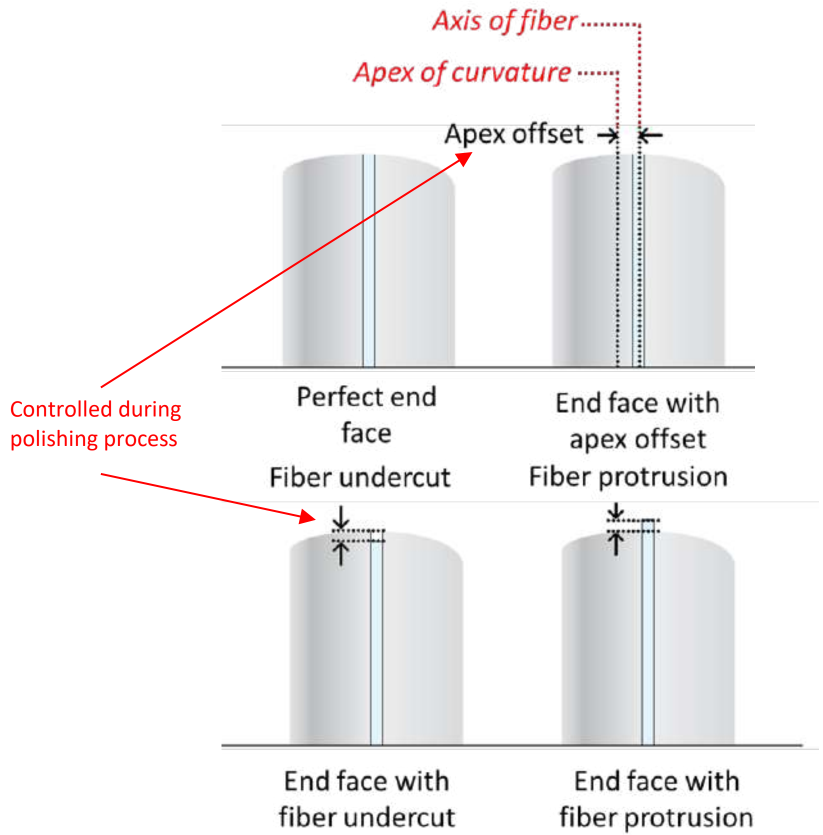


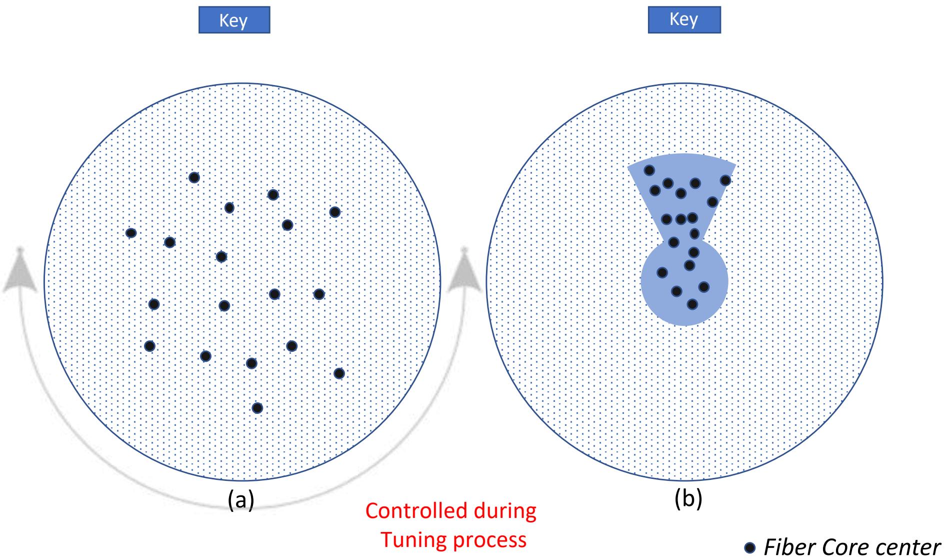
Ferrule Concentricity



Ferrule fiber hole diameter error

How to improve IL and RL in connectors





Fiber Core center location in (a) Untuned Connector and (b) Tuned Connector

What kind of Optical Connector will QKD needs?

- Based on existing international standards
- Target:
  - 'Optical connector' that performs like a fusion splice
  - Insertion Loss : <0.1dB
  - Optical Return Loss : >60dB

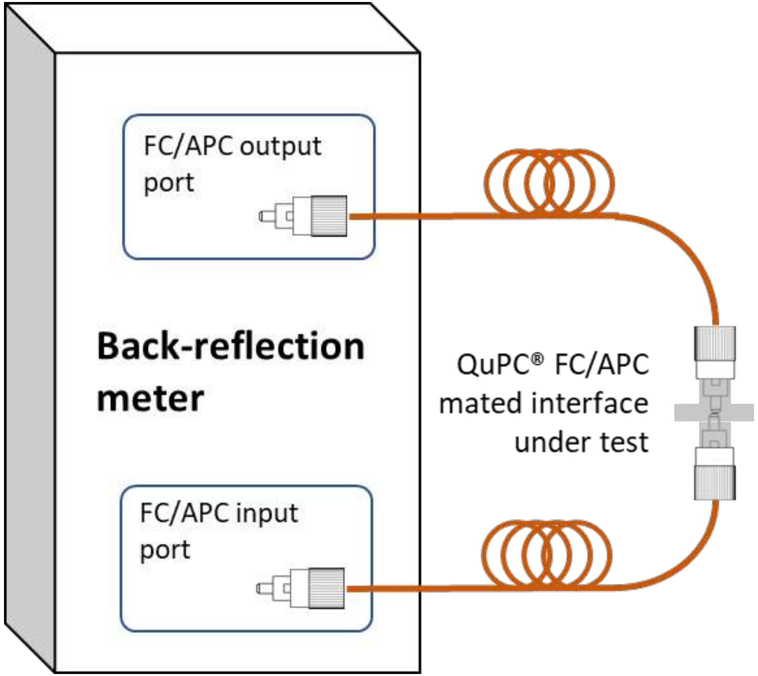
Same requirement as fusion splice

Table 1 – Recommended characteristics for single-mode fibre splices

Nº	Test	Method	Severity	Mechanical splice (single fibre) (Note 3)	Fusion splice with protector (single fibre) (Note 3)
6.1.1	Attenuation/ Insertion loss (IL)	IEC 61300-3-7	IL at 1310 nm, 1550 nm and 1625 nm	≤ 0.2 dB average ≤ 0.5 dB max in 97%	≤ 0.1 dB average ≤ 0.2 dB max in 97%
6.1.2	Return loss (RL)	IEC 61300-3-6 method 1 or 2	RL at 1310 nm, 1550 nm and 1625 nm	When straight cleaved: ≥ 35 dB (grade 3) ≥ 45 dB (grade 2) When angle cleaved: ≥ 60 dB (grade 1)	≥ 60 dB

** Table in L.400*

Experimental Results – Component Test

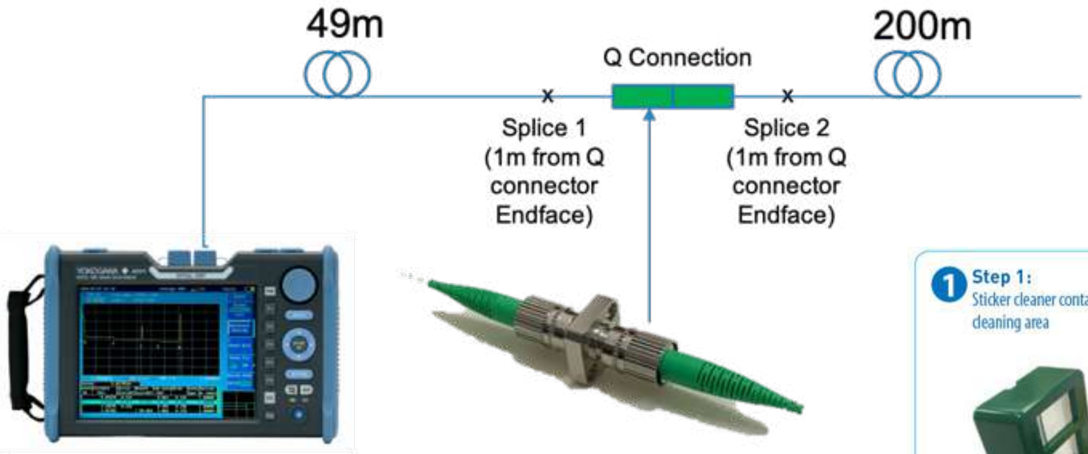


Experimental Setup: Component Testing

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

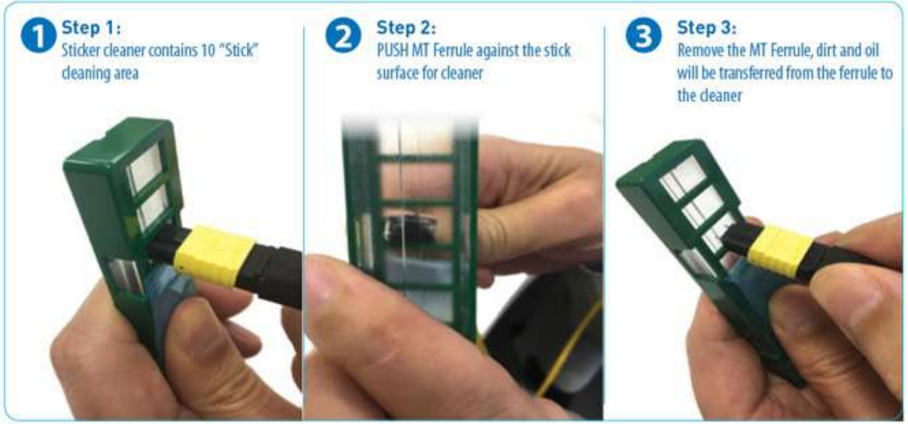
Experimental Results – Link Test



Tested with narrow pulse (3ns) width for IL detection to wide pulse width (200ns) to detect reflection

Connector A : IL 0.03dB
Connector B : IL 0.07dB

Experimental Setup: Link Test

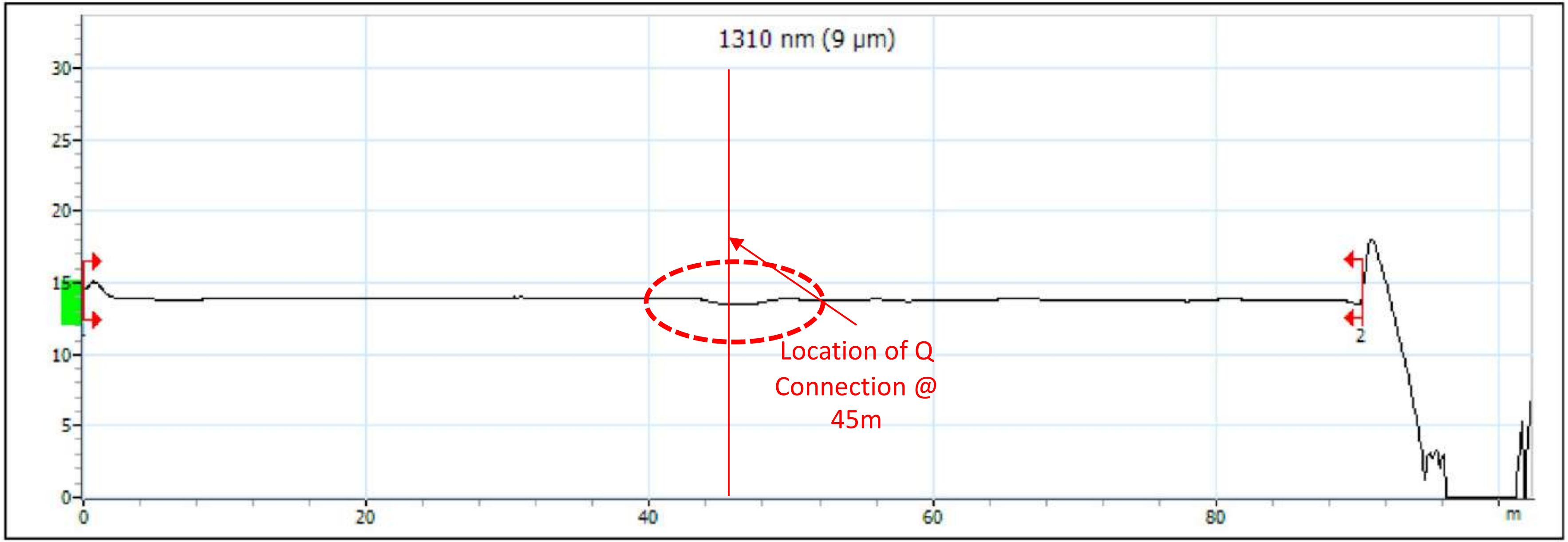


** Non-abrasive gel based cleaner was use to avoid creating micro-scratches on the connector end faces*

OTDR Trace 2019

OTDR Trace 2020

Graph



Type	No.	Pos./Length (m)	Loss (dB)	Reflectance (dB)	Attenuation (dB/km)	Cumulative (dB)
First Connector	1	0.0	---	-70.4		0.000
Section		90.4	0.174		1.928	0.174
Reflective	2	90.4	---	-61.2		0.174

Results : QuPC Connectors were not detected by OTDR

Pulse Width	λ	Splice 1		Q Connection		Splice 2	
(ns)	(nm)	IL (dB)	ORL (B)	IL (dB)	ORL (B)	IL (dB)	ORL (B)
3	1310	X	X	X	X	X	X
	1550	X	X	X	X	X	X
10	1310	x	X	X	X	0.13	X
	1550	X	X	X	X	X	X
20	1310	X	X	X	X	X	X
	1550	X	X	X	X	X	X
50	1310	x	X	X	X	0.32	X
	1550	X	X	X	X	X	X
100	1310	X	X	X	X	X	X
	1550	X	X	X	X	X	X
200	1310	X	X	X	X	X	X
	1550	X	X	X	X	X	X

X – connector not detected

The QuPC Connection is as ‘good’ as a ‘splice’ & exceed target

Reliability Assurance – GR-326-CORE

General Requirements

These General requirements cover documentation, packaging, design features, intermateability, product markings and safety

Service Life Testing

A sequence of environmental and mechanical tests that simulate possible conditions the connectors or connector assemblies may be under while in service

Extended Service Life Testing

Various tests intended to determine long term reliability of the connector or connector assemblies. Usually simulating 25 year lifetime.

Reliability Assurance Program

The program focuses on requirements for the manufacturing process that relate to long term reliability and performance of the finish product. Also includes additional testing to ensure the stability of the manufacturing process

GR 326
COMPLIANT

Service Lifetime Test @ approx 60 days

Environmental Testing

Thermal aging

Thermal cycle

Humidity aging

Dry-out step

Humidity/condensat
ion cycle

Post condensation
thermal cycle

Mechanical Testing

Vibration Test

Twist Test

Flex Test

Durability test

Impact test

Proof test

TWAL test

Extended Service Lifetime Test @ >2000 hrs

Environmental Tests

Extended Thermal aging

Extended Thermal cycle

Extended Humidity aging

Exposure Tests

Airborne contaminants

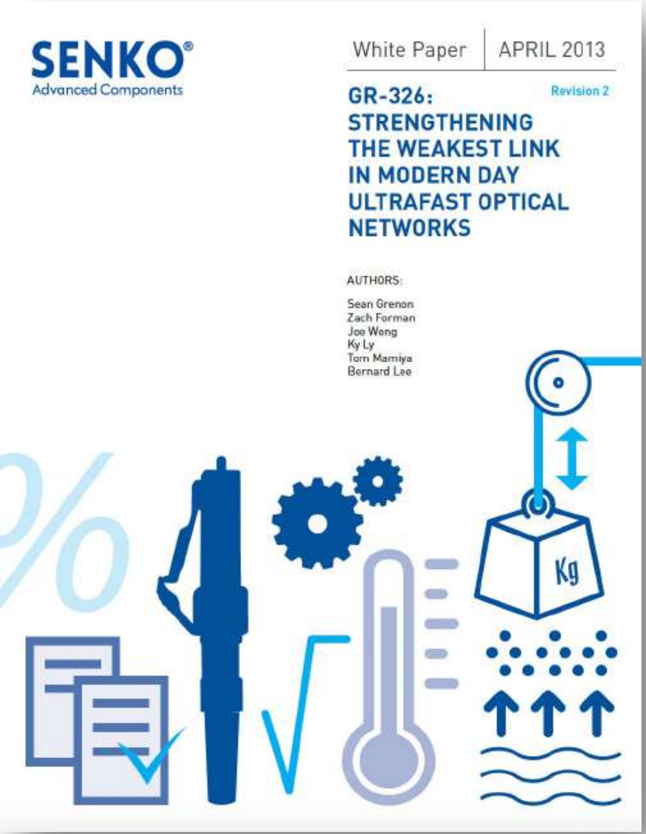
Salt spray

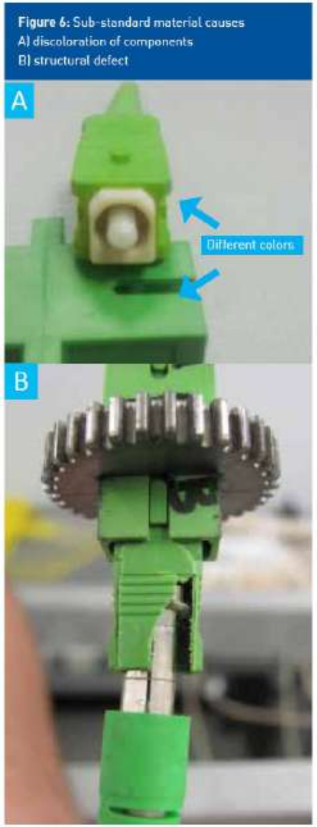
Corrosion Test

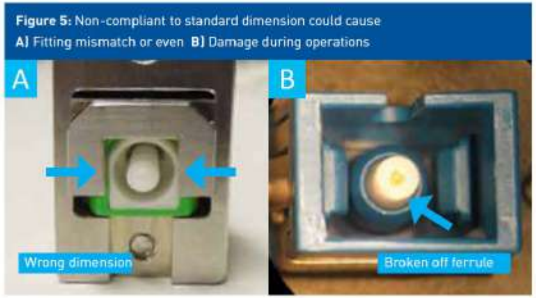
Dust

Ground Water Test

References:







https://www.senko.com/technical/senko-group-technical.html

PIC-to-Fibre Coupling

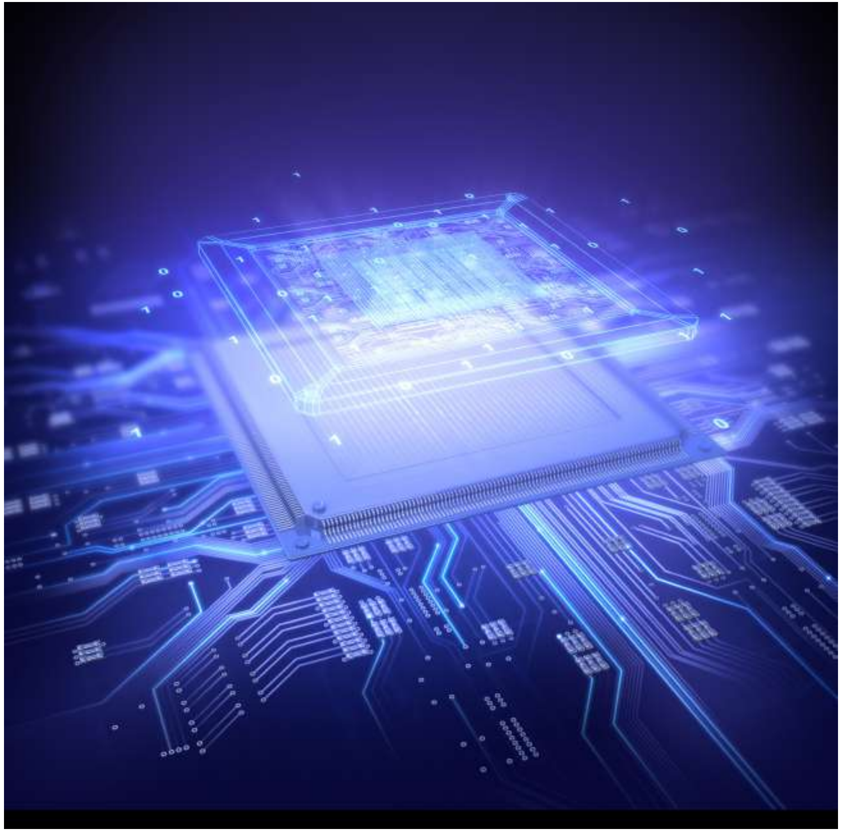
Key Challenges

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)

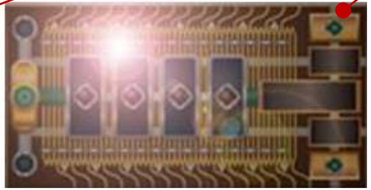
- Quantum Photonic Integrated Circuit (QPIC) are PICs developed for quantum cryptography, communications, and computing requires reducing existing table-top experiments (e.g. quantum light source, quantum number generators, etc)

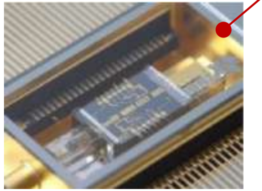


Photonic integrated circuit platforms

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

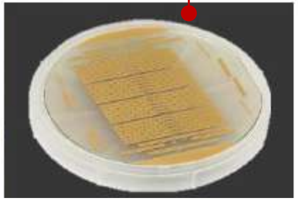

Silicon
(Source: CEA LETI)


Indium Phosphide
(Source: Infinera)

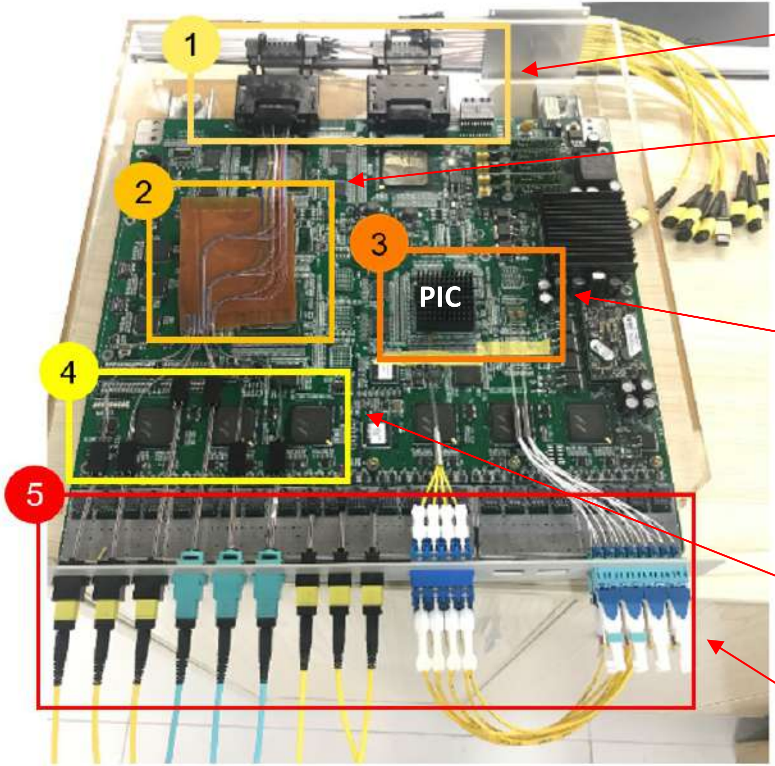

Silicon Nitride
(Source: Lionix)


Silica (Glass)
(Source: Teem Photonics)


Polymer
(Source: Lightwave Logic)


Lithium Niobate $LiNbO_3$

PIC related Optical Interconnect



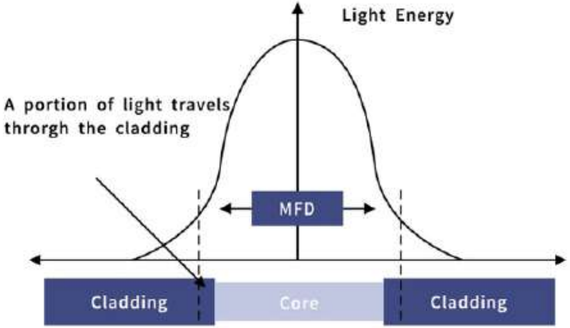
1. Backplane Interconnectors
2. Fibre Routing
   - Fibre Shuffles
   - Fibre Coating/Lamination
3. **Photonic Integrated Circuit Coupling**
4. On-Board/Mid-Board Interconnect
5. Front Panel /Face Plate

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:

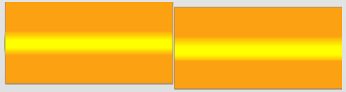
$$\text{loss (dB)} = -10\log\left\{\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right\}$$

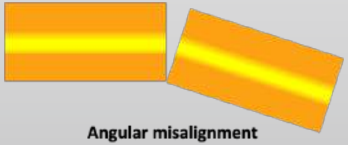
Best Coupling efficiency is achieved when

$$MFD_1 = MFD_2$$

$$Loss\ (dB) = 0$$

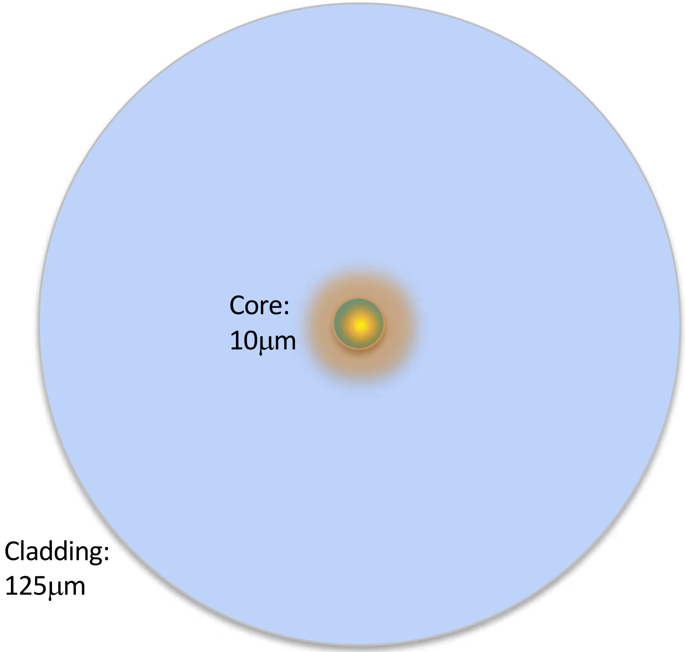
Not considered:





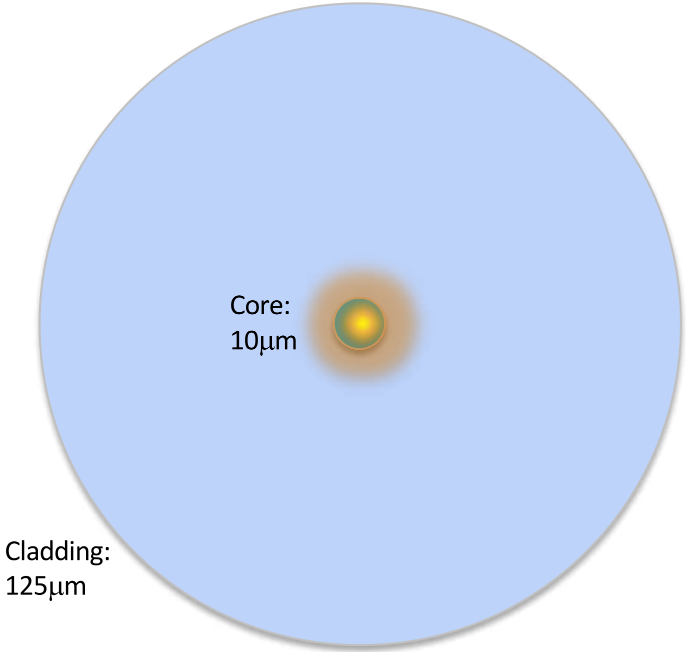
Conventional single-mode Fibre

Optical Fibre 1



Typical MFD_1
- 10µm
- Circular

Optical Fibre 2

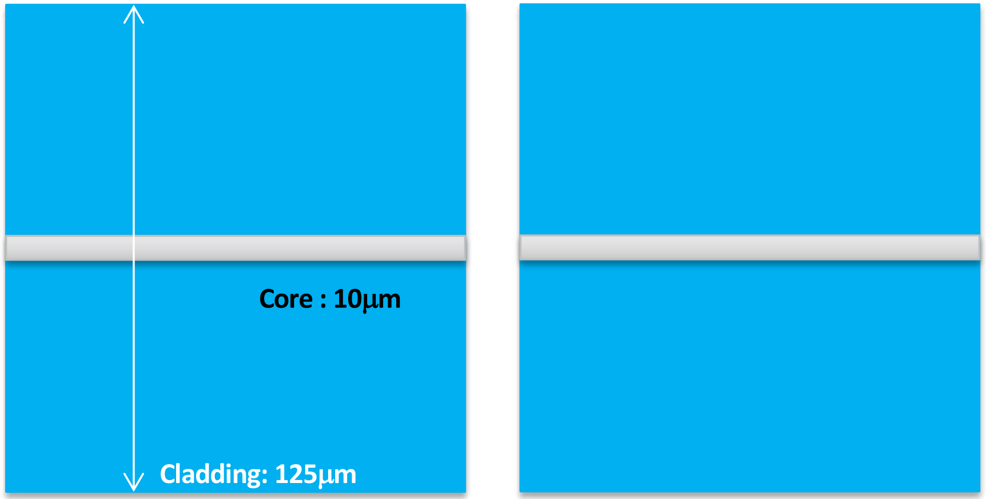


Typical MFD_2
- 10µm
- Circular

Conventional Fibre-to-Fibre Coupling

Estimated coupling efficiency high because

$$MFD_1 \approx MFD_2$$



Typical MFD_1
- Circular
- 10μm

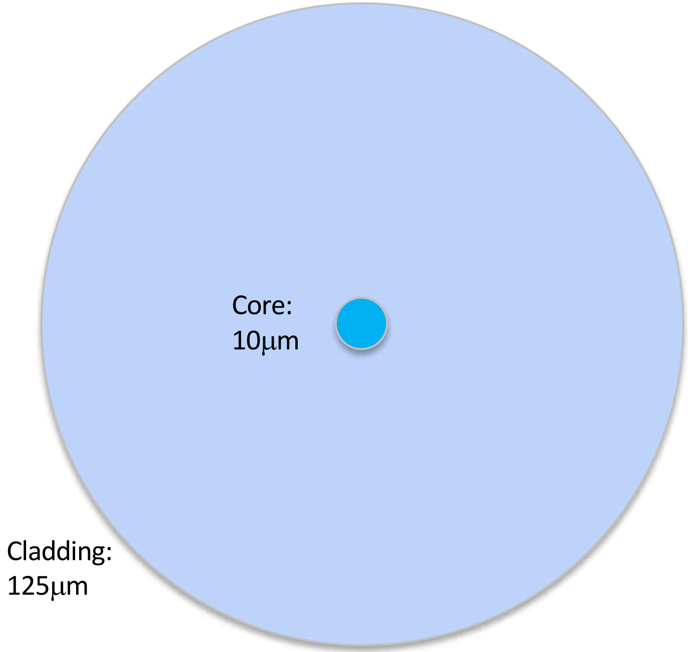
Typical MFD_2
- Circular
- 10μm

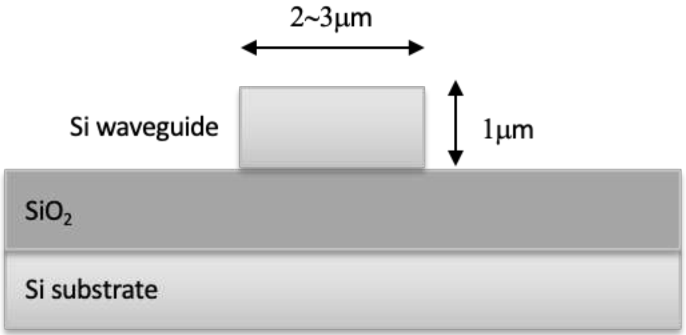
Connector No:	*Insertion Loss (dB)*		*Backreflection (dB)*	
	1310nm	1550nm	1310nm	1550nm
001	0.03	0.05	88.6	87.5
002	0.04	0.04	88.9	87.1
003	0.02	0.01	87.3	85.9
004	0.01	0.01	87.5	87.5
005	0.01	0.02	87.5	86.4
006	0.02	0.03	85.4	86.3
007	0.06	0.03	87.3	86.1
008	0.06	0.05	87.5	85.9
009	0.06	0.07	87.9	87.9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

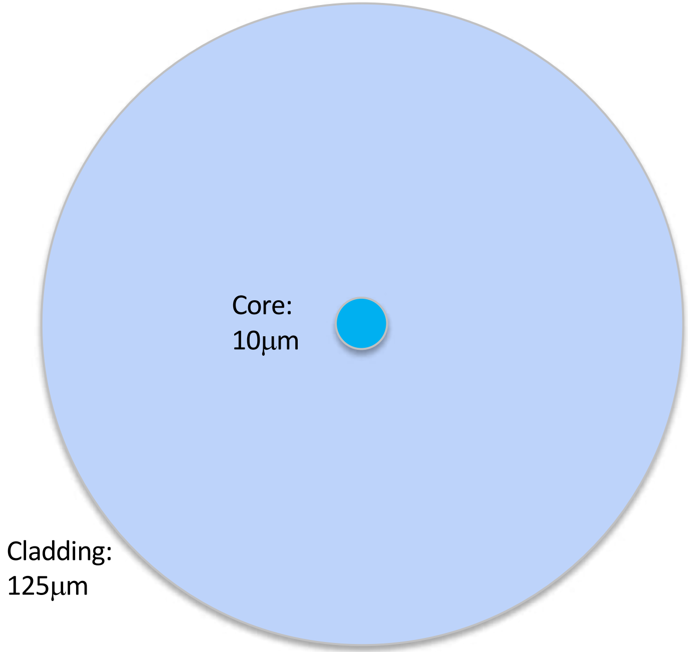


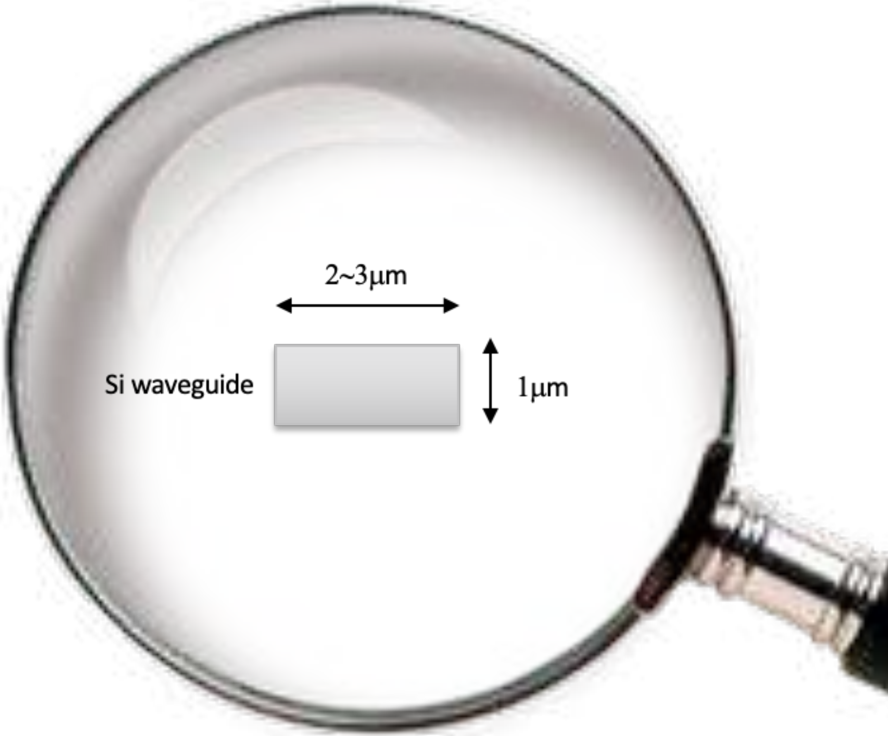


Typical MFD:
- 10µm

Typical MFD:
- <2µm

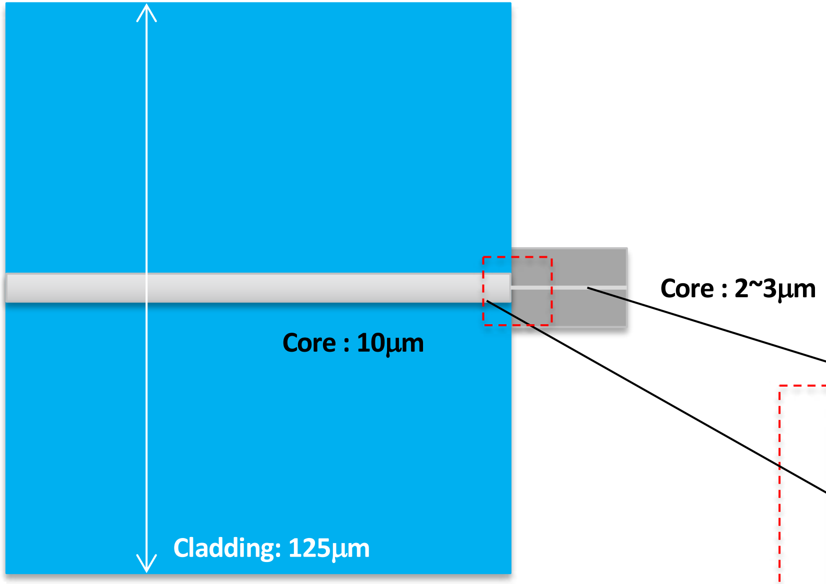
Fibre vs PIC: Dimensional Mismatch





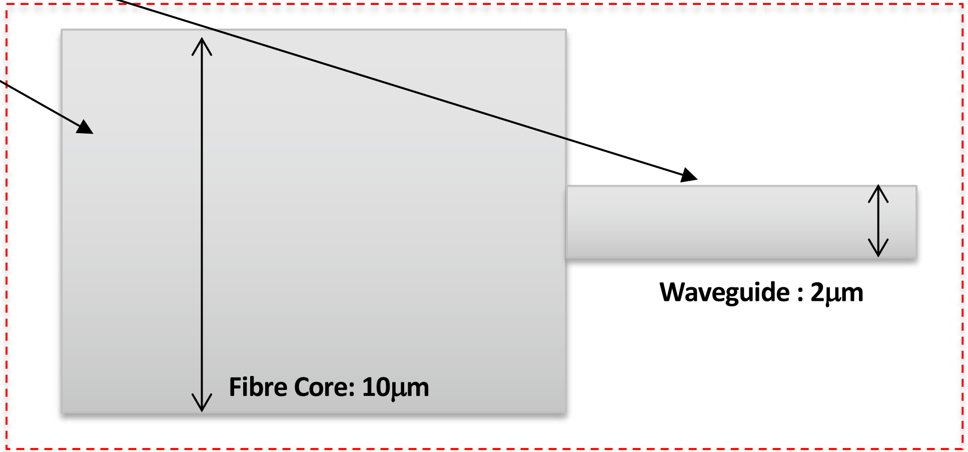
Scale to approximate size

Conventional Fibre vs PIC



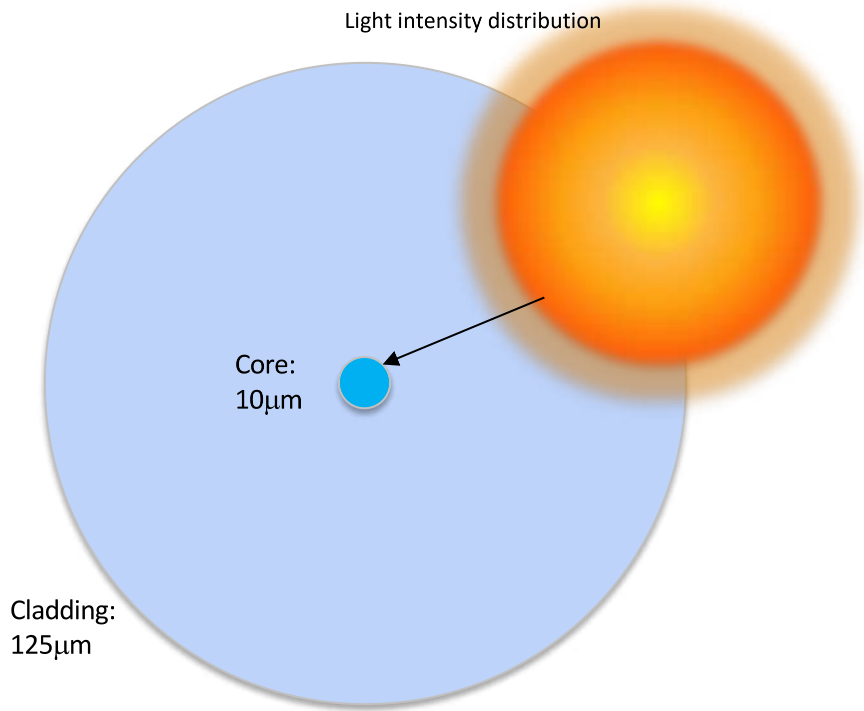
$$\text{loss (dB)} = -10\log\left\{\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right\}$$

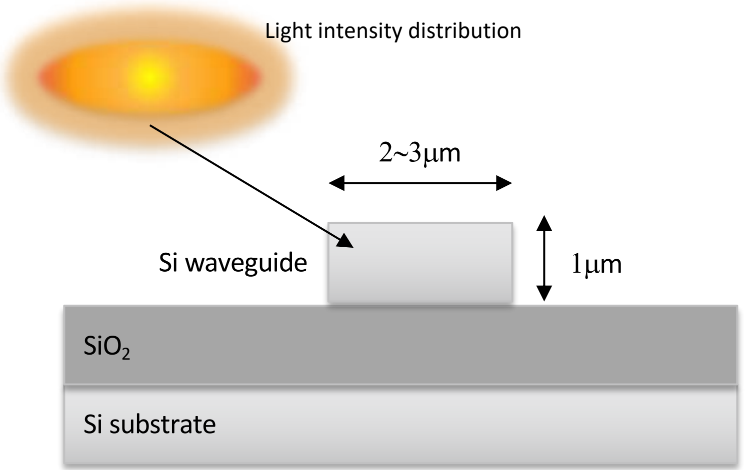
Difference in area is 35 time



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

Fibre vs PIC Waveguide : Light Distribution



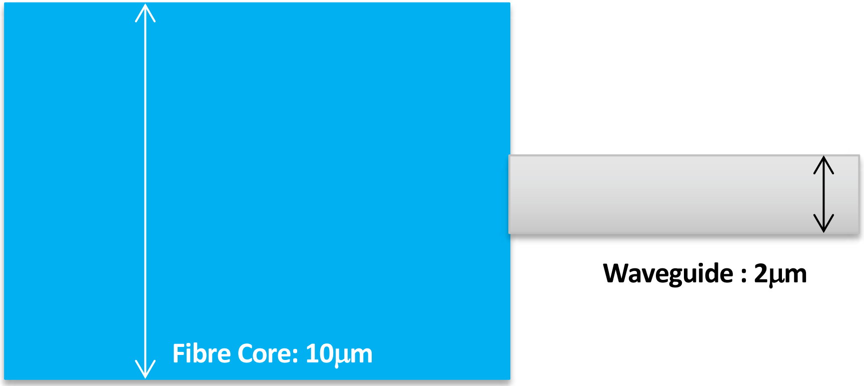


Typical MFD:
- 10µm
- Circular

Typical MFD:
- <2µm
- Elliptical

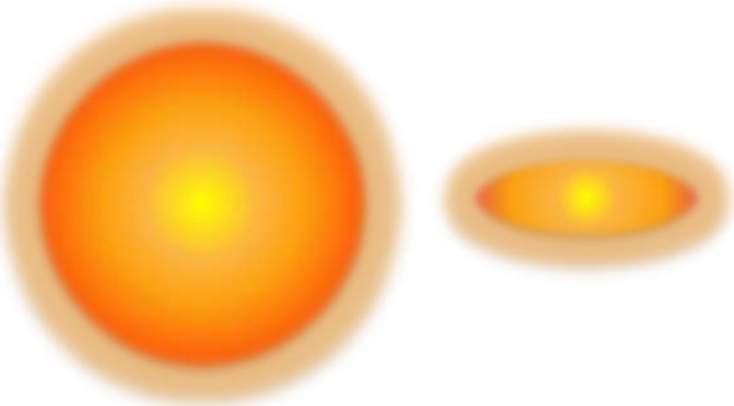
PIC-to-Fibre

- 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

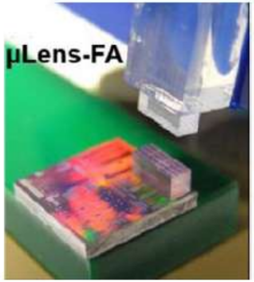
- Vertical fixed coupler or vertical free space coupler

End-fire/Edge coupling

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

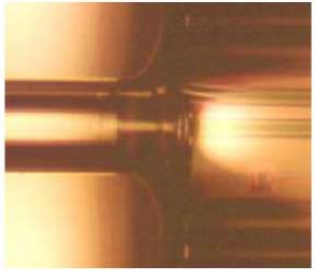
Vertical fixed coupler

Vertical free space coupler

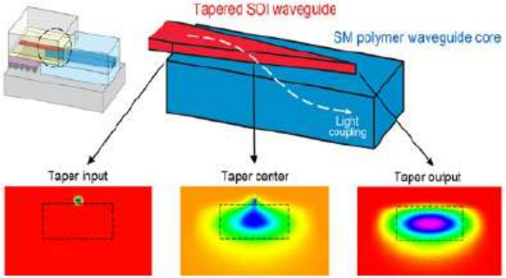


Source: *Tyndall*

Active Edge coupler

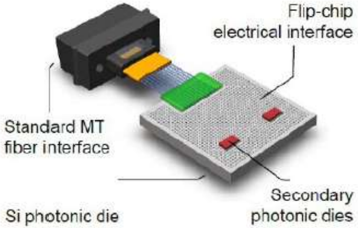


Adiabatic Coupling



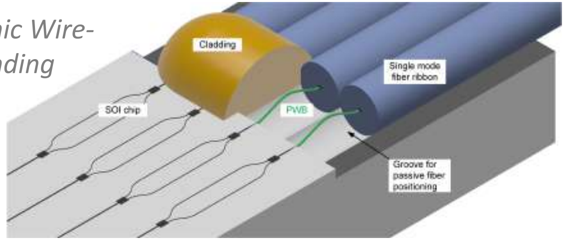
***Source:** IBM*

Passive Edge coupler



***Source:** IBM*

Photonic Wire-bonding



Source: *Vanguard photonics*

Vertical Grating-Based Coupling

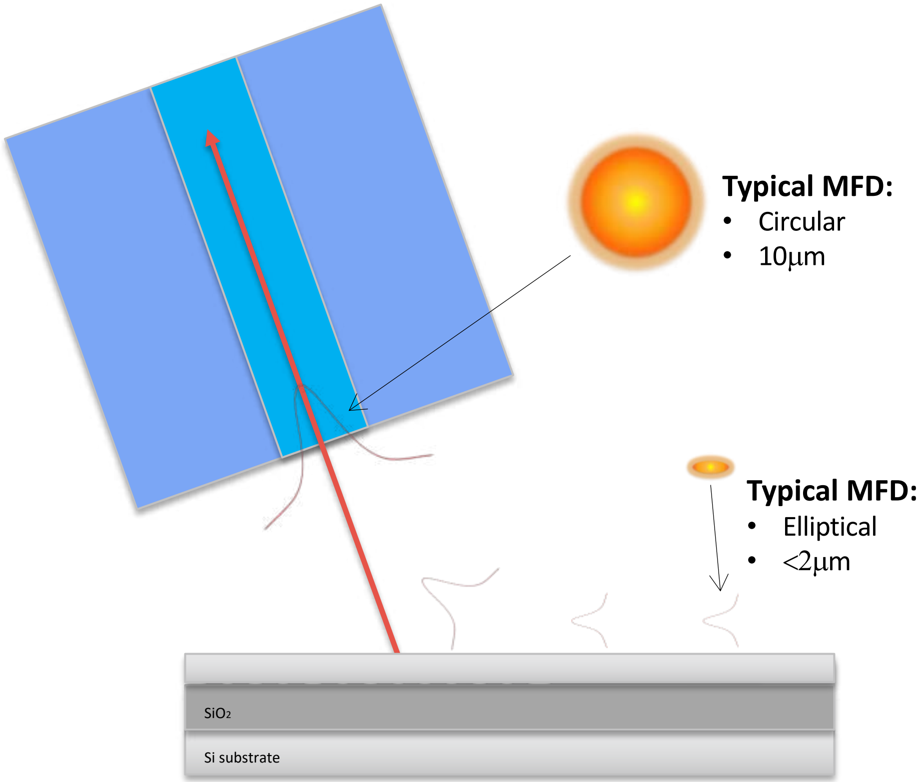
Diffraction Grating-Based Coupling

- 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

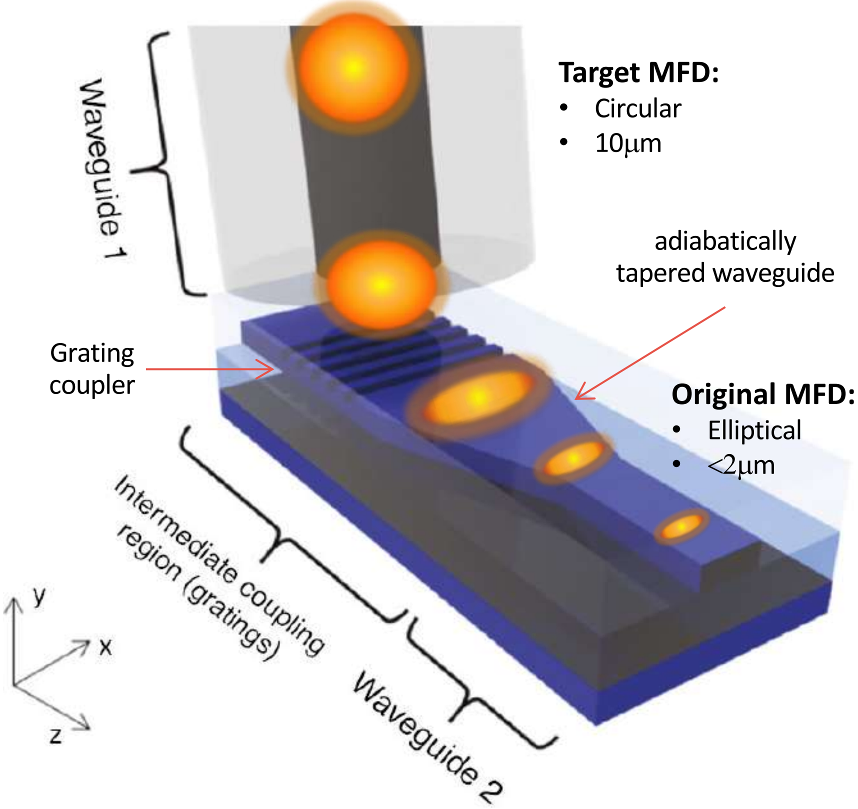
DIFFRACTION GRATING-BASED COUPLING

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

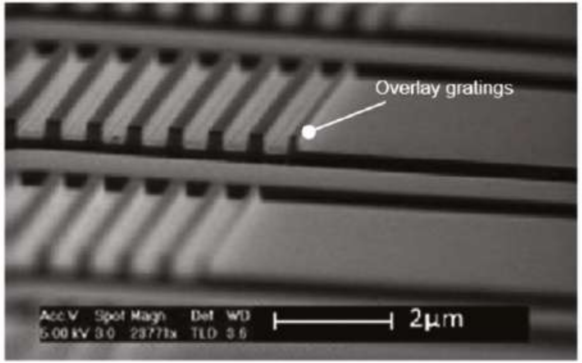
Diffraction Grating-Based Coupling

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

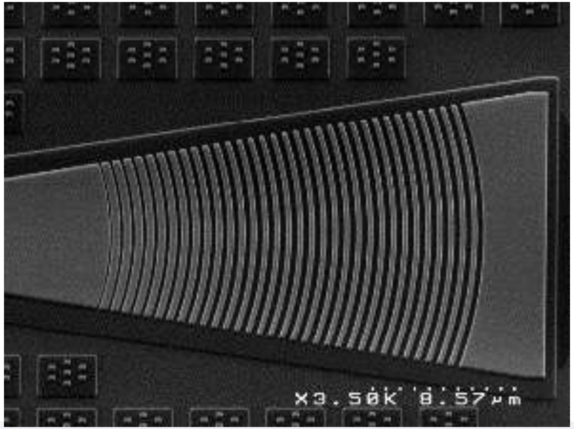
- **Post processing** such as dicing, or polishing is **not required**. This allows in-process wafer-scale optical characterization and testing
- The coupler structures **do not need to be located at the chip edges**, which improves layout design flexibility and optical port scalability
- Alleviated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

The disadvantages of grating-based couplers are:

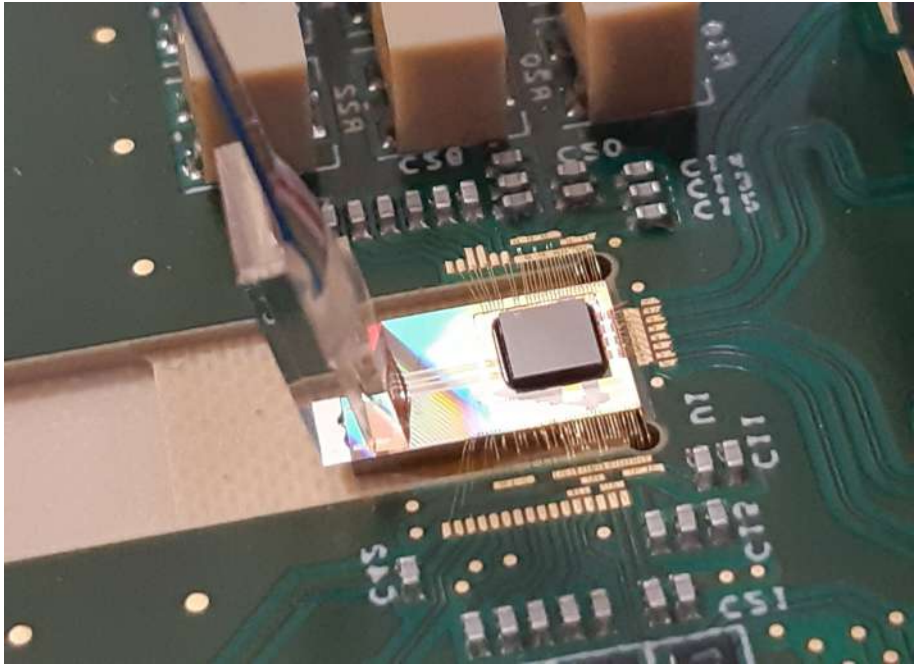
- **Polarization and wavelength dependent**
- **Lower coupling** efficiencies when compared to End-Fire Couplers
- **More complex and costly PIC design** including additional layer for mode conversion



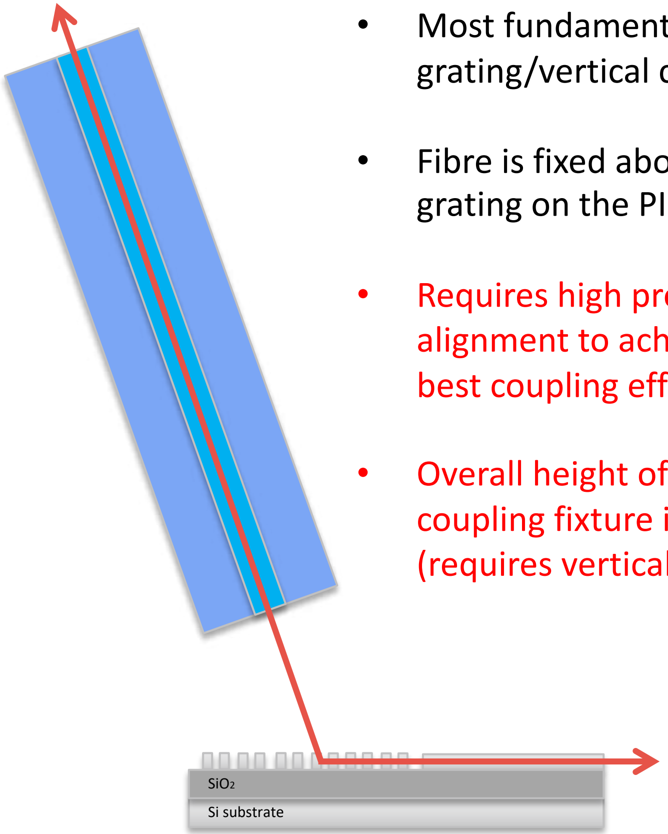
Scanning Electron Microscope (SEM) image of a grating structure.



Variation of Grating Coupling techniques

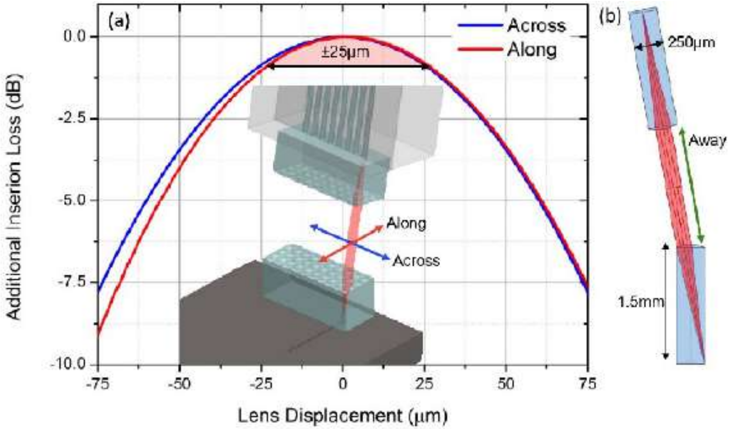


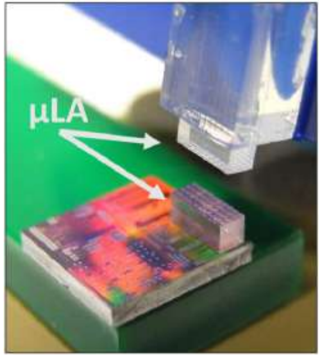
Source: Resolute Photonics



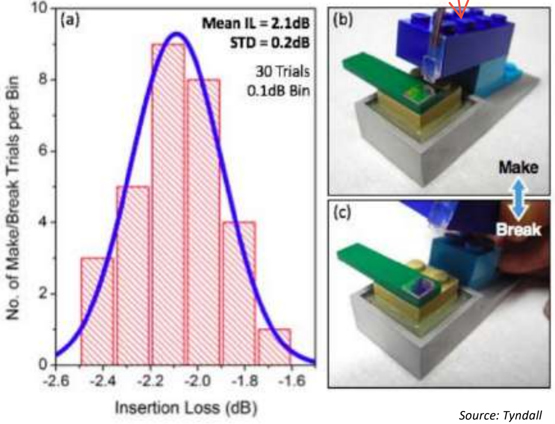
- Most fundamental of grating/vertical coupling
- Fibre is fixed above the grating on the PIC
- Requires high precision alignment to achieve best coupling efficiency
- Overall height of the coupling fixture is high (requires vertical space)

Variation of Grating Coupling techniques

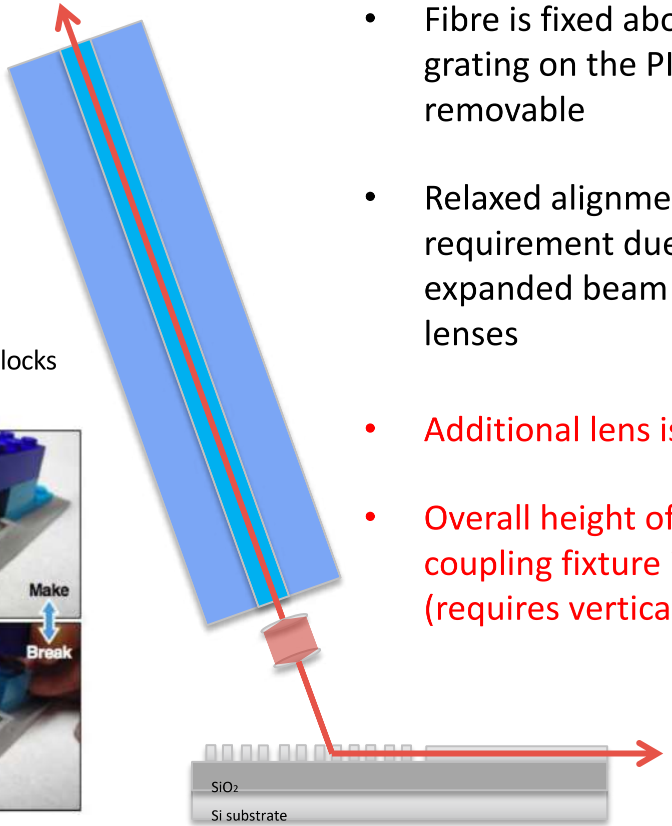




LEGO® Blocks

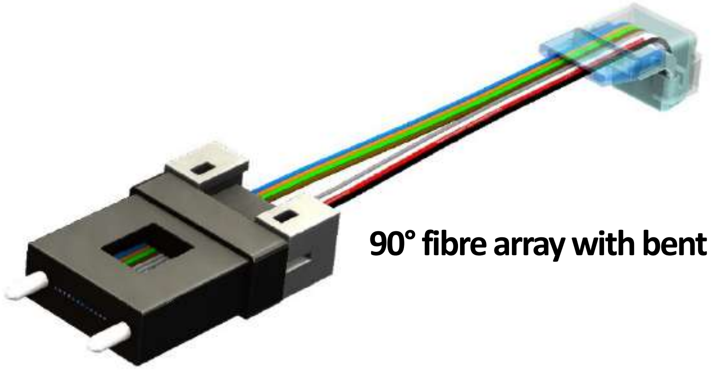


Source: Tyndall



- 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)

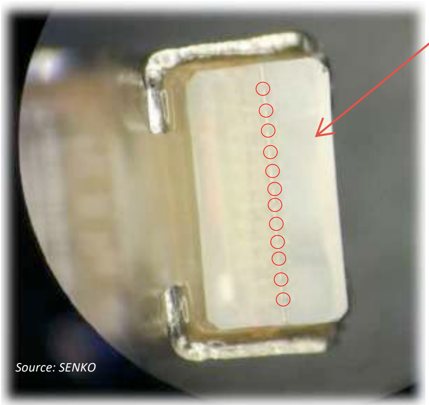
90º Bent Fibre Array

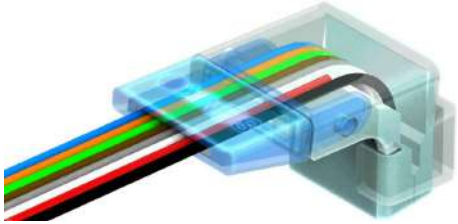


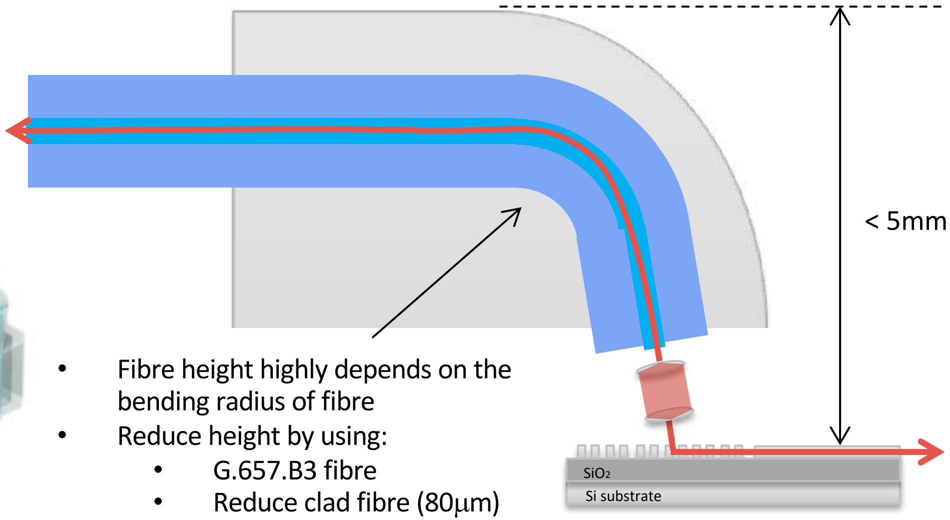
90° fibre array with bent fibre

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

Fibre End-face

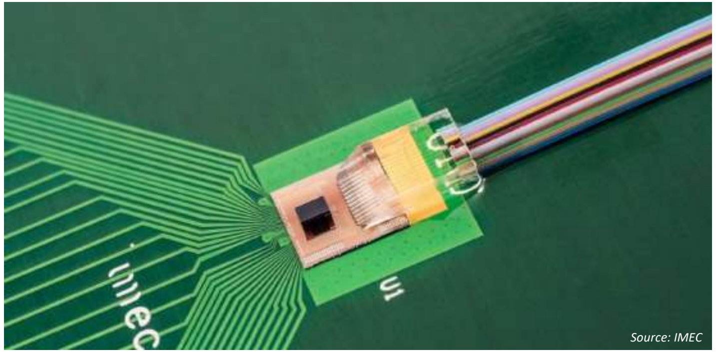


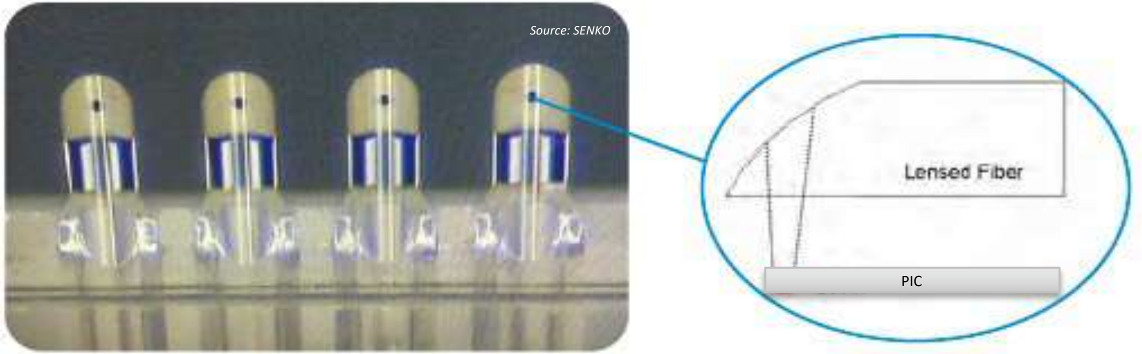




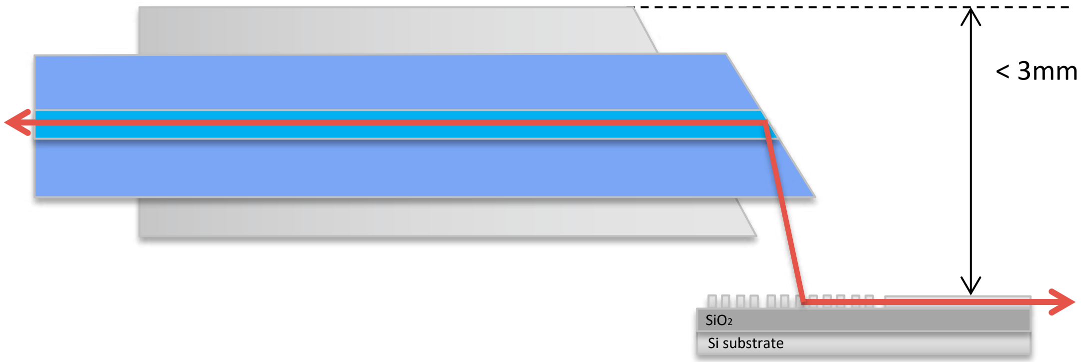
- Fibre height highly depends on the bending radius of fibre
- Reduce height by using:
  - G.657.B3 fibre
  - Reduce clad fibre (80μm) or etched clad fibre

45° Curve Polished/Cleaved Fibre Array



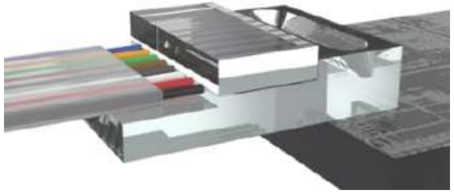


- Fibre is fixed parallel to the PIC which allows the total height to be significantly reduced to <3mm
- Signal is reflected using the polished end-face of the fibre
- A lensed polishing can be performed on fibre end face for better coupling efficiency

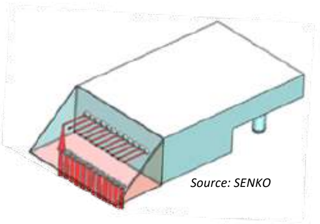


45º Reflective Fibre Array

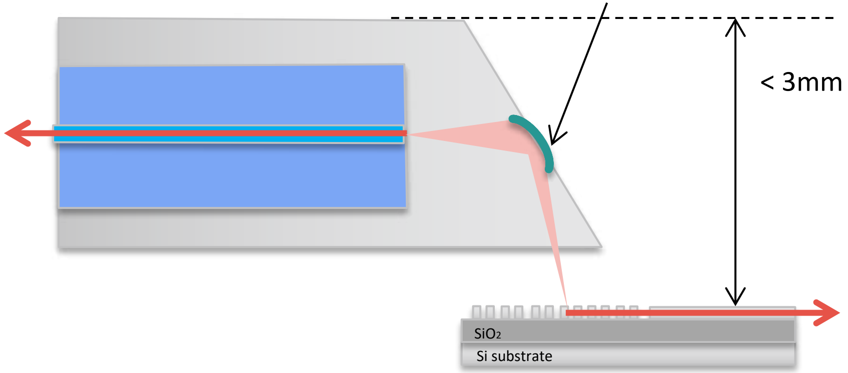
Source: Cudoform

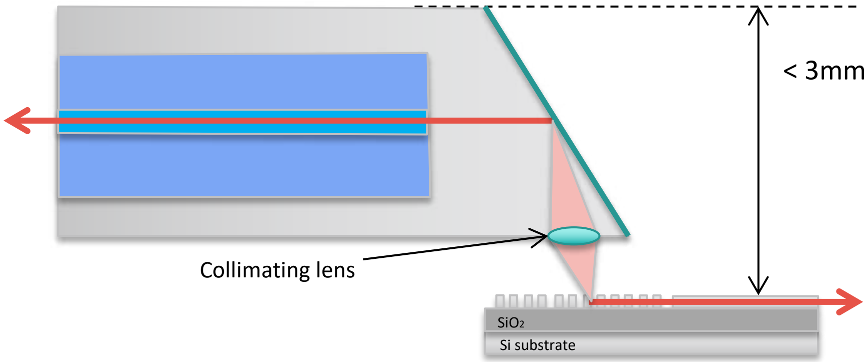


Source: Optoscribe



- 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

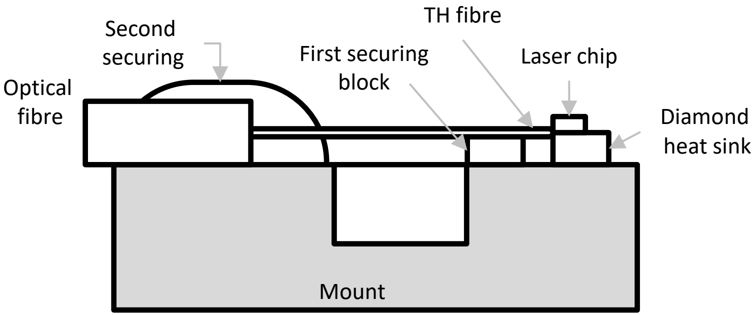


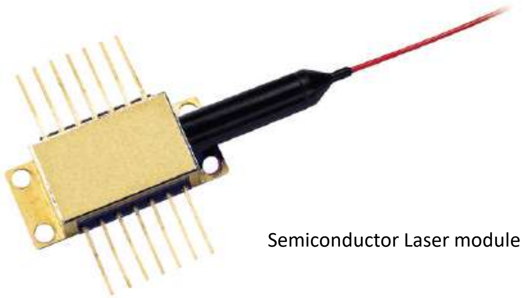


End-Fire/Edge Coupling

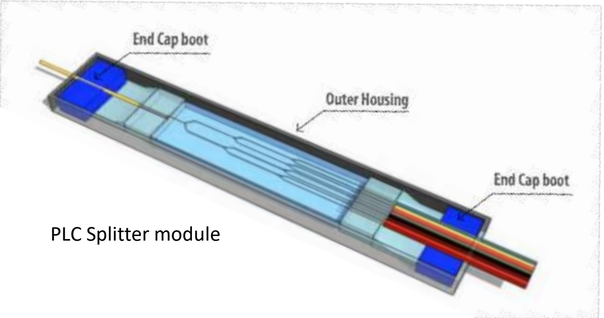
END-FIRE/EDGE COUPLING

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

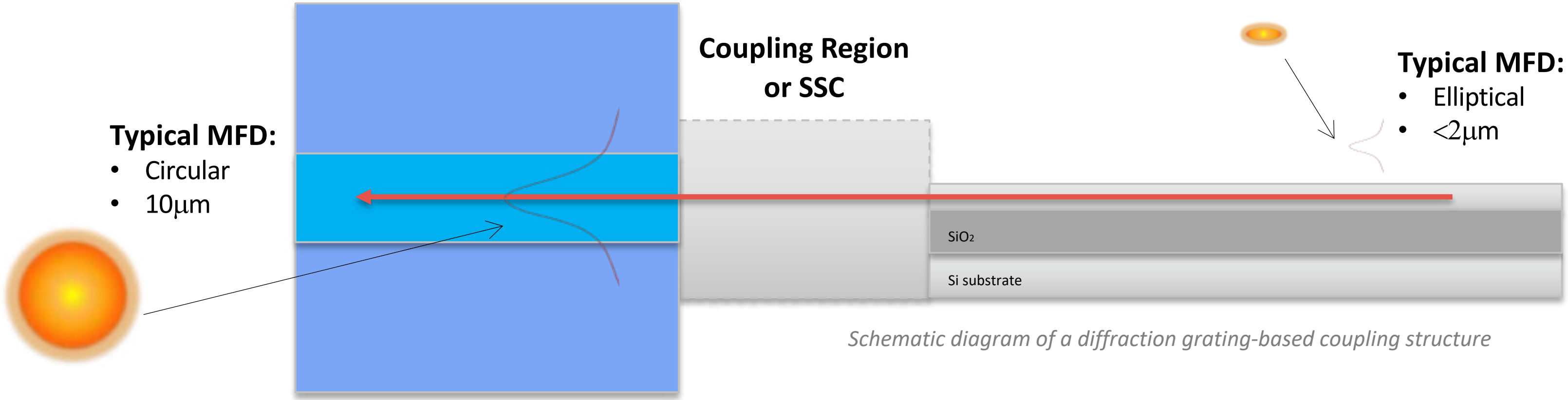


PLC Splitter module

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

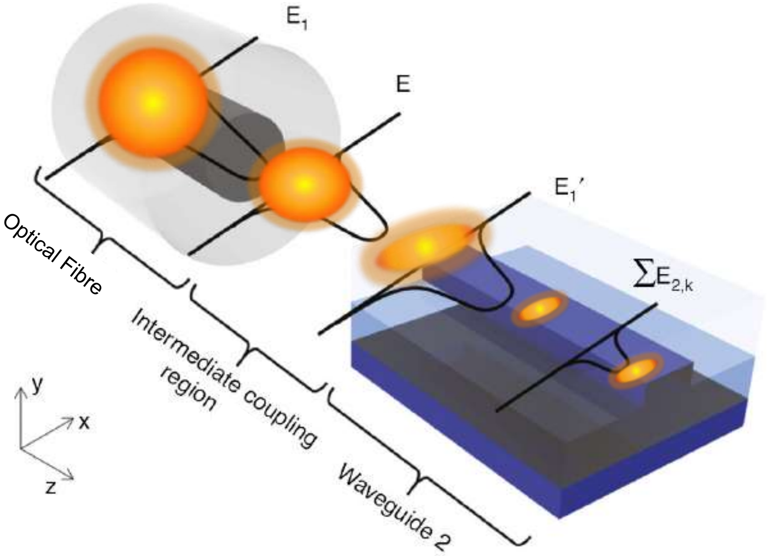
The guided mode of the input waveguide is first radiated through the intermediate coupling region (of a spot size converter) and arrives at the front facet of the second waveguide.

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

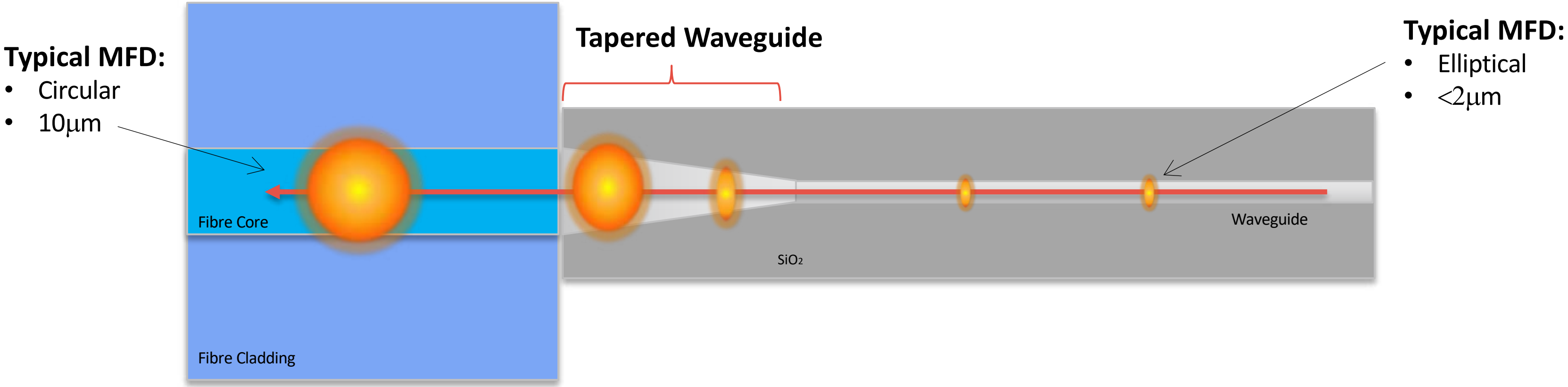


Adapted from : Nanophotonics

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.

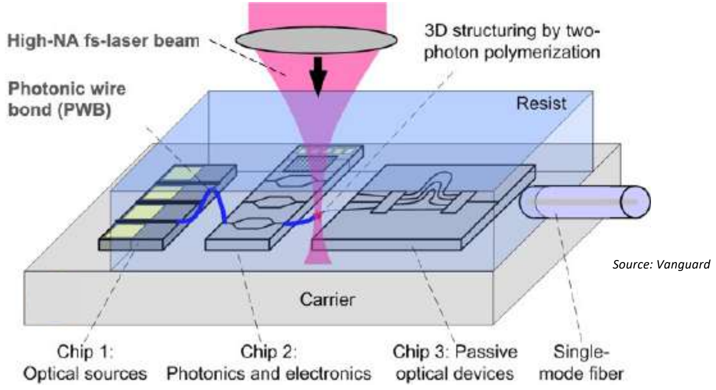
3D tapered SSC is an efficient optical fibre and PIC waveguide coupler where the final waveguide width can be made close to the standard single-mode fibre MFD. Dedicated fabrication steps, such as polishing, thick material deposition, and etching are required. It may also occupy more space when compared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



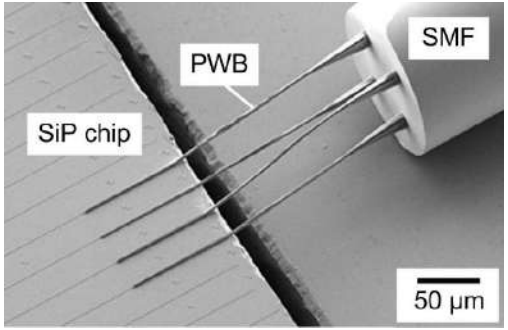
END-FIRE COUPLING – PHOTONIC WIRE BONDING

- 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.

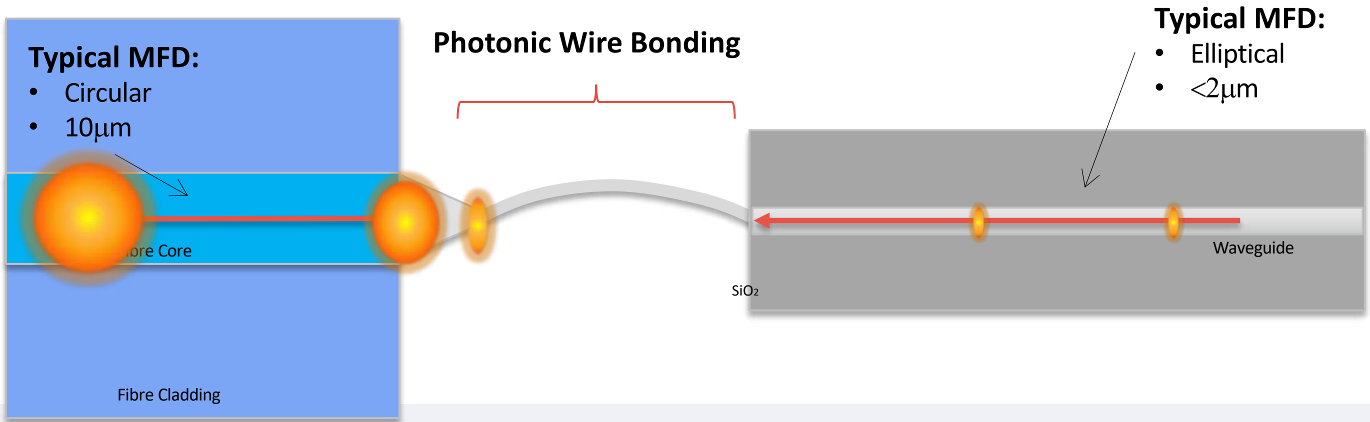
- An additional advantage of PWB is that it is not limited to PIC to fibre but also PIC-to-PIC coupling



Source: Vanguard



Source: Karlsruhe Institute of Technology

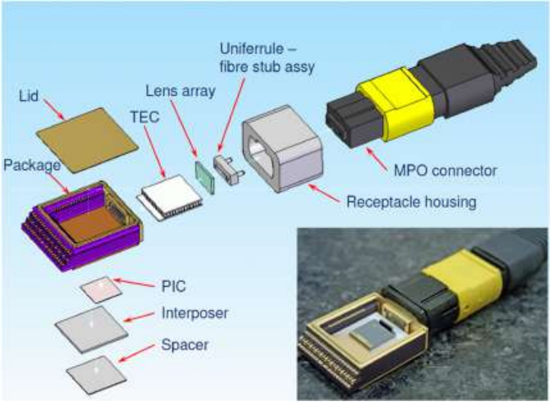


END-FIRE COUPLING – MICRO LENS

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

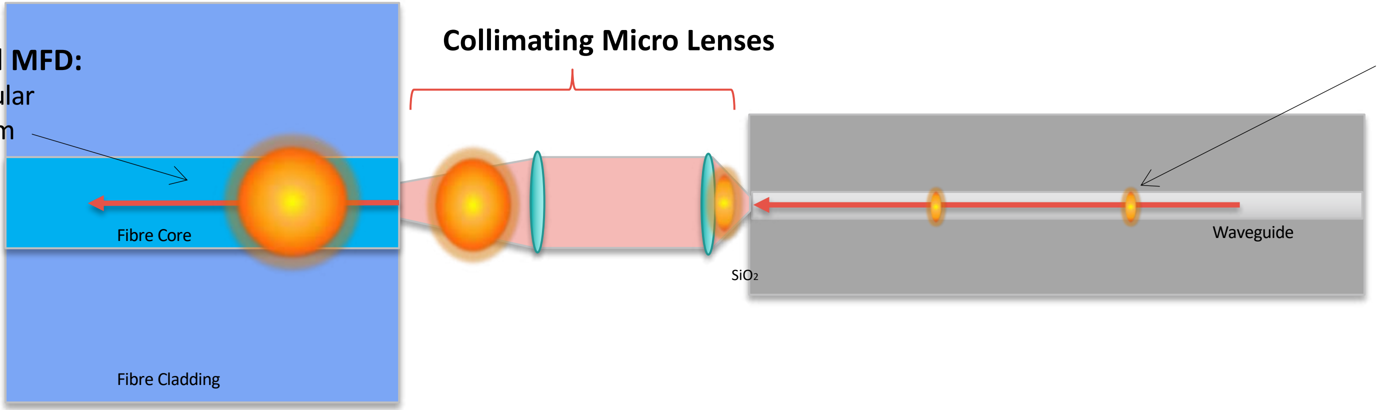
- A different type of microlens has two flat and parallel surfaces and the focusing action is obtained by a variation of refractive index across the lens. These are known as **gradient-index (GRIN) lenses**.

Source: Findlight



Source: FP7 PARADIGM

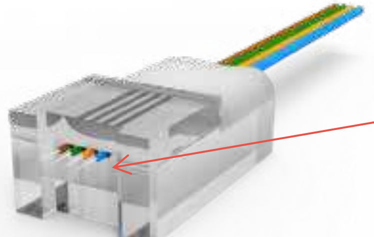
Typical MFD:
- Circular
- 10µm



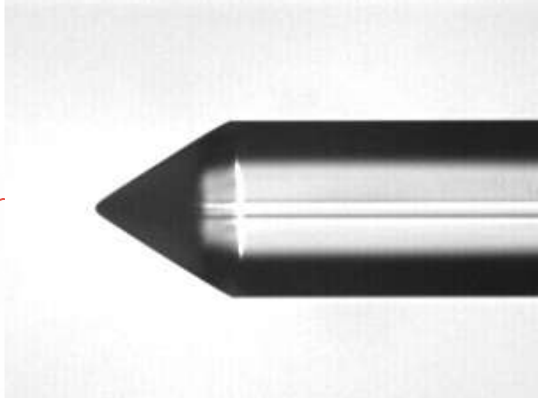
Typical MFD:
- Elliptical
- <2µm

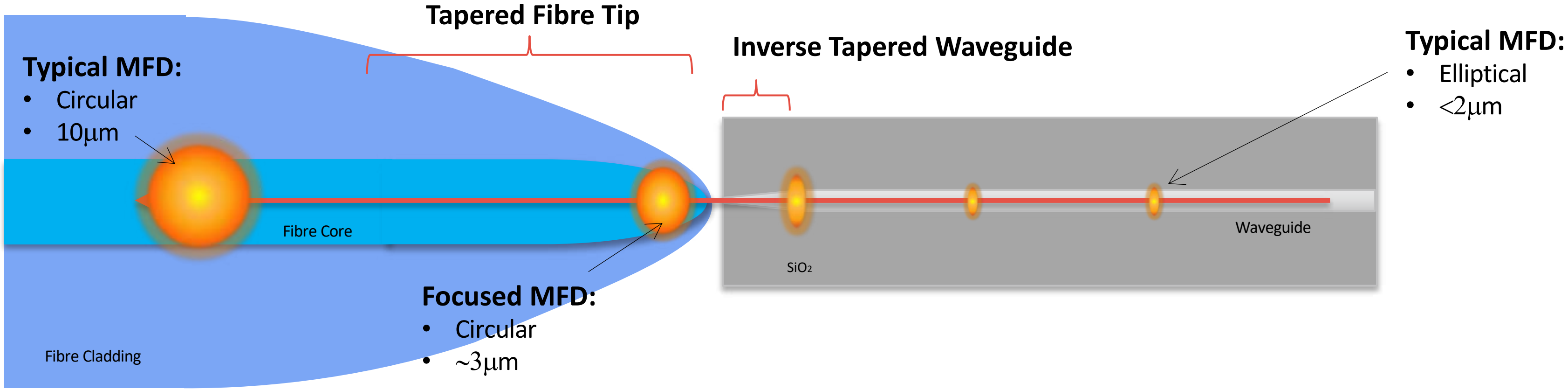
END-FIRE COUPLING – LENSED FIBRE & INVERSE TAPER

- 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.



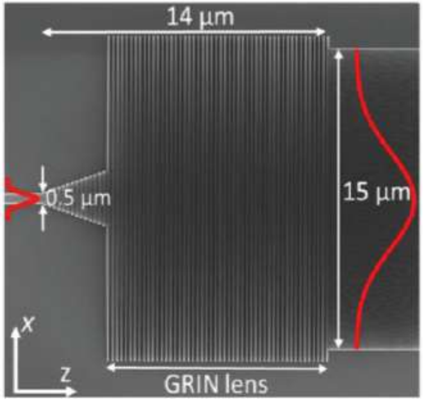
Source: SENKO



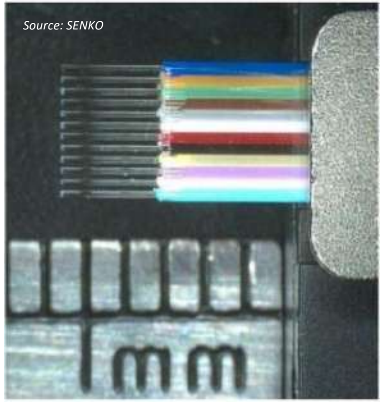


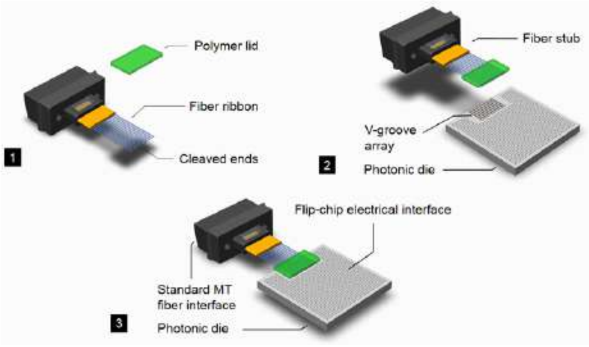
END-FIRE COUPLING – METAMATERIAL

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.

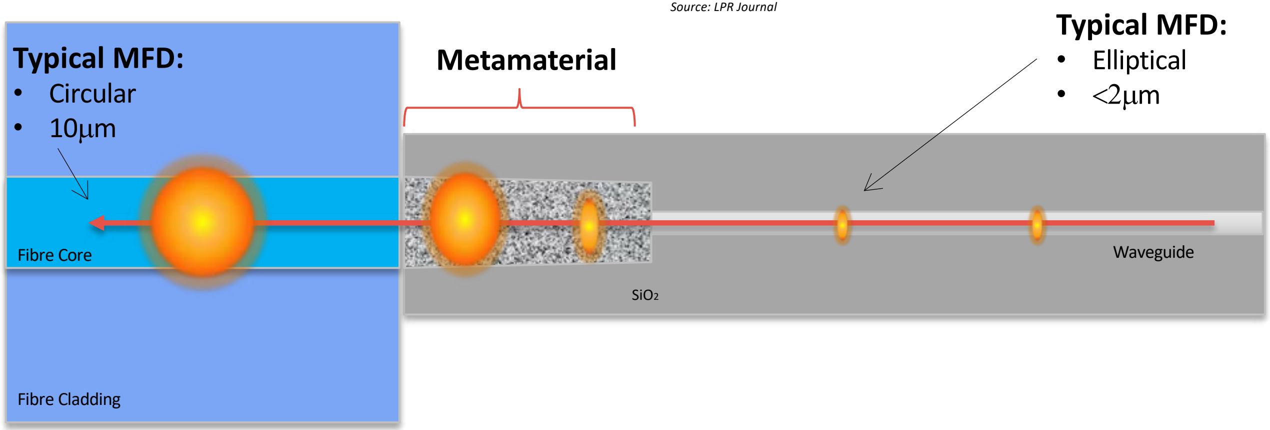


Source: LPR Journal





Source: IBM



Outline of GR-1221 Reliability Test Standards

Mechanical Integrity

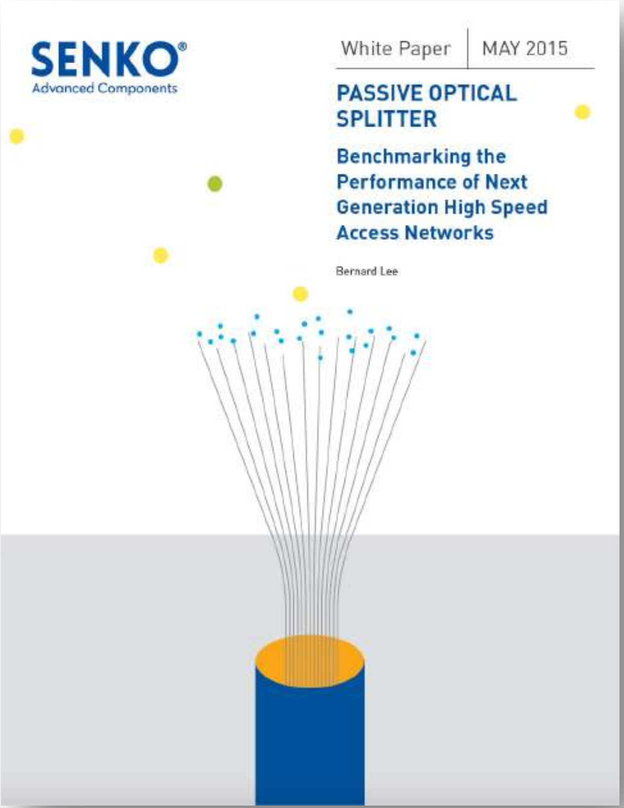
- Mechanical Shock
- Vibration
- Straight Pull

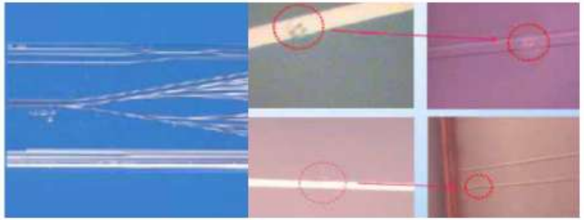
Endurance

- High Temperature Storage (Dry)
- Temperature Cycling
- High Temperature Storage (Damp)
- Cyclic Moisture Resistance
- Low Temperature Storage
- Thermal Shock

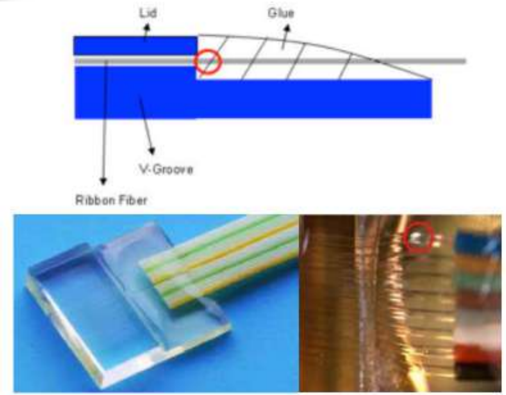
GR 1221 COMPLIANT

References:

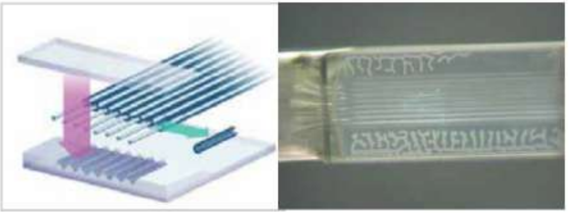




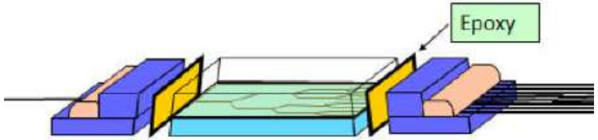
Damaged Waveguide



Damaged FIber



Delamination



Misalignment (Epoxy Shrinkage)

https://www.senko.com/technical/senko-group-technical.html

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

Summary

- Quantum Key Distribution (QKD) is a key encryption approach to a secure 'hack-proof' network which will be an essential part of future cloud applications

- Current optical technology is sufficient but not ideal to support QKD on existing fiber network. One of the key components will be ultra low loss optical connectors and QPIC interconnects

- Ultra-low loss Optical Connectors is achievable utilizing available state-of-the-art components and manufacturing approach, and its reliability is tested using standardized industrial testing methodology such as the GR-326-CORE

- Research and development into quantum grade QPIC interconnect to provide ultra-low loss coupling solutions between fiber and quantum photonics integrated circuits are still evolving. In the meantime, performance and reliability standards such as the GR-1209-CORE and GR-1221-CORE will provide quality assurance to the industry.

Thank you…

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