G&H OCT fibre component technology: focus on passives

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SVP Business Development

Enabling Photonic Technologies…

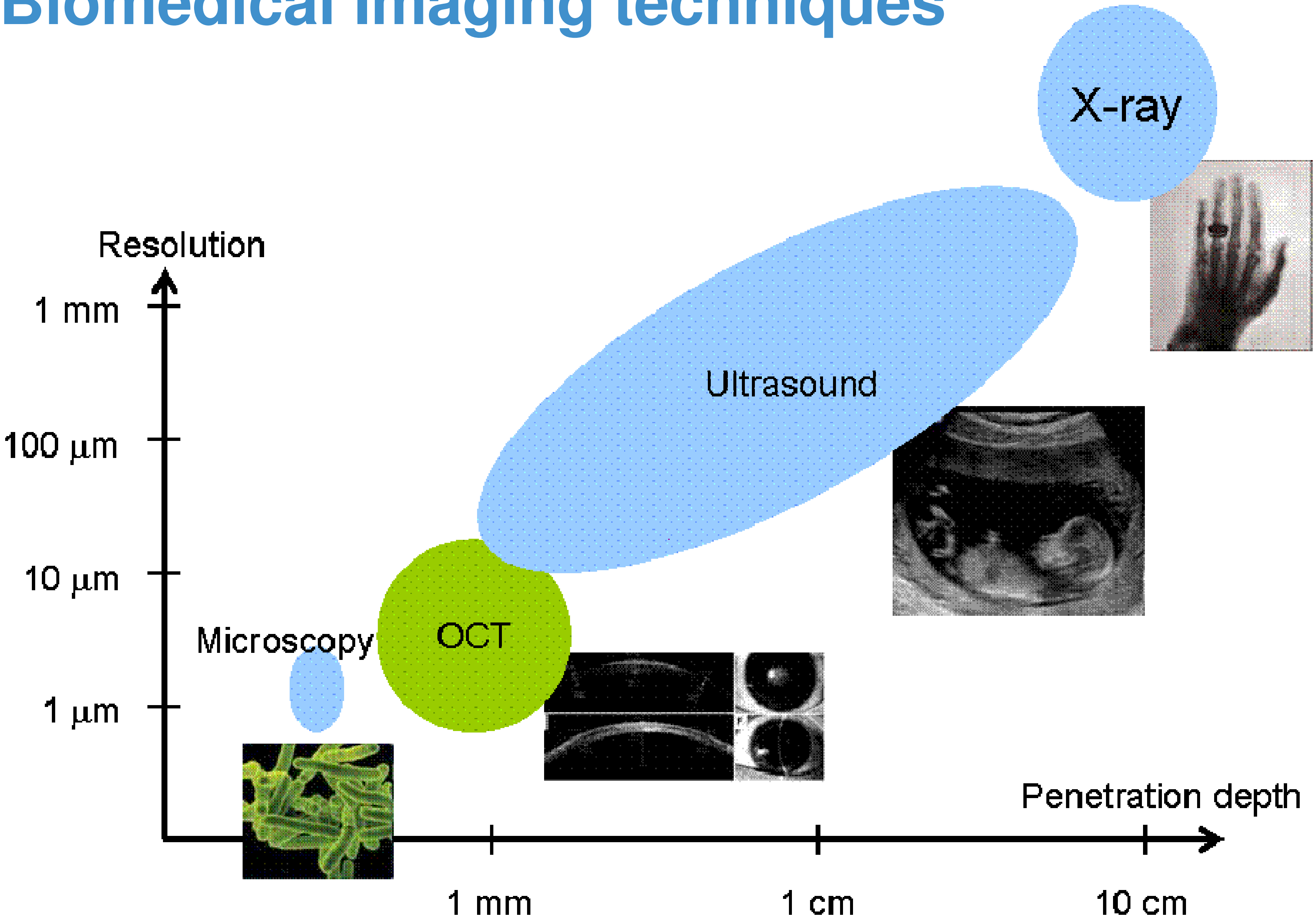
Presentation Outline

- OCT Basics
  - Applications & Technologies
  - TD OCT, FD OCT, SS OCT
- Fibre Interferometer
  - Basic Interferometer designs
  - Coupler Technology
  - Collimator Technology
  - Additional fibre component requirements
- Optical sub-system level considerations
- Current Market
- Future

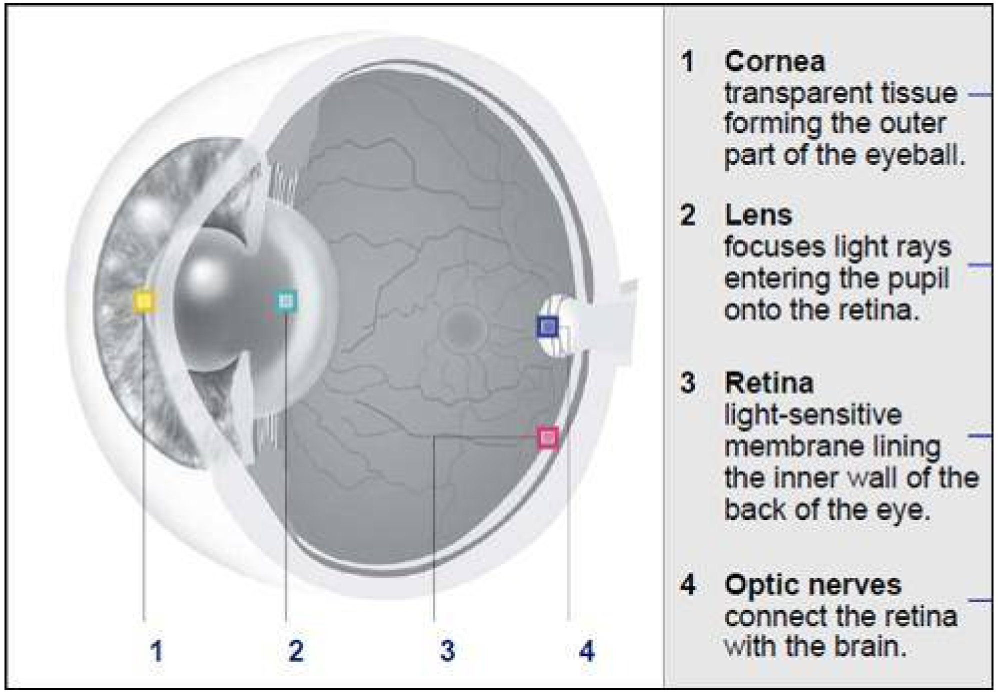
OCT: A biological imaging modality

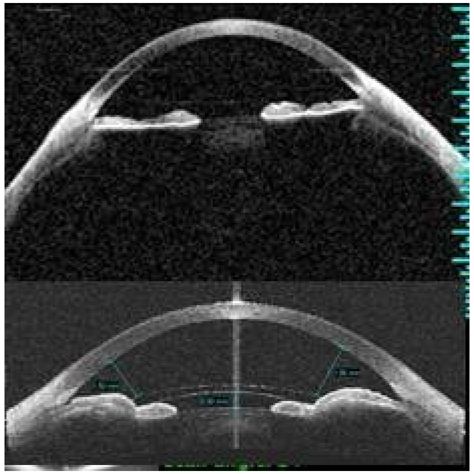
- *In vivo* imaging of tissue interiors using light
  - ✓ High resolution, 3D imaging
  - ✓ Non-toxic, non-invasive
  - ✓ Compact, relatively inexpensive
  - ✓ Versatile
  - ✘ Light scattering different in different tissues
  - ✘ Short penetration depth
  - ✘ Pathology lagging technology

Biomedical Imaging techniques

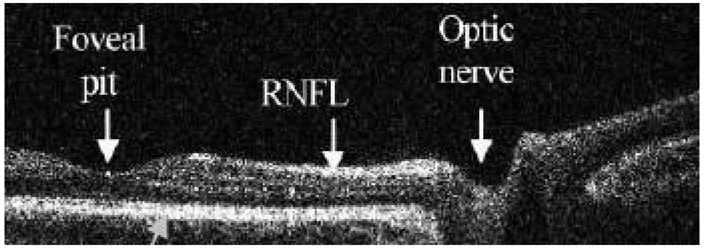


Ophthalmic OCT





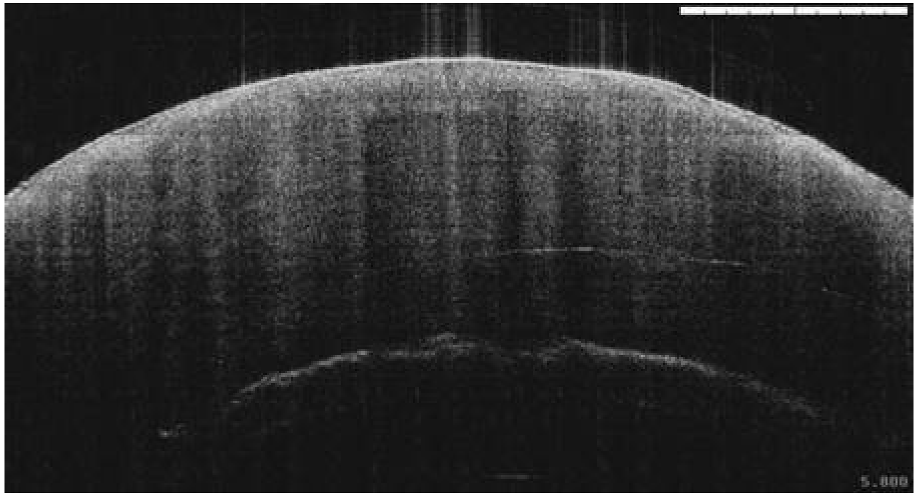
Cornea and Lens

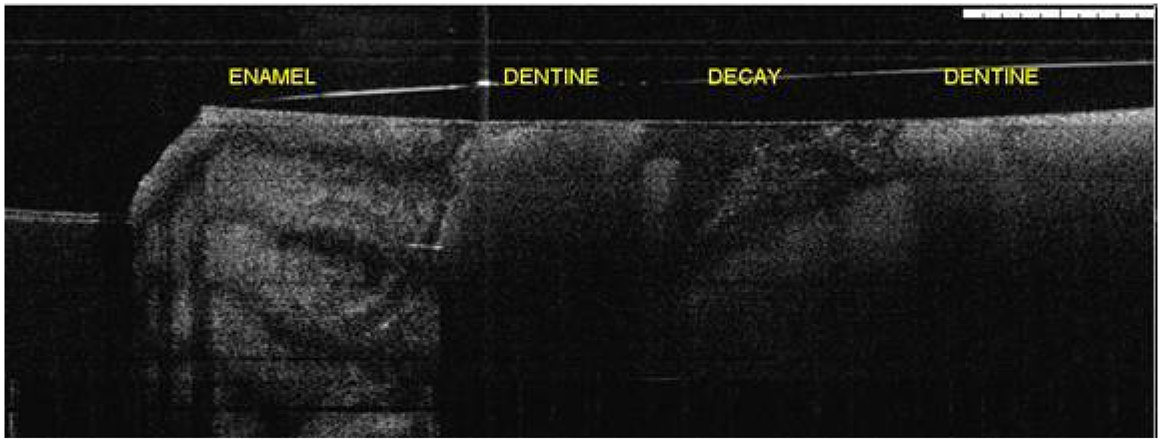


Retina

Courtesy of A. Podoleanu, University of Kent

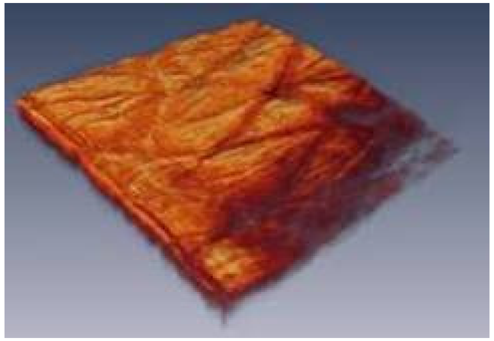
Dental OCT

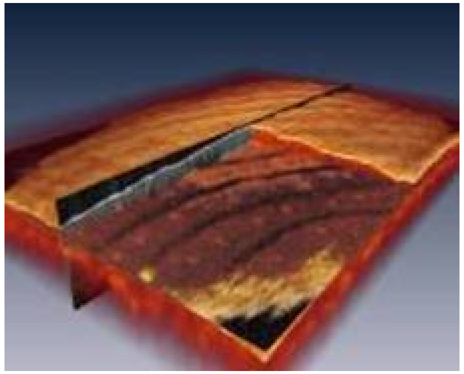


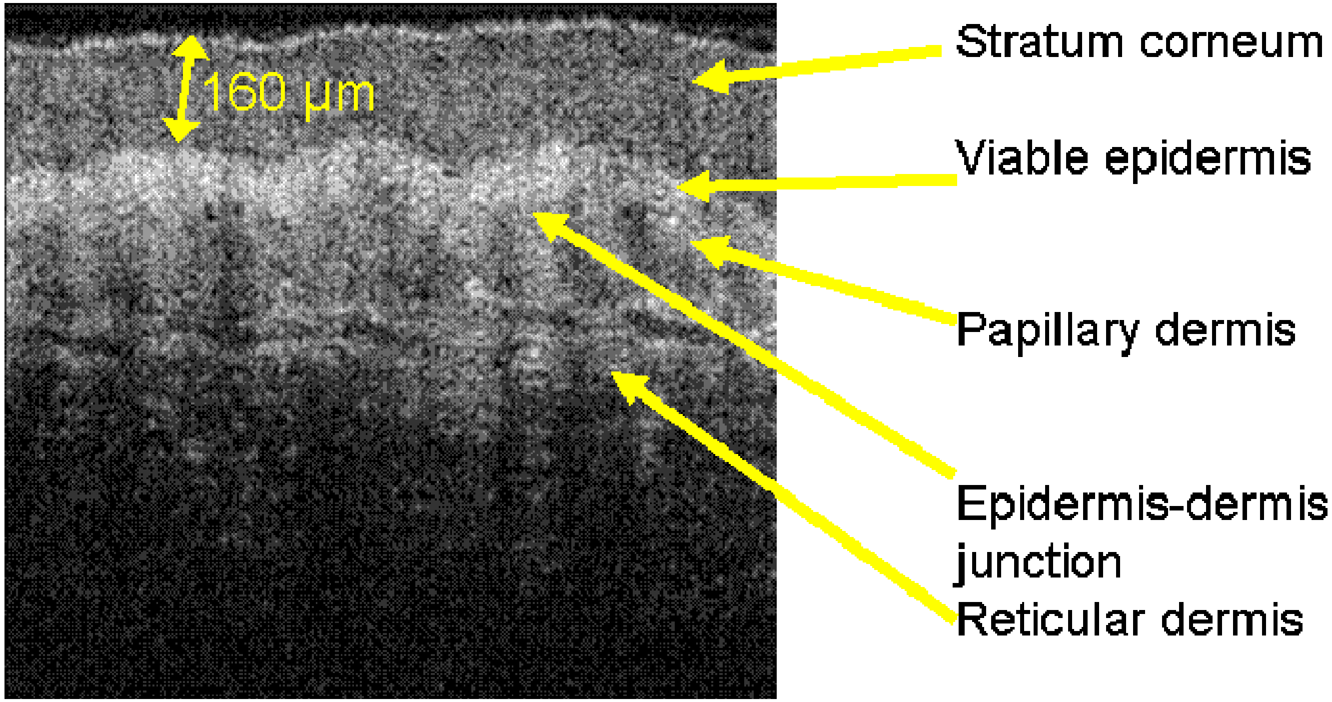


Courtesy of Michelson Diagnostics

Dermatological OCT



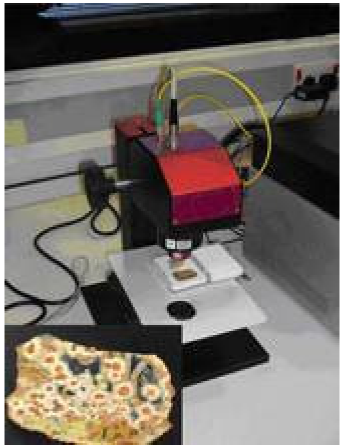




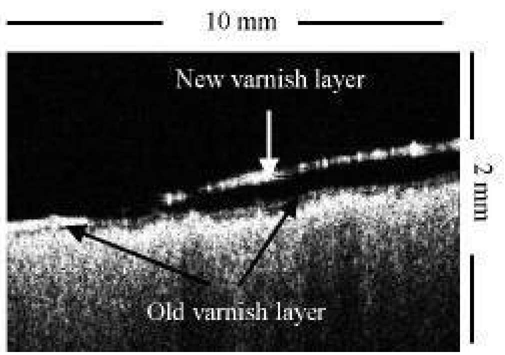
Courtesy of Michelson Diagnostics

Non Biomedical OCT

- Art Conservation
  - Glass corrosion
  - Varnish depth



Courtesy The British Museum



Courtesy Haida Laing, Nottingham Trent Uni, UK

- Micromachining

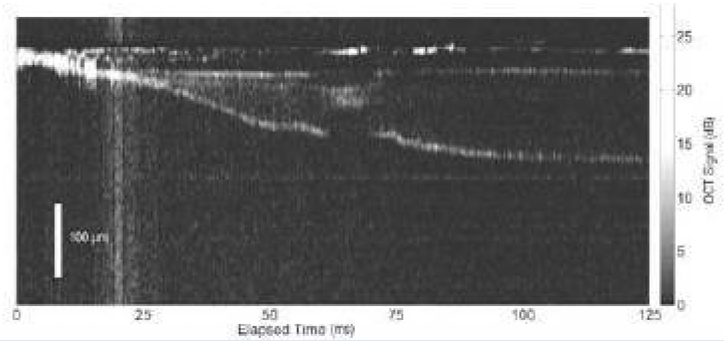
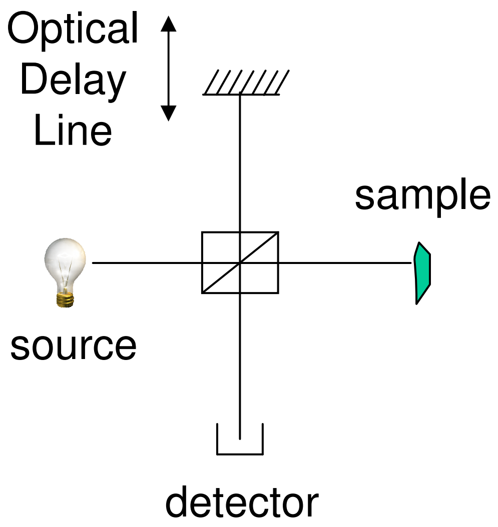


Fig. 4 304 stainless steel undergoing laser micromachining.

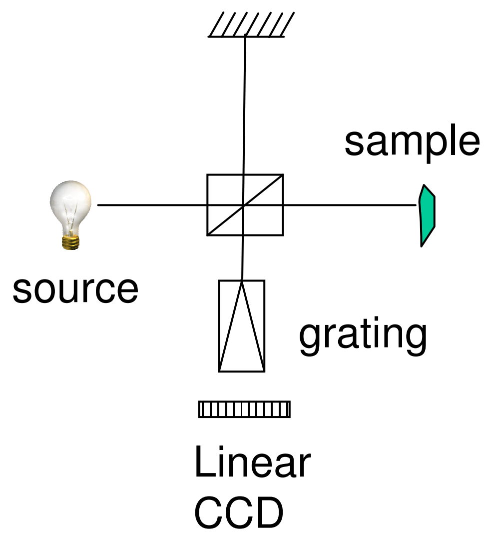
Courtesy M.S.Muller et al Queens University, Ontario

Common OCT techniques

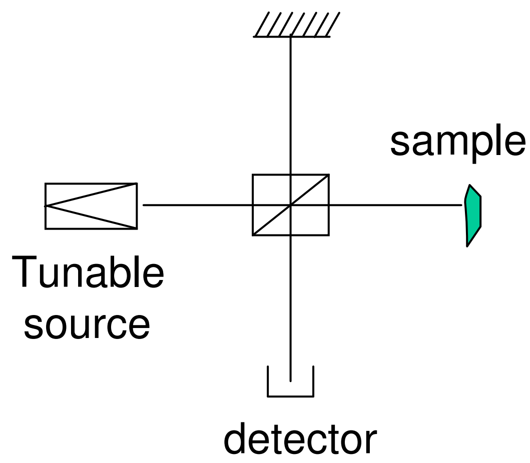
Time Domain OCT
(TD OCT)



Fourier Domain OCT
(FD OCT)

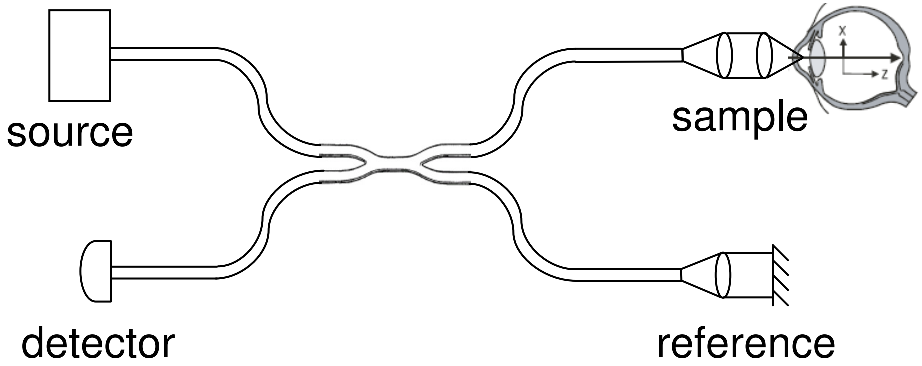


Swept Source OCT
(SS OCT)

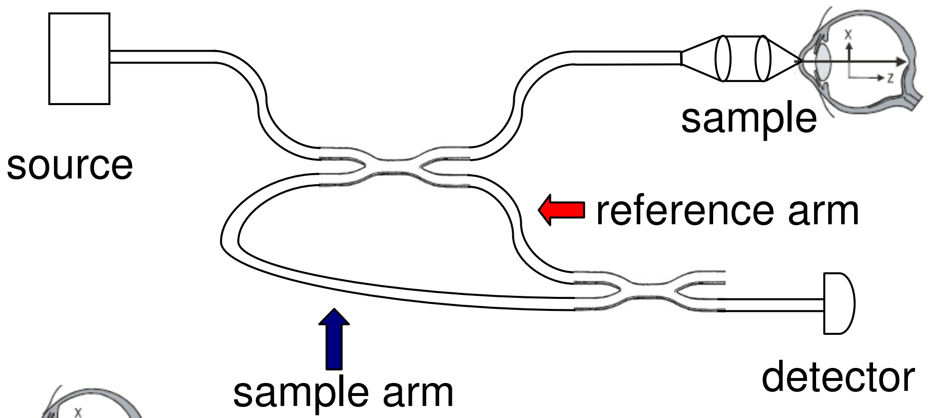


Basic interferometer networks

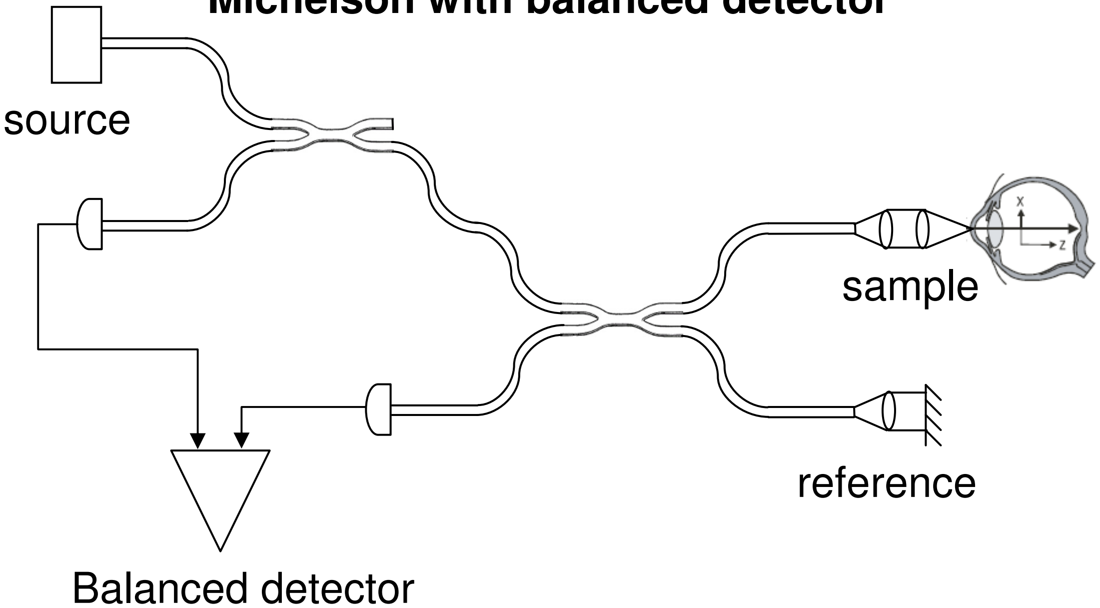
Michelson



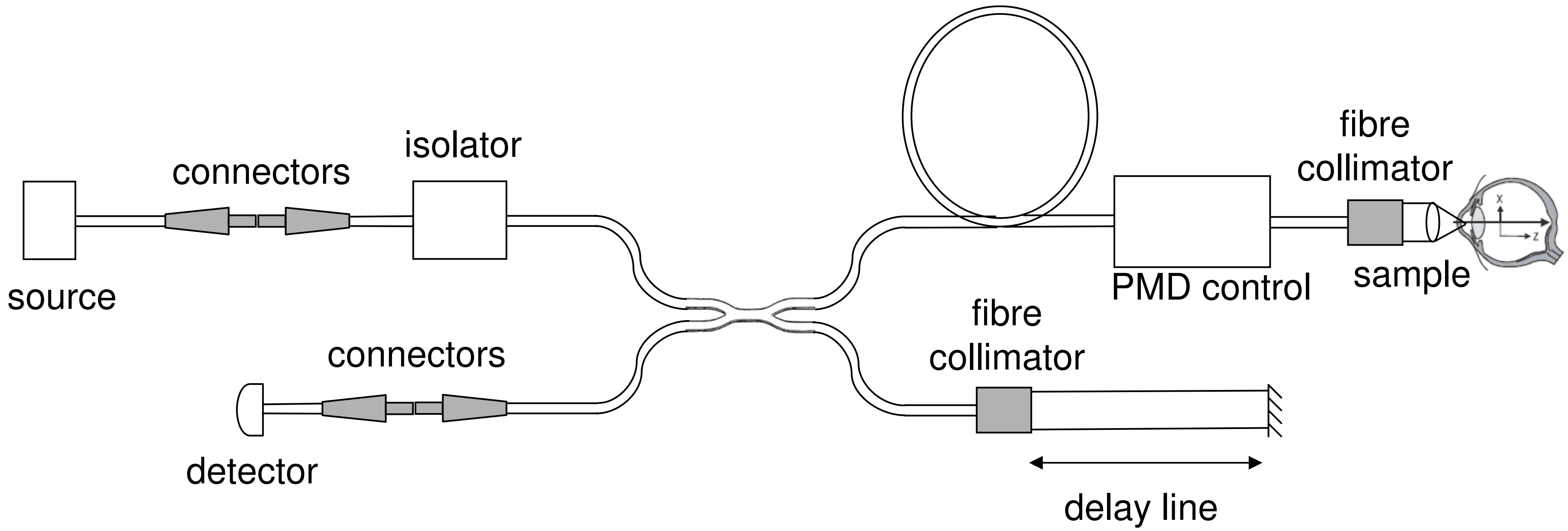
Mach Zehnder



Michelson with balanced detector



Practical interferometer networks



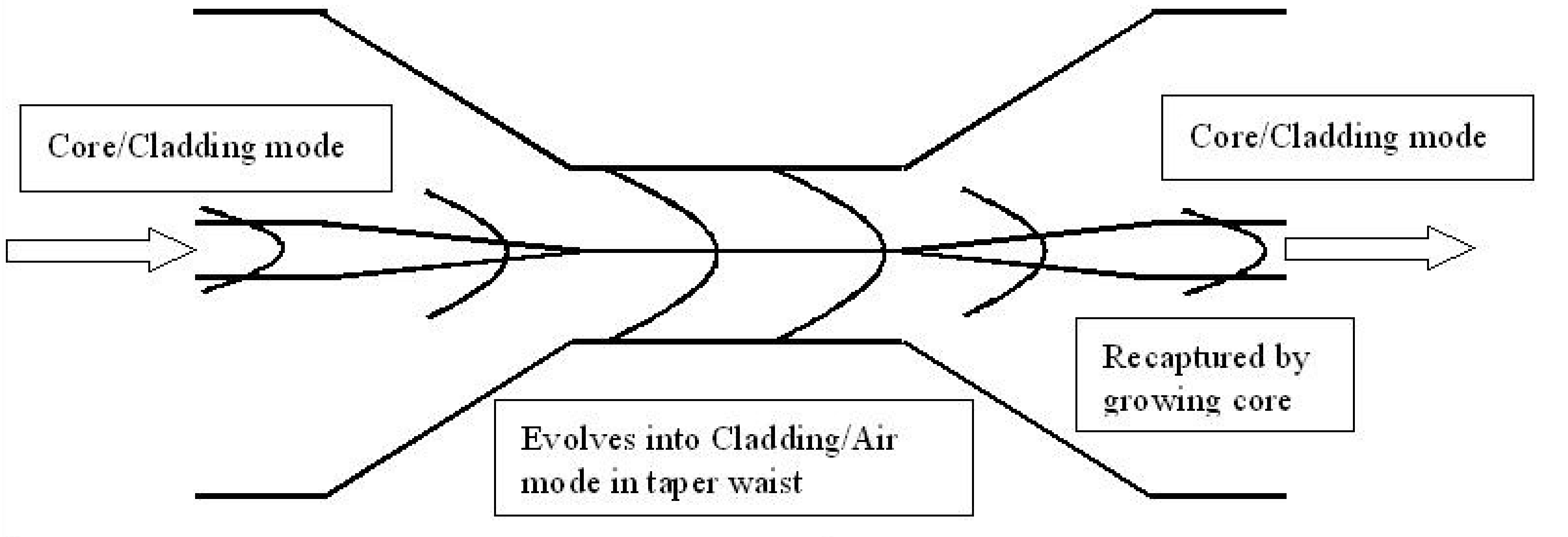
- Low loss fused couplers
- Fibre Collimators
- Connectors – loss, cost (if faces AR coated, gold standard)
- Sources
- Isolator – loss, cost (840nm), added PMD
- PMD controller – cost, complexity

Why use fibre system

- ✓ Fibre packaging convenient (routing fibre around system)
  - ✓ Free space system would be too large
- ✓ Small aperture of fibre core offers convenient con-focal design
- ✓ No alignment issues
- ✓ Flexibility and ruggedness
- ✓ Ability to leverage telecoms component pricing
- ✗ Need to balance material dispersion
- ✗ PMD can be a problem
- ✗ Not all components at all non-telco wavelengths cost effective
  - ✗ e.g. 840nm isolator

Fused bi-conical taper

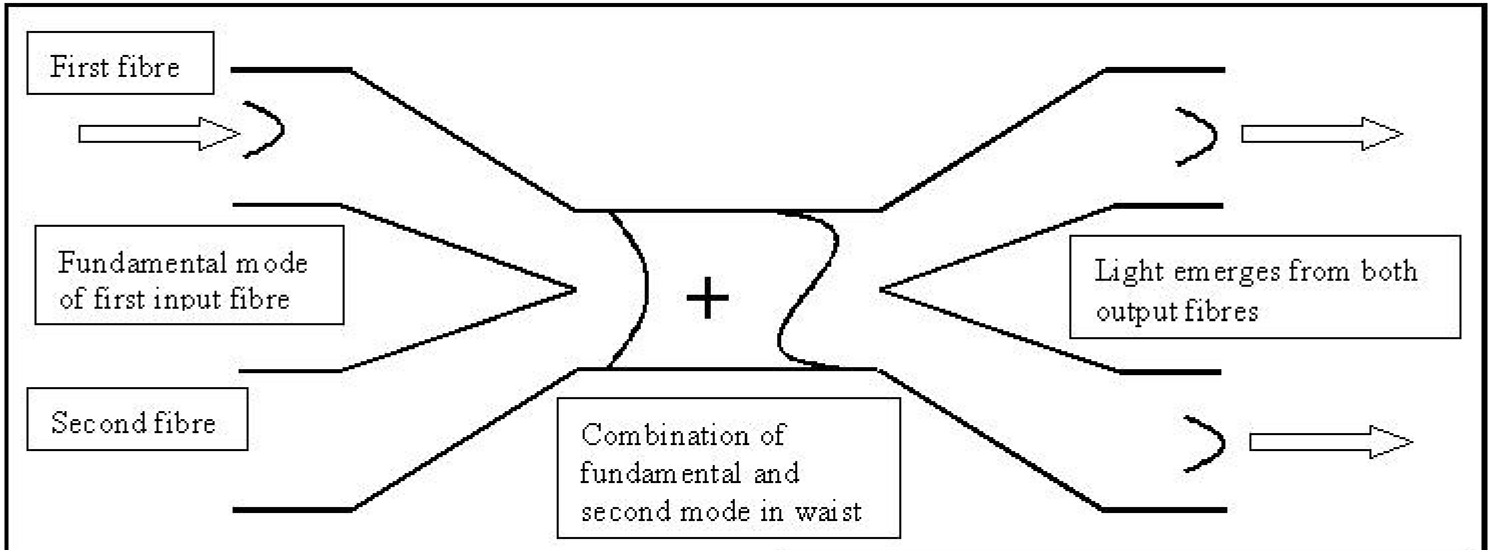
- Fibre is heated and drawn creating “down-taper” and “up-taper” as well as narrow waist region
- As core size decreases its effect on light guidance decreases
- Fundamental mode spreads out from core extending further into cladding
- If process continued, the mode spreads further out and light guided by cladding-air boundary only (core plays no role)



Evolution of fundamental mode in tapered fibre

Fused Couplers

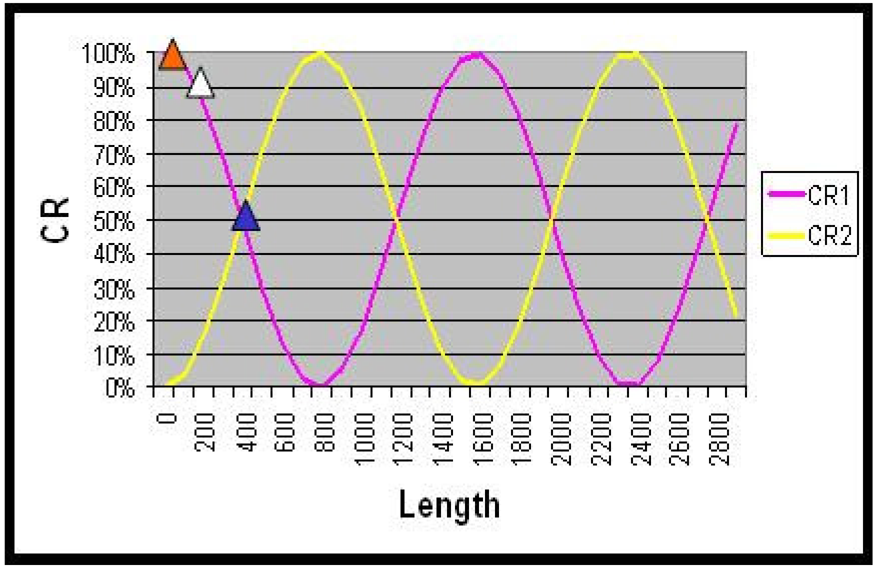
- Two fibres must be treated as composite waveguide, light exiting core in "down-taper" leaks from one waist to another, exciting 1st and 2nd order mode
- 1st and 2nd order modes have different propagation constants and acquire phase difference in taper waist
- Interference between these two modes can produce a complete transfer of power between fibres
- Power transfer between fibres dependent on taper length, waist size and taper steepness



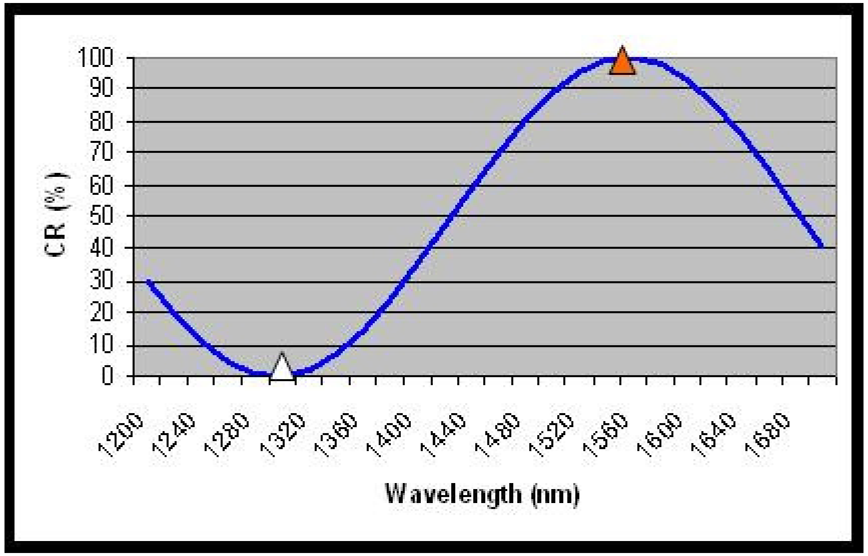
Excitation of modes in fused tapered coupler

Gooch & Housego

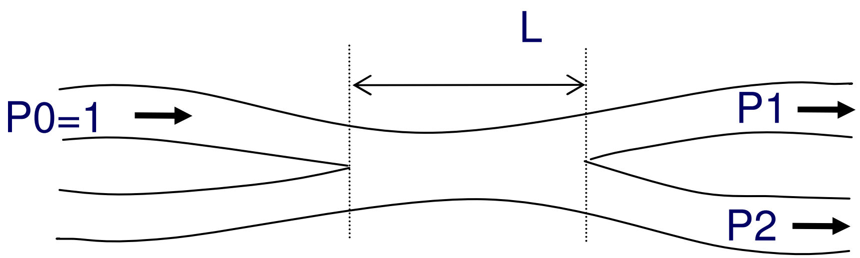
Sinusoidal Response of Fused Couplers



Tap coupler and splitter – amplitude response



WDM – wavelength response



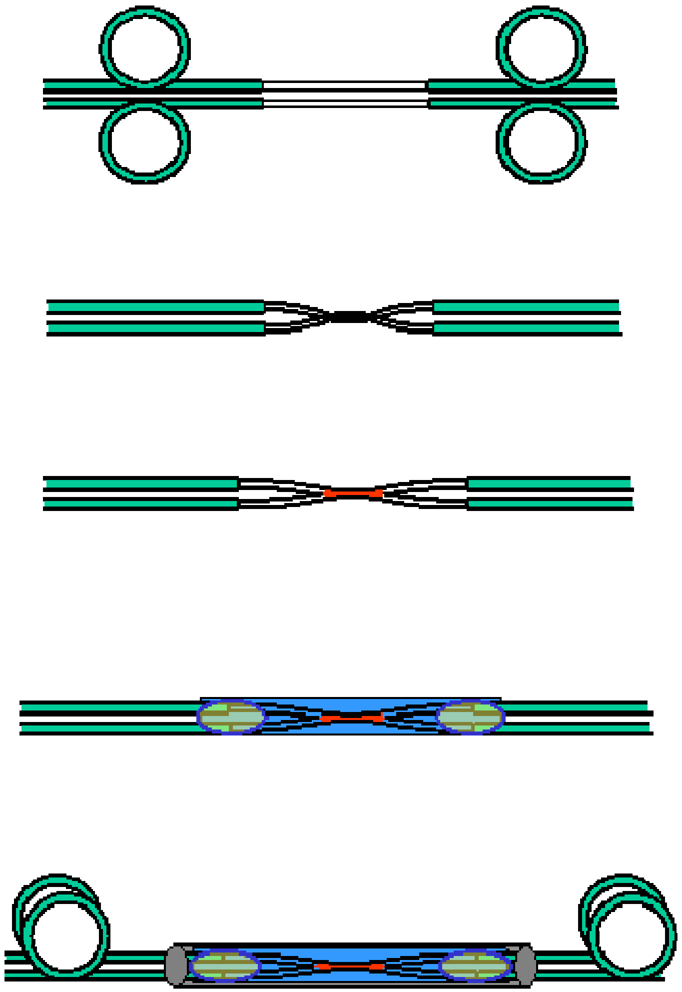
$$\begin{pmatrix} A_1(L) \\ A_2(L) \end{pmatrix} = \begin{pmatrix} \cos(CL) & i\sin(CL) \\ i\sin(CL) & \cos(CL) \end{pmatrix} \begin{pmatrix} A_1(0) \\ A_2(0) \end{pmatrix}$$

P1 = $\cos^2$[C L]

P2 = $\sin^2$[C L]

Coupling Ratio
(P1/[P1+P2]) x 100%
(P2/[P1+P2]) x 100%

Fused coupler manufacture



Strip
    Primary fiber coating removed

Fuse
    Silica fibers brought into contact and heated to fuse together

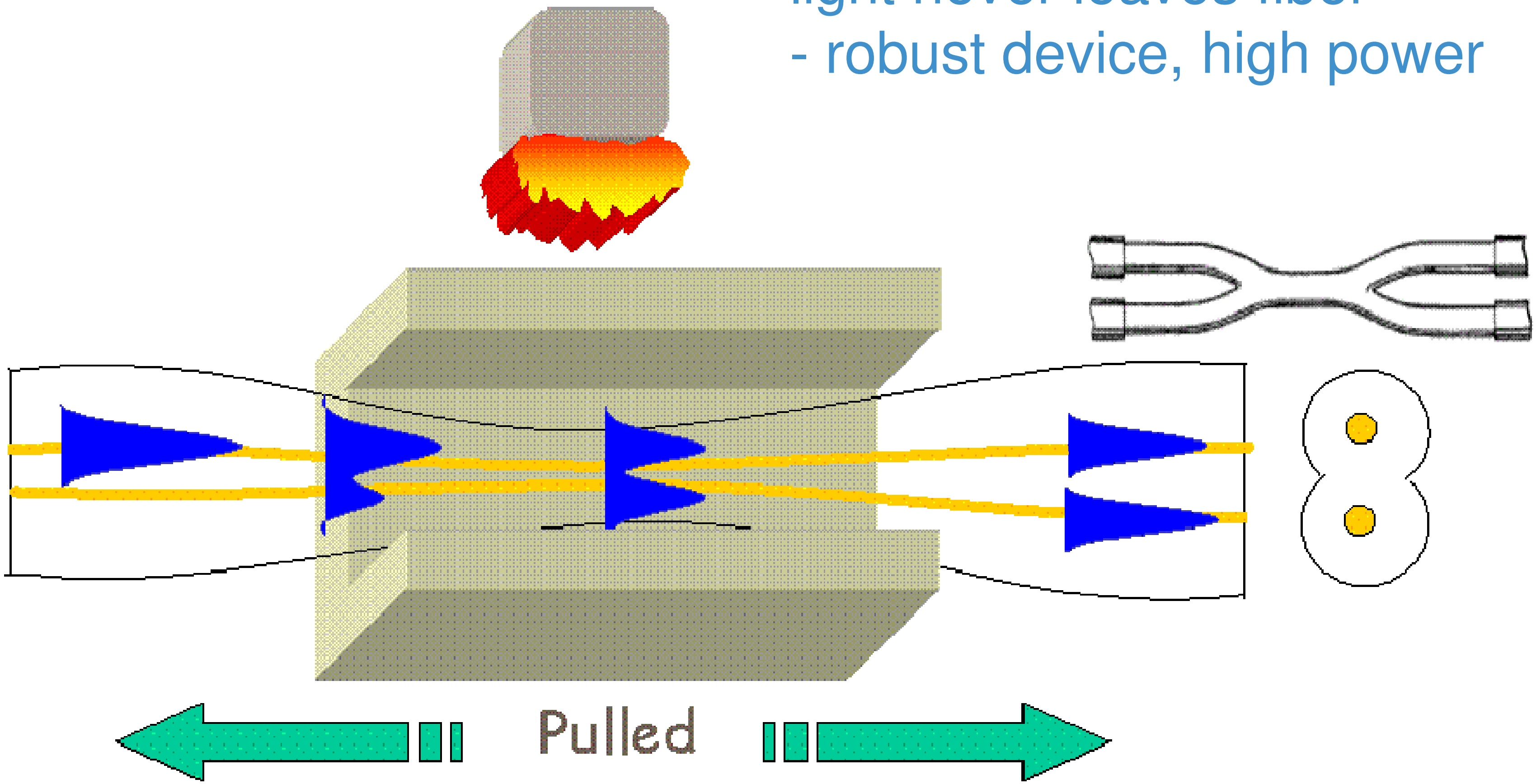
Draw
    Tension applied from both sides to form fused biconical taper (FBT)

Mount
    FBT mounted on Silica substrate

Package
    Device packaged in metal tube

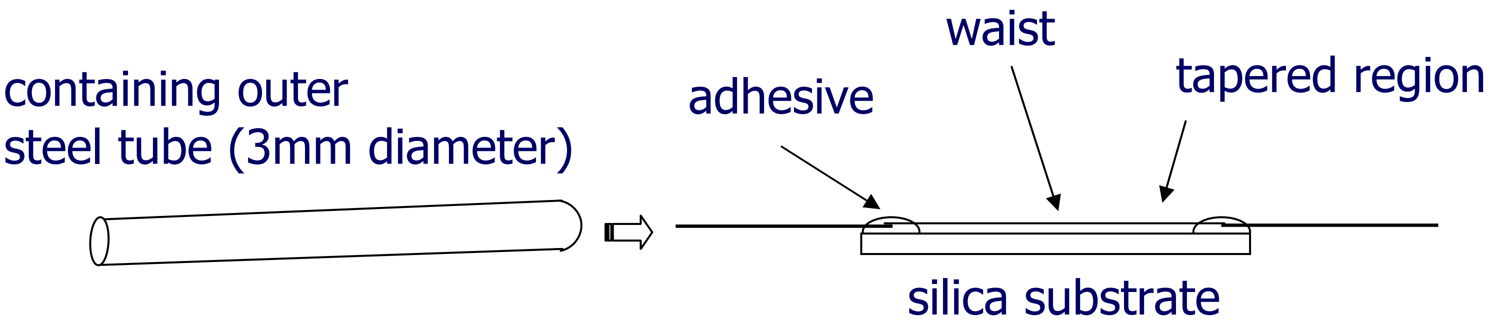
Controlled Fusion Process

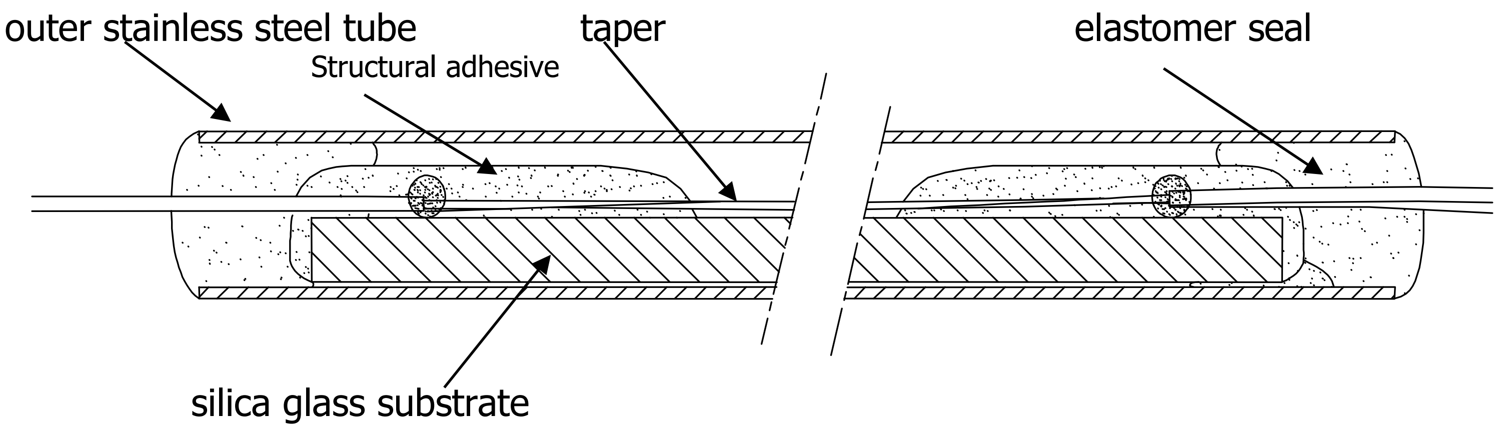
light never leaves fiber
- robust device, high power



Very accurate control of process and heating profile required for uniform low loss taper and optimum device performance

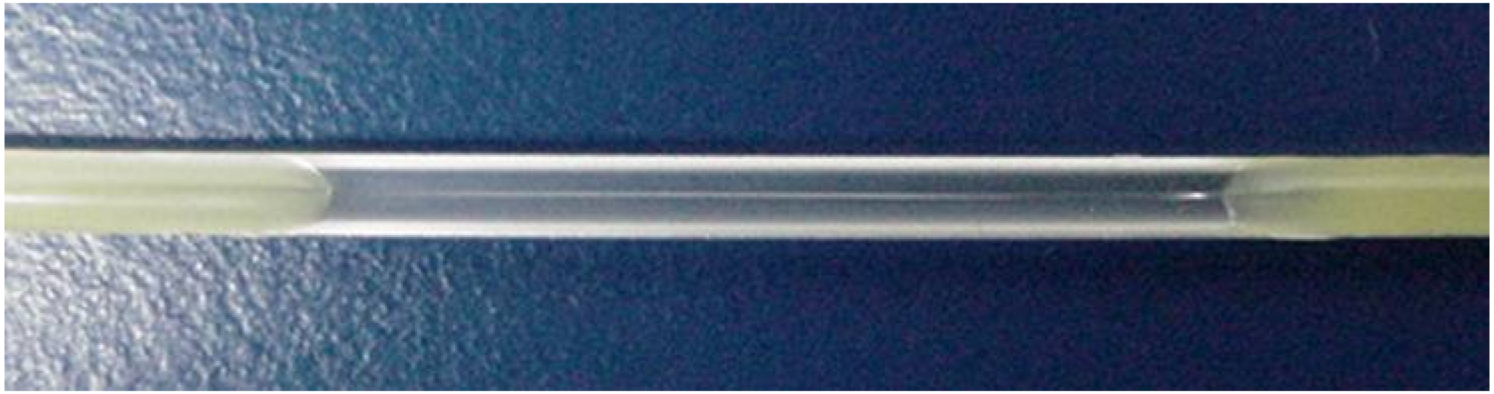
Fused taper housing

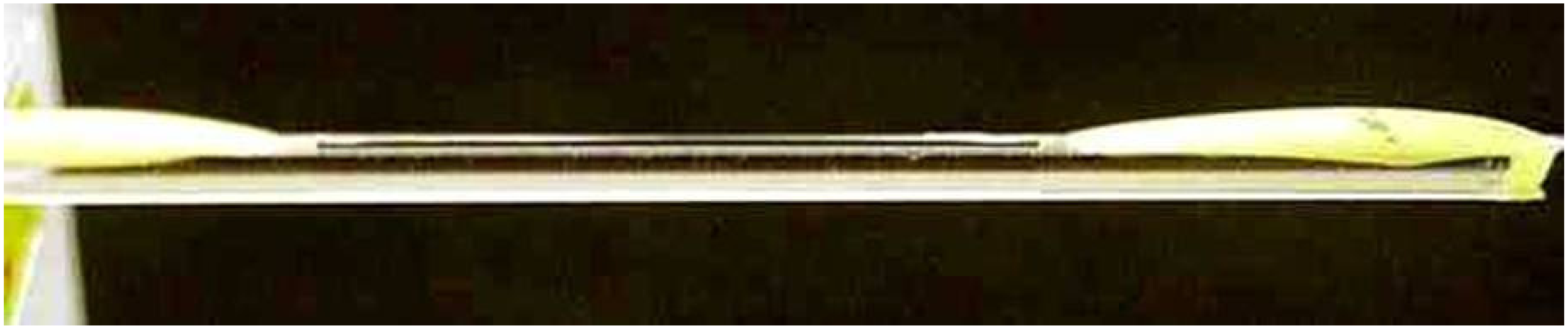




Gooch & Housego

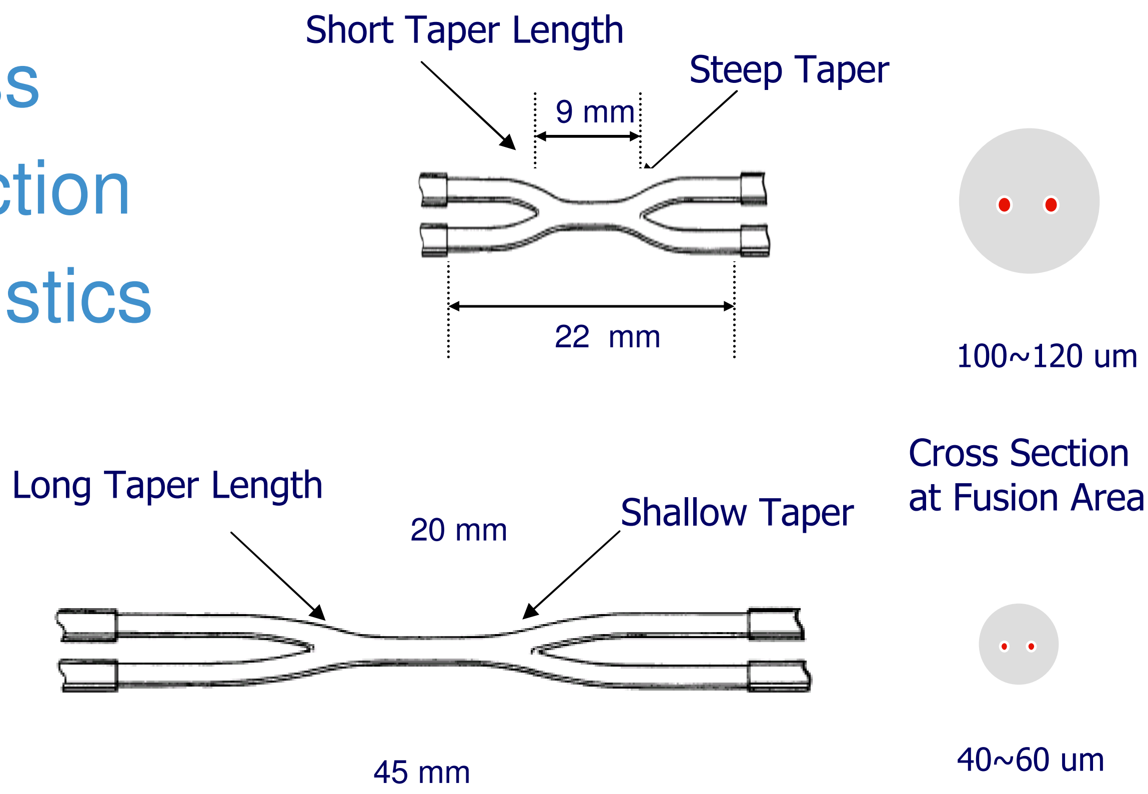
Taper region images





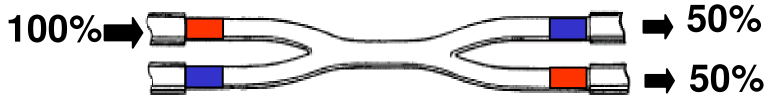
Taper design options

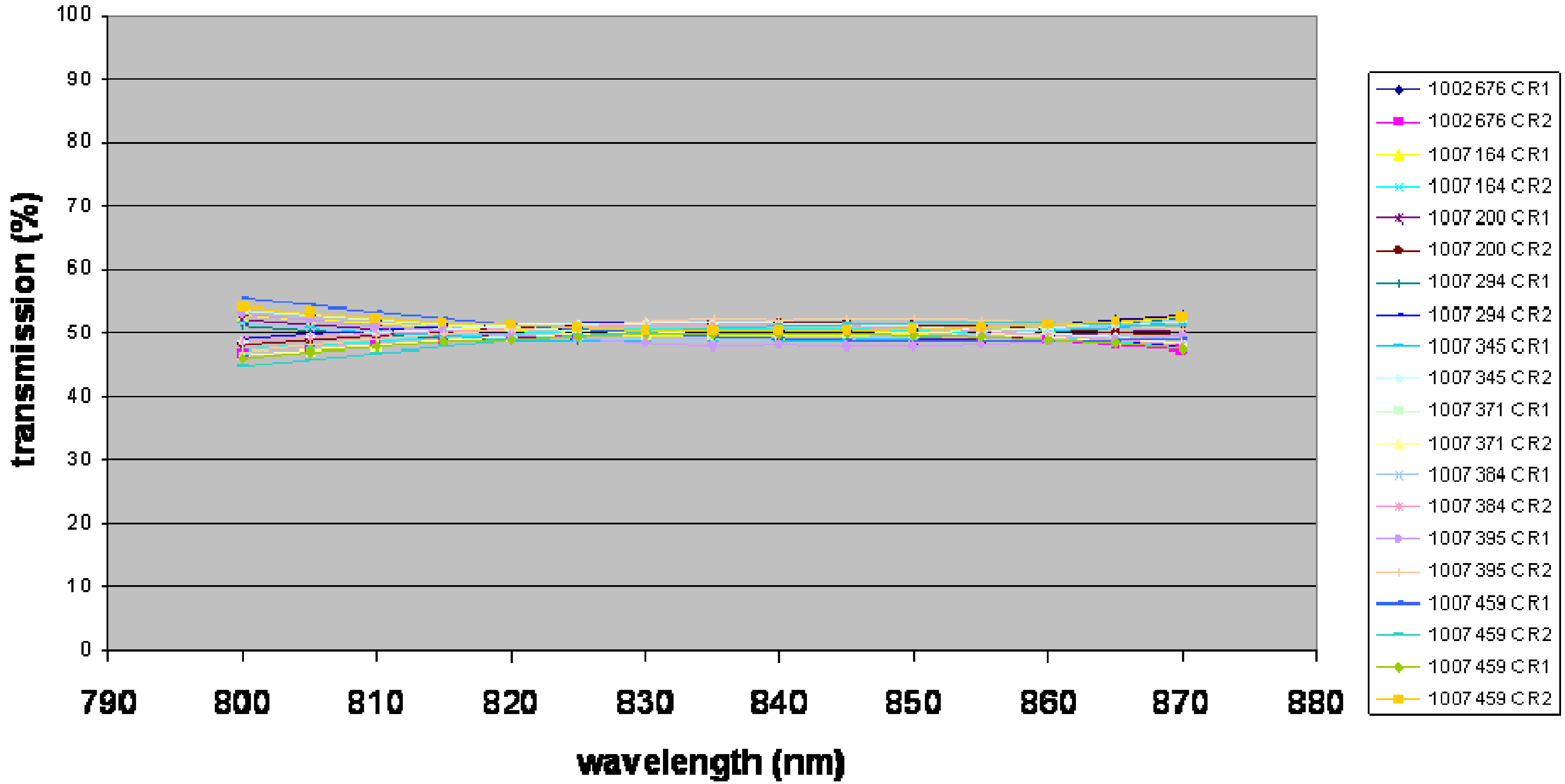
- Optical characteristics governed by
  - Taper length
  - Taper steepness
  - Waist cross-section
  - Fibre characteristics



Performance in 800nm region (retina)

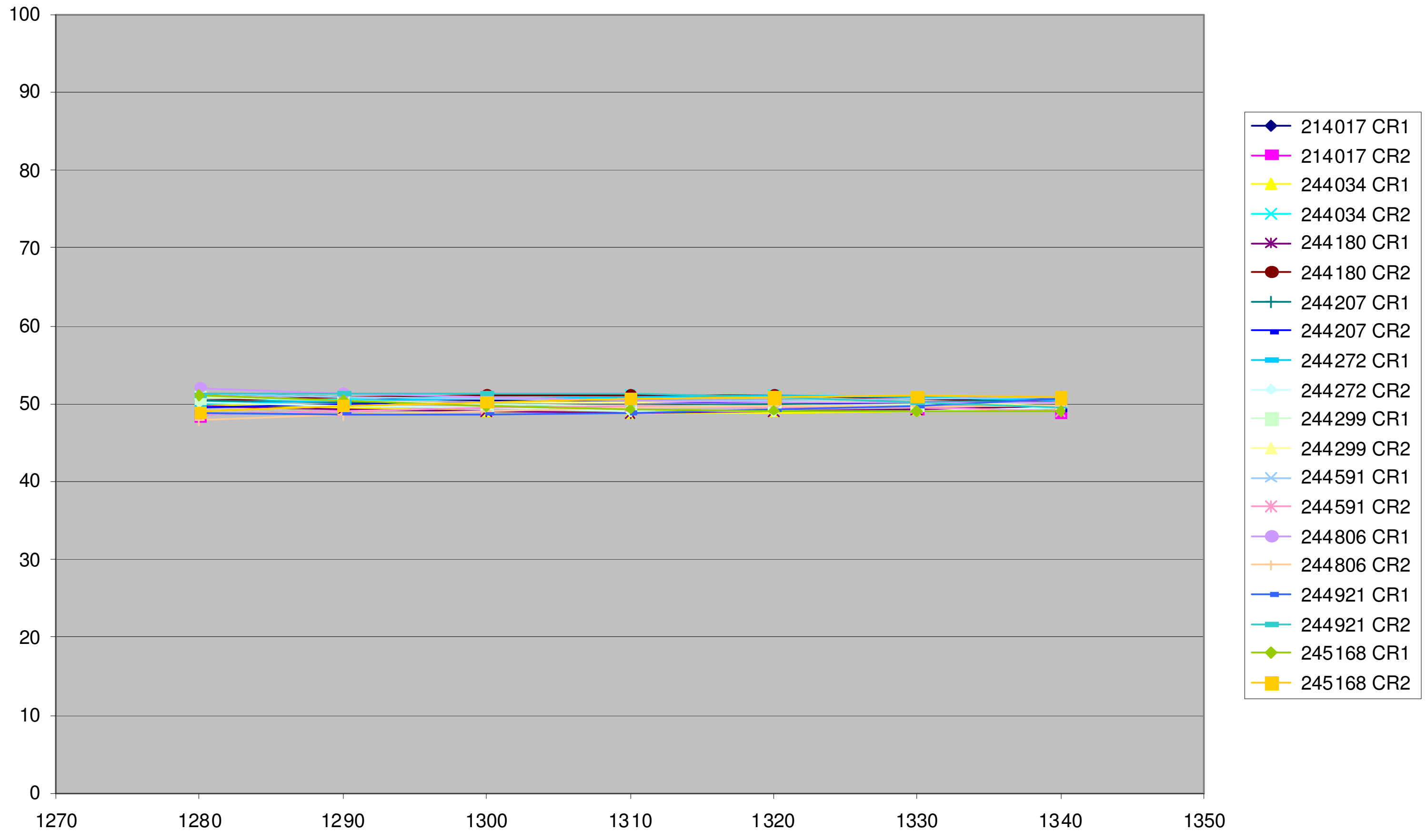
- 50:50 coupler performance
  - 10 devices centred at 835nm





Performance in 1300nm region (cornea)

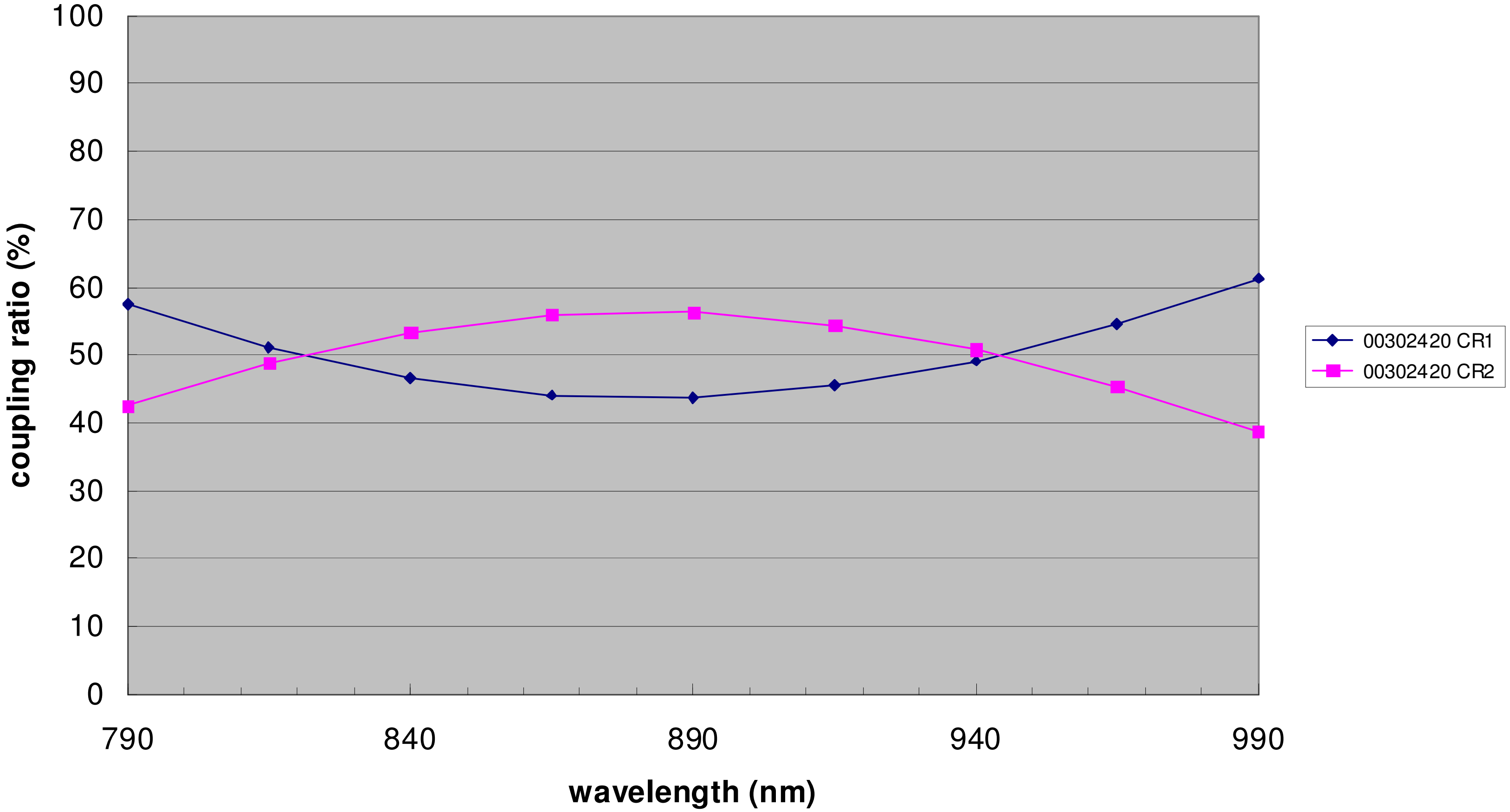
- 50:50 coupler performance
  - 10 devices centred at 1310nm



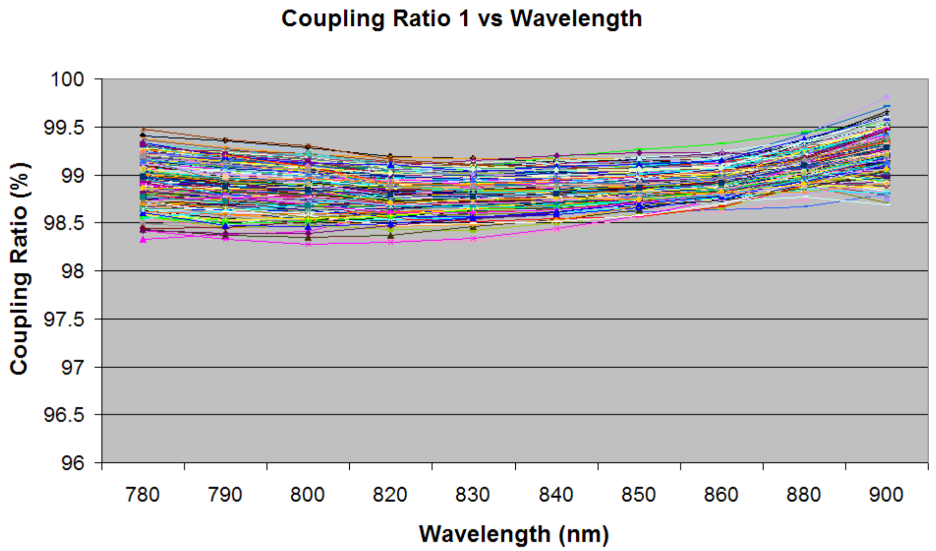
Gooch & Housego

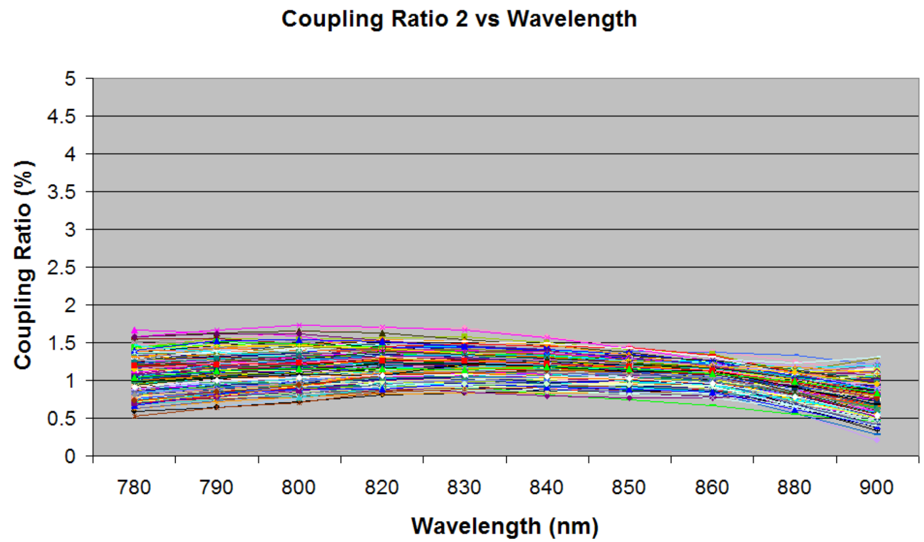
Superflat performance (200nm)

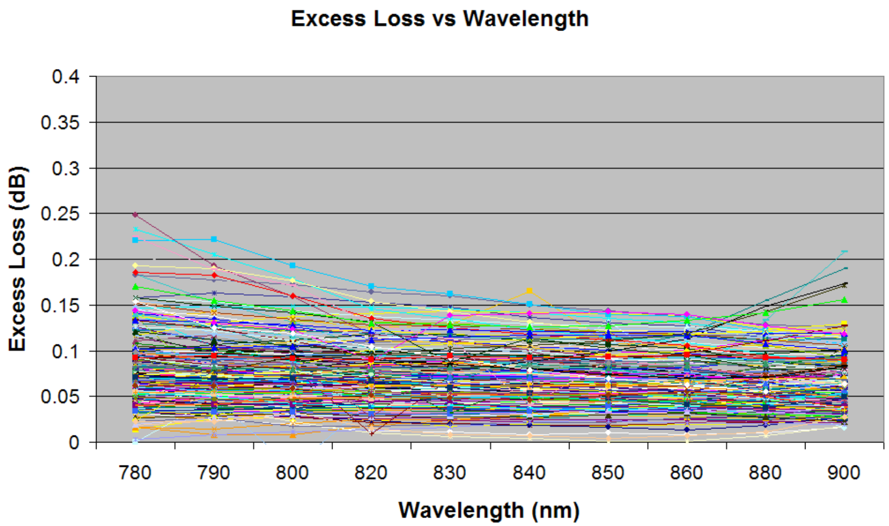
- 50:50 Superflat coupler performance
  - 200nm bandwidth, 50%±10%



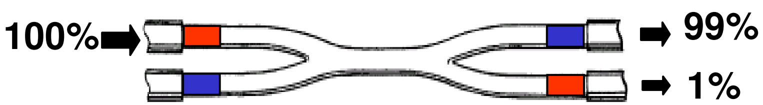
Volume 800nm OCT Couplers (1% Tap)





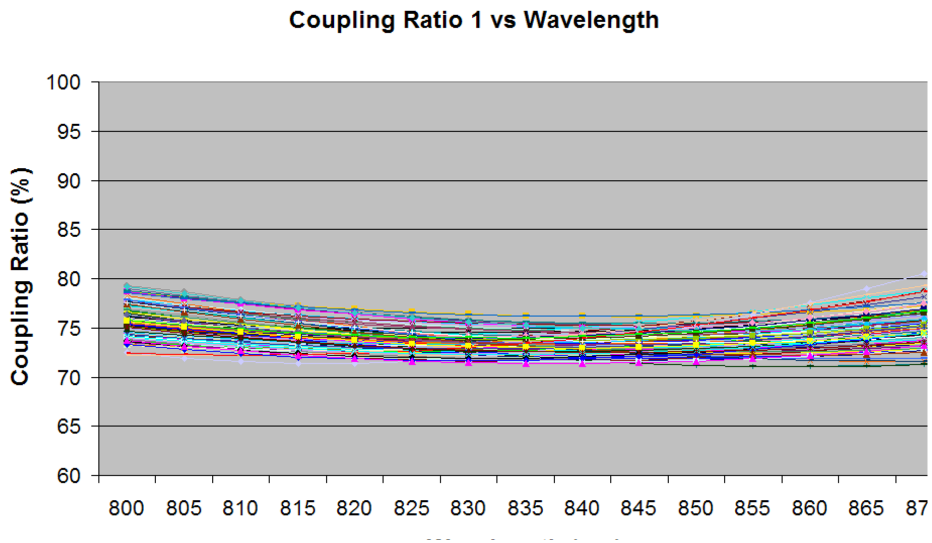


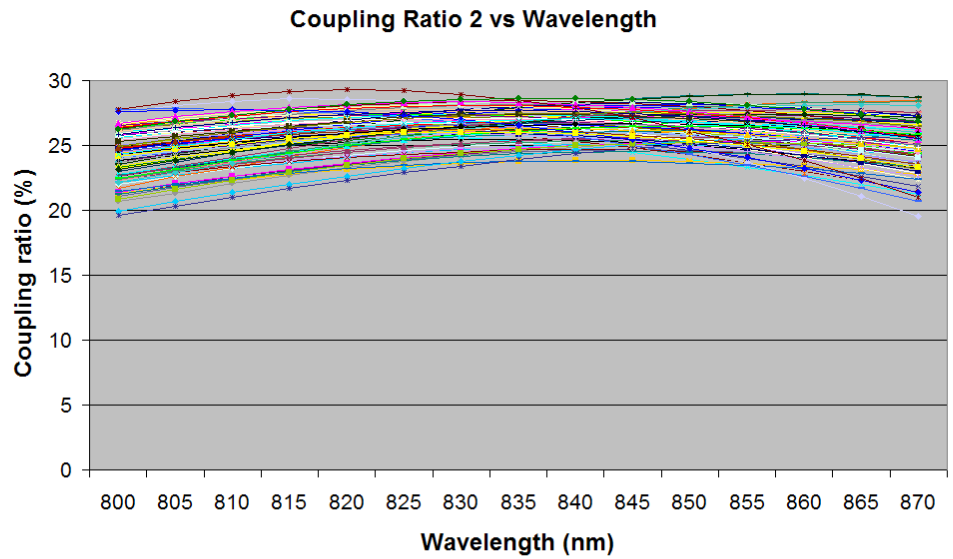
- 99/1 Coupler
  - Centred at 840nm
  - Max WDL +/-0.5% over 80nm
  - 6000 manufactured to date
  - Excess Loss <0.25dB

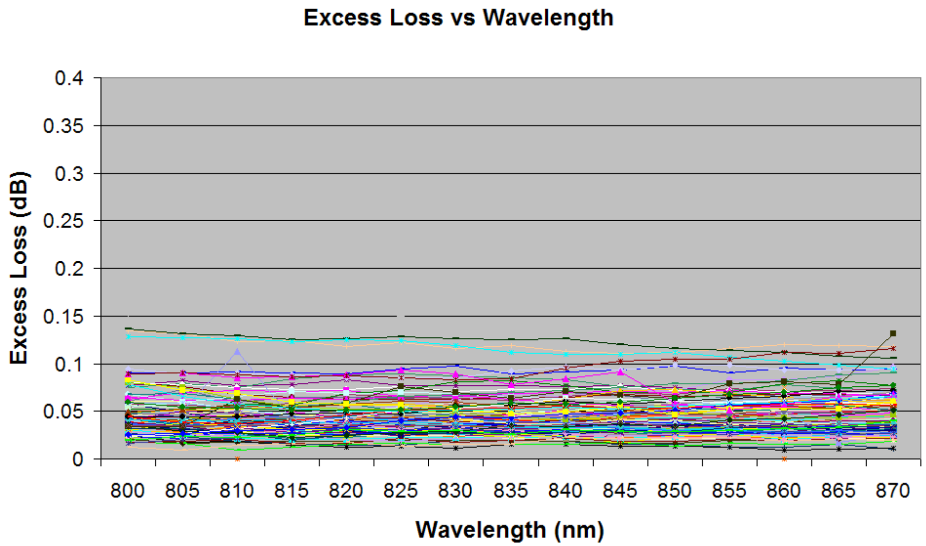


Gooch & Housego

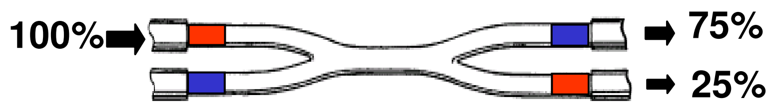
Volume 800nm OCT Couplers (25% Tap)



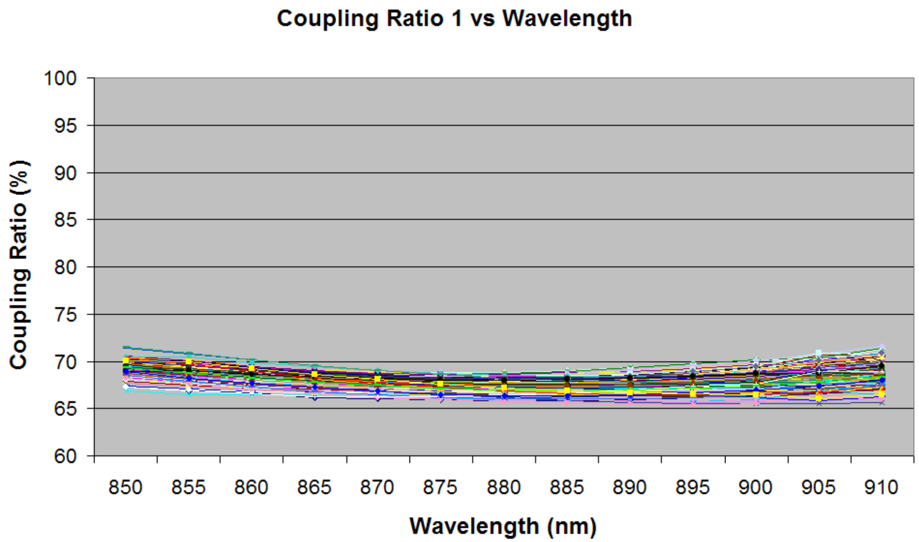


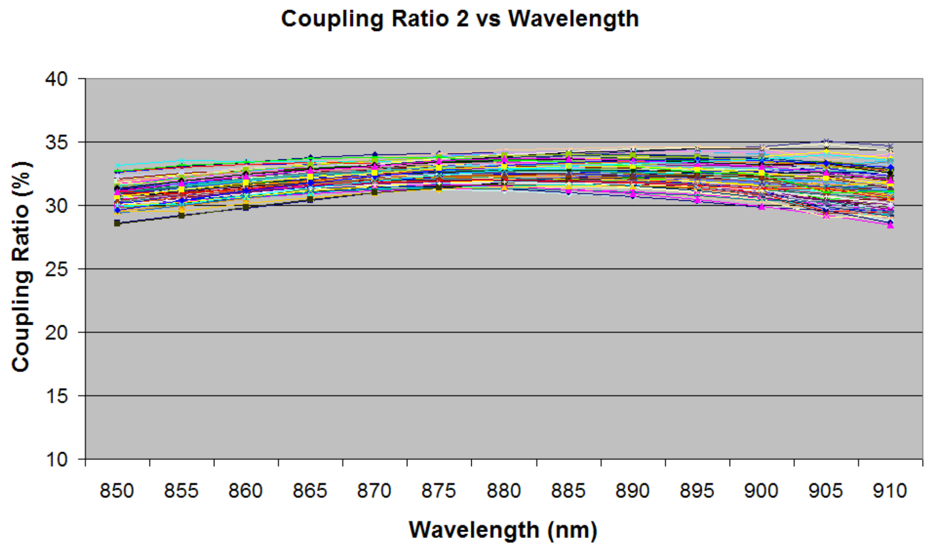


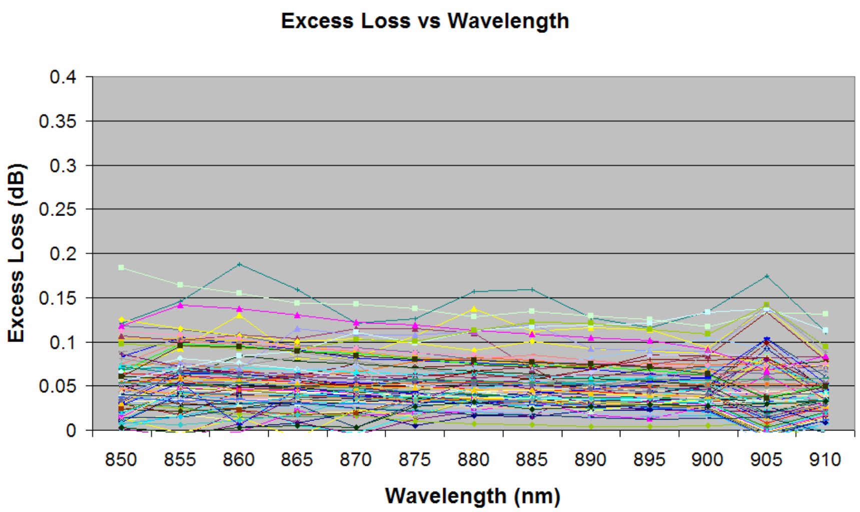
- 75/25 Coupler
  - Centred at 830nm
  - Max WDL +/-5% over 70nm
  - ~2000 manufactured to date
  - Excess Loss <0.15dB



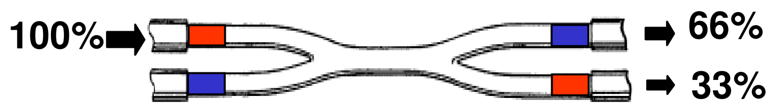
Volume 800nm OCT Couplers (33% Tap)







- 67/33 Coupler
  - Centred at 830nm
  - Max WDL +/-5% over 60nm
  - ~500 manufactured to date
  - Excess Loss <0.20dB



G&H Fused Coupler Advantage

- Manufacturing fused components since 1985.
- Proprietary fusion process ensures lowest loss achievable.
- Precise control of manufacturing parameters ensures repeatable manufacture.
- Over 1,000,000 fused components shipped.
- Standard component FIT rate of 1 (1 failure in 10^9 hours) with supporting data available.
- Widest range of fused components available from any manufacturer (fibres, wavelengths, SM, MM, PM)

Reliability

- Regular Telcordia qualification
- Harsh Environment testing
  – Military & avionic requirements
- Customer specific testing programmes
  – Sub-marine cable customers
  – Avionic gyroscope customers (800nm & 1300nm)
  – Satellite customers
  – Military customers

OCT Fused coupler summary

- Manufactured ~ 30000 components in the for OCT use over 10 years.
- Variety of fibres
  - Corning, OFS FITEL, Nufern
- Not one single returned device failure
- 50%, 30%, 25%, 10%, 1% coupling ratios
- Flat response over 50nm, 100nm, and “superflat” 200nm demonstrated

Fibre Collimators

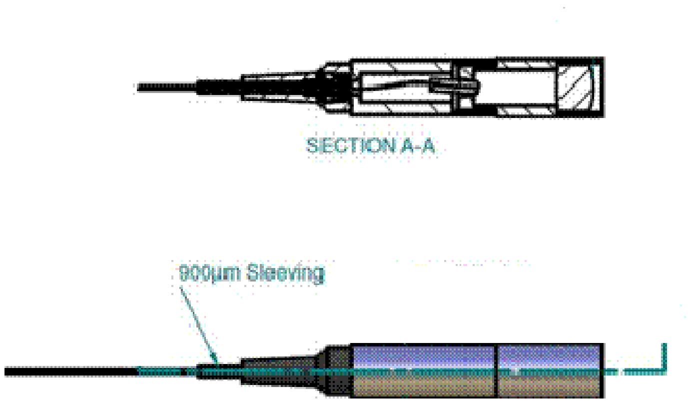
- Collimators may be used at several critical points
- Main decision is whether to attach collimator directly to end of fibre or use free space or recepticalized collimator
- Free space option increases manufacturing variability and risk of contamination of fibre end during manufacture/servicing
- Direct attach collimator eliminates contamination problem and reduces performance variability

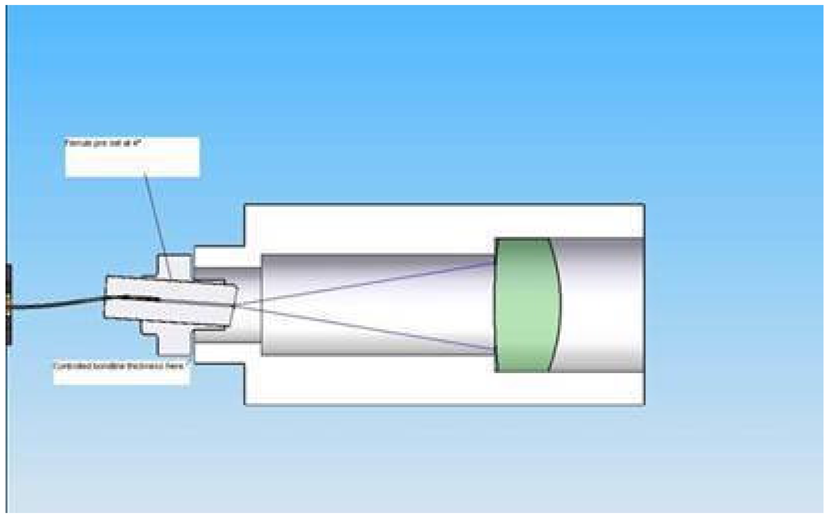
recepticalized collimator

Direct attach collimator

Direct attach fibre collimators

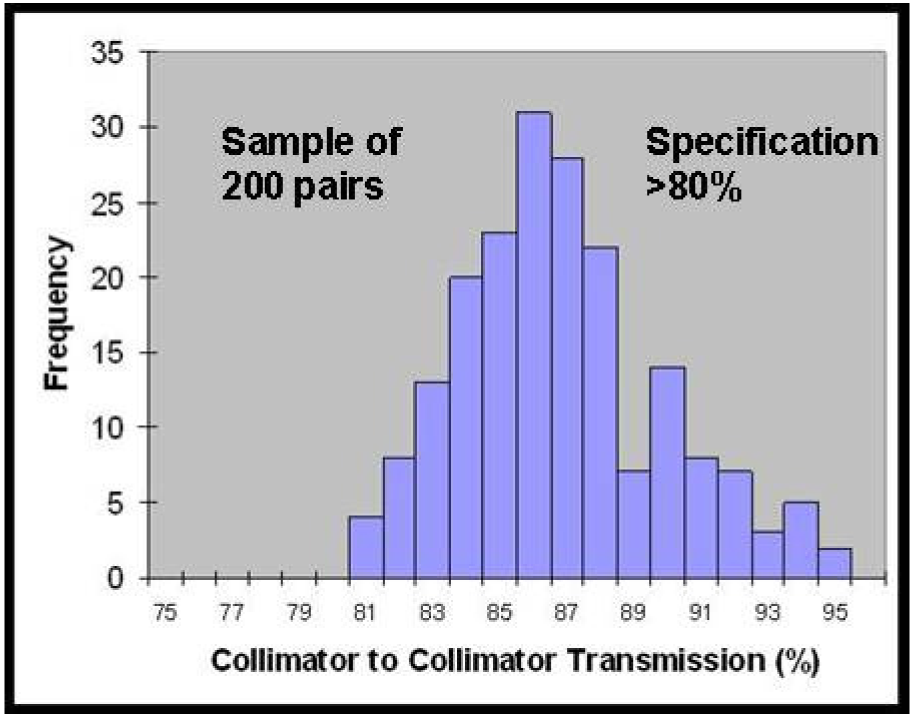
- Key parameters
  - Beam centring specification
  - Beam movement over temperature
  - Collimator to collimator insertion loss (if design requires this)
  - Back reflection
  - Elipticity

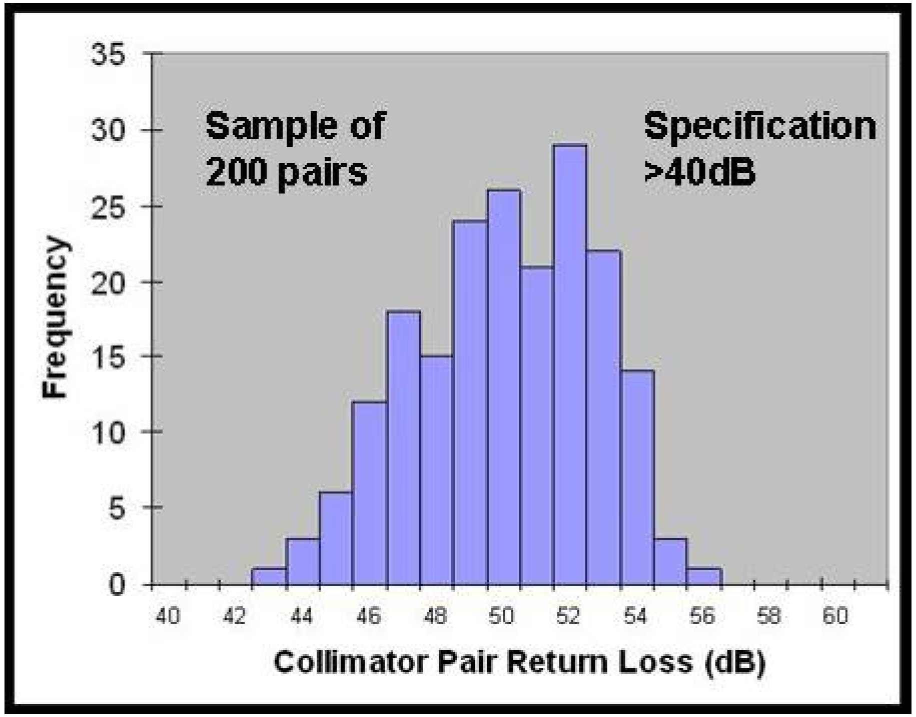




Collimator Transmission & Return Loss

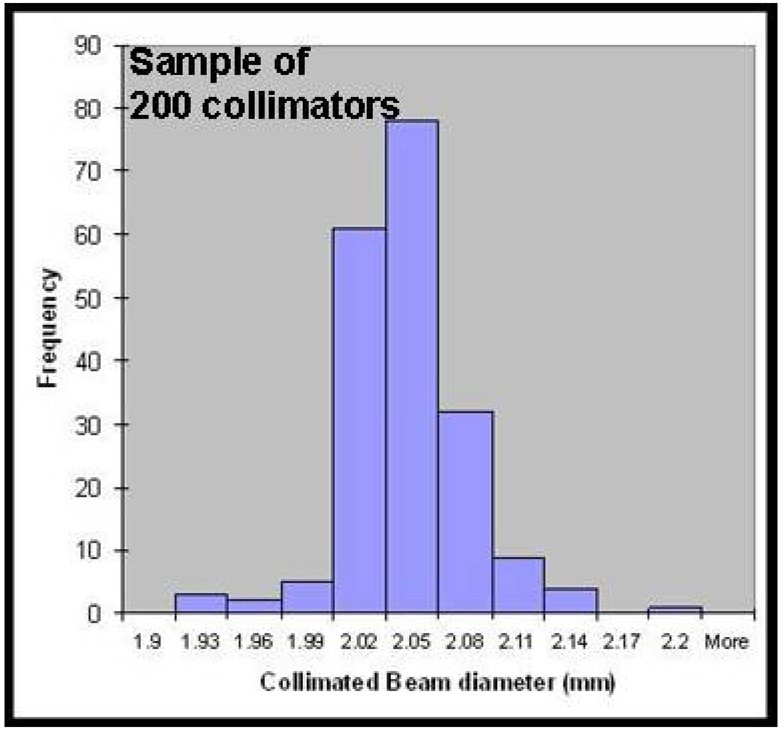
- Histogram data from sample of 200 collimator pairs
  - Collimator to collimator transmission
  - Return loss from collimator pair (including connectors)
- Tight distribution ensures ease of manufacture

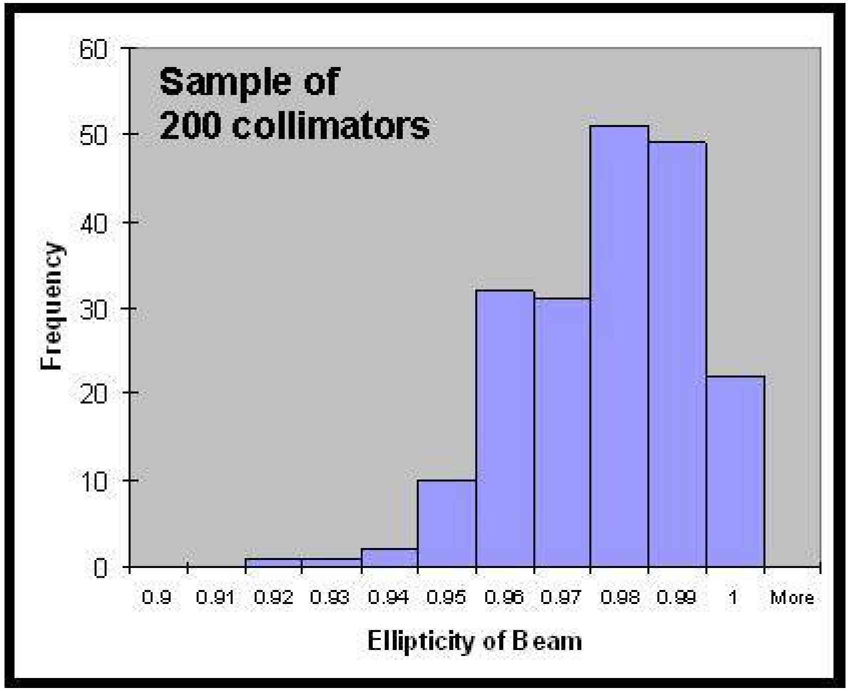




Collimator spatial characteristics

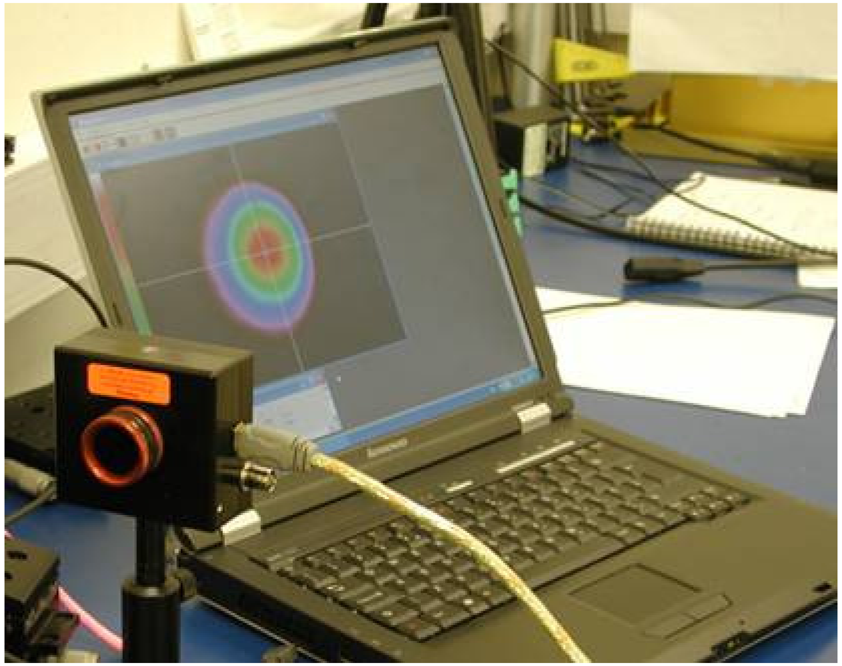
- Histogram data from sample of 200 collimators
  - Beam diameter at a given distance
  - Beam Elipticity
- Tight distribution ensures ease of manufacture

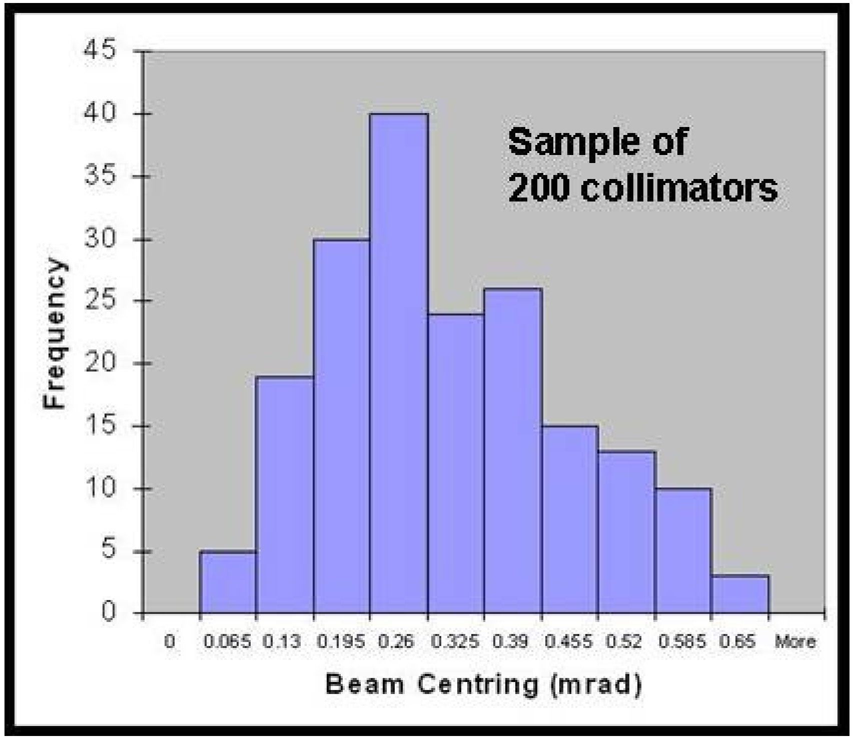




Collimator beam centering

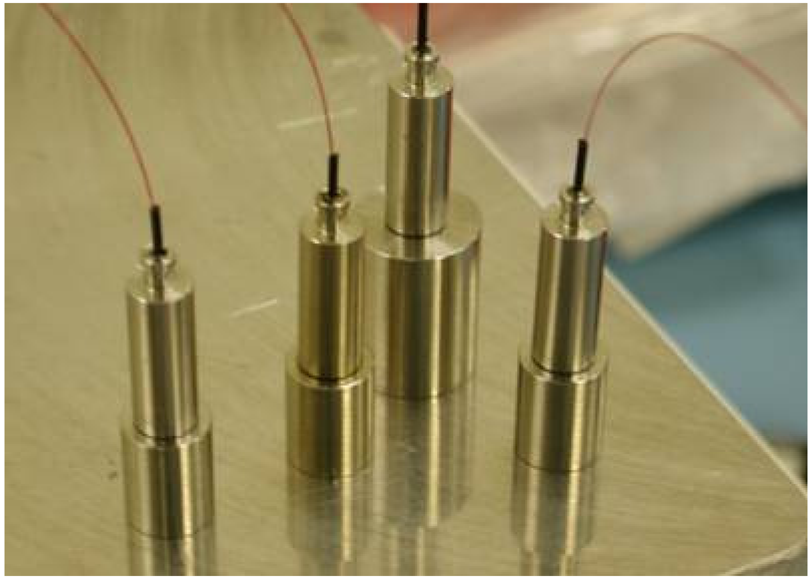
- Critical for fibre to fibre requirements
- Critical when the beam exiting fibre must pass through a number of optical elements before reaching target





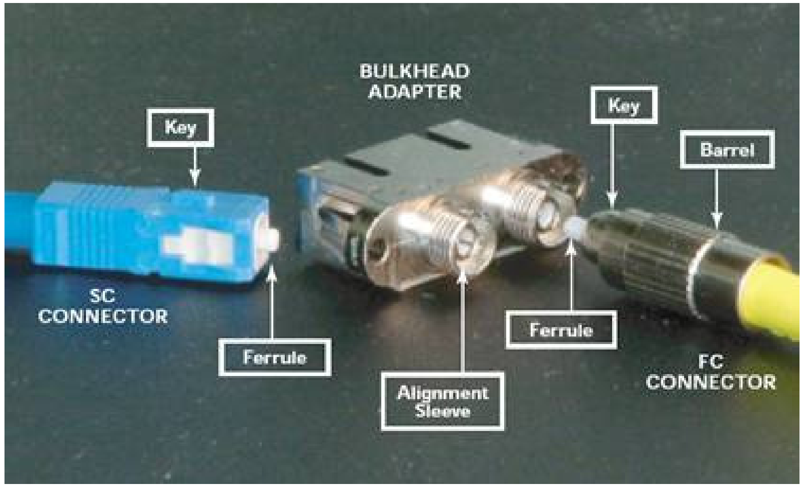
G&H Collimator Advantage

- Custom build capability ensures very tight specifications
- Precise control of manufacturing parameters ensures repeatable manufacture.
- Over 5000 fibre collimators shipped
- Hermetic and non-hermetic packages available
- High power end-capped capability

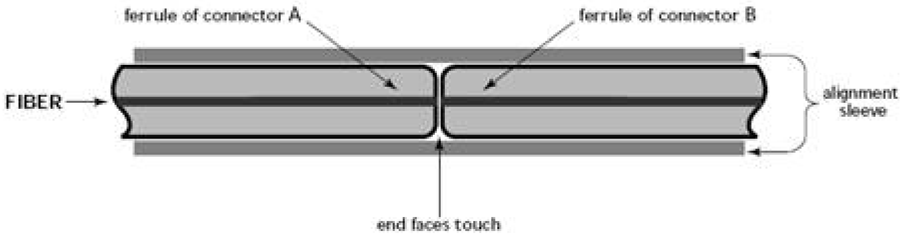


Connectors

- Offer flexibility of design
- Disadvantage is loss and repeatability of performance
- Many different types!
  - FC, DIN, ST, SMA
    - Bayonet or screw type
  - LC, E-2000, MU, SC
    - Push/pull

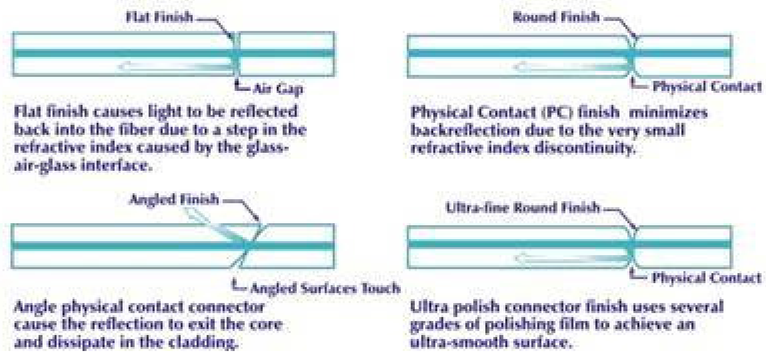


- Most are Physical Contact (PC) type
  - Physical contact between two end faces when connected
  - Ferrules and sleeves used to maintain accurate alignment



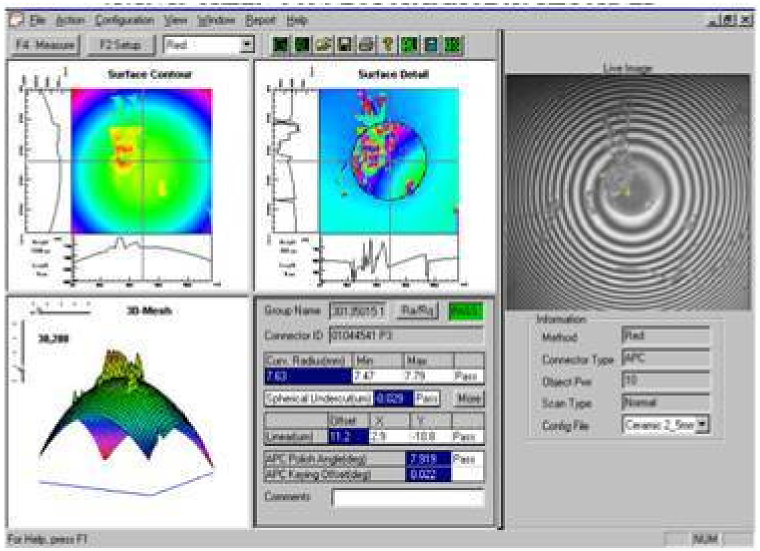
Connector performance

- Insertion Loss
  - Poor “in field” insertion loss performance, especially in the 800nm range (small core fibre)
  - 0.4-1.5dB for 2 connectors + adapter
  - **<0.05dB for good splice!!!!!**
- Back Reflection
  - Back reflections causes instability of source
  - Back reflection from splice more than 70dB down (typically un-measurable)
- Repeatability of Insertion Loss
  - Very poor repeatability
  - Critical “in field” parameter

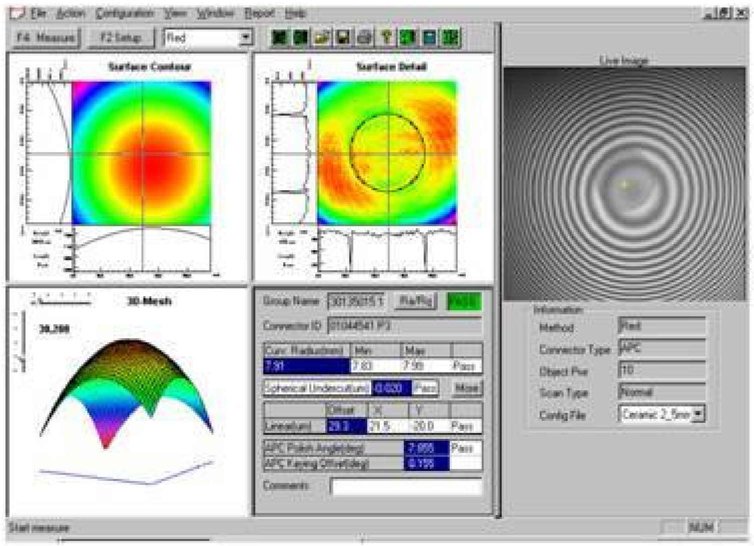


Connector “usage” problems

- Cleanliness, FOD (Foreign Object Debris)
  - Majority of module “returns” from non-telco customers related to dirty connectors
  - Dirty connectors cause direct attenuation if debris on core
  - Also lead to improper physical contact
    - Attenuation & increased return loss!!!
    - Scratching of surface



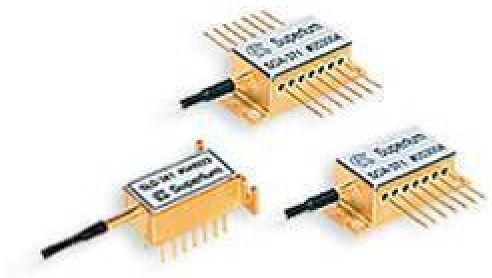
Returned module

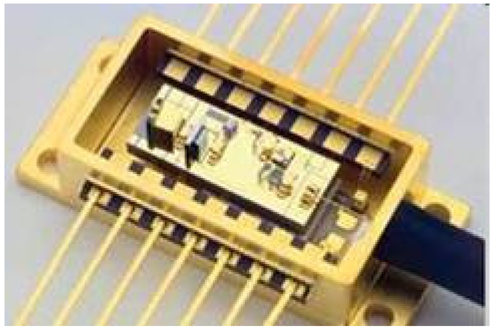


Post-cleaning

OCT Sources

- Superluminescent diodes (SLDs)
  - Reliable, standard fibre coupling techniques
  - Low cost
  - 10nm – 210nm bandwidth
  - Need spectrometer for FD-OCT
- Tunable laser/swept source
  - Does not require spectrometer
  - More complicated
  - Currently expensive – but lower cost roadmap
- Ultra-short pulse lasers
  - Very wide bandwidth (ultra high resolution)
  - Very complicated and expensive

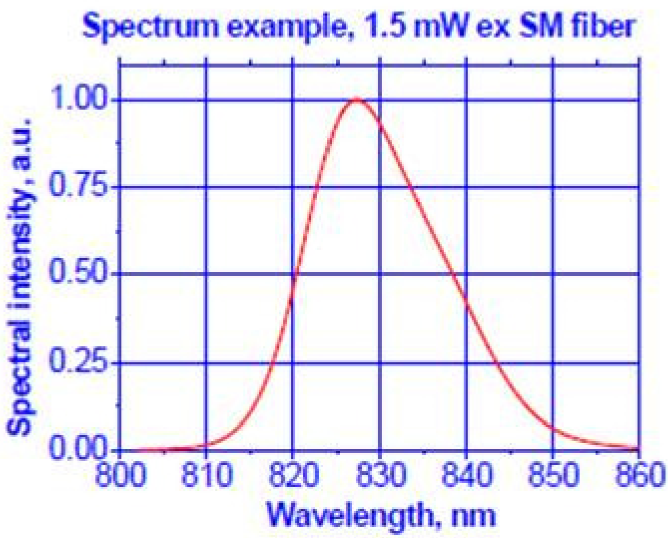




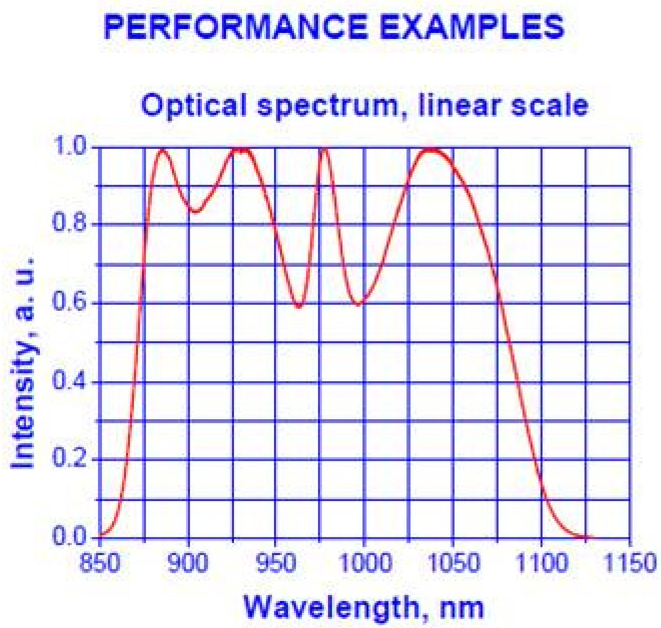
Vast majority of commercial units use SLDs

Practical SLD Sources

- Good device to device performance repeatability
- Low susceptibility to back reflections
- High power out of fibre
- Low noise



Superlum Diodes Ltd SLD-381-MP

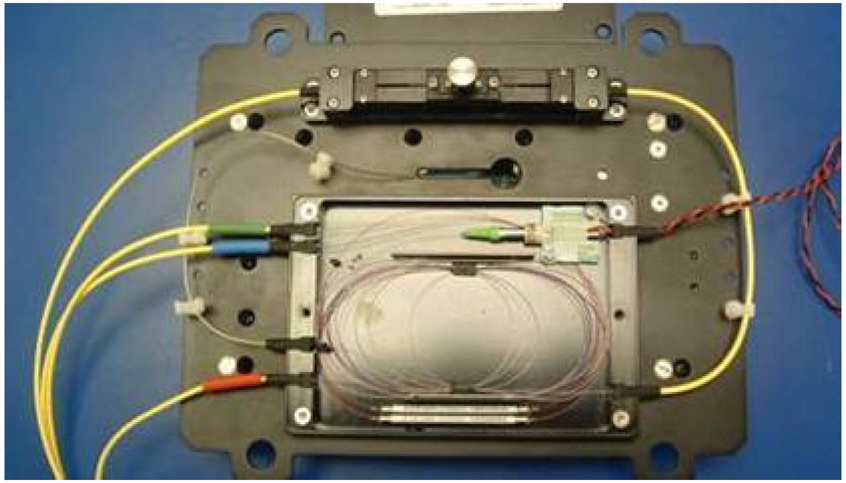


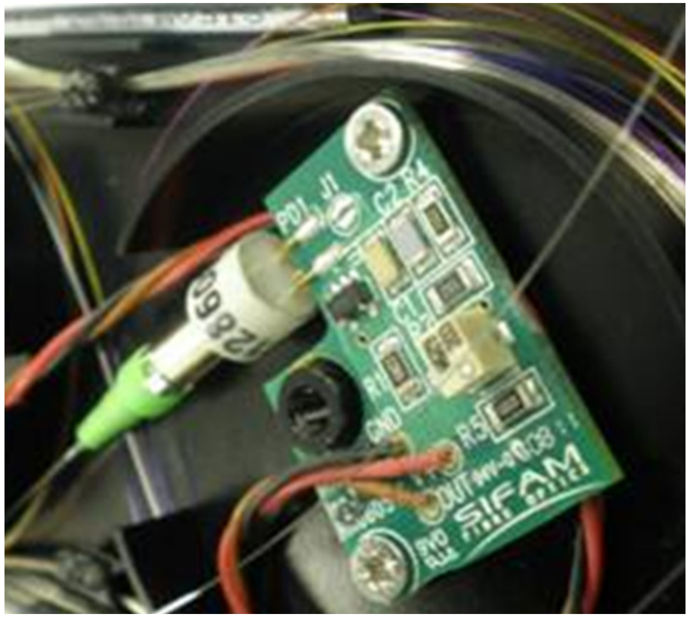
Superlum Diodes Ltd Broadlighter

Gooch & Housego

Additional fibre optic components

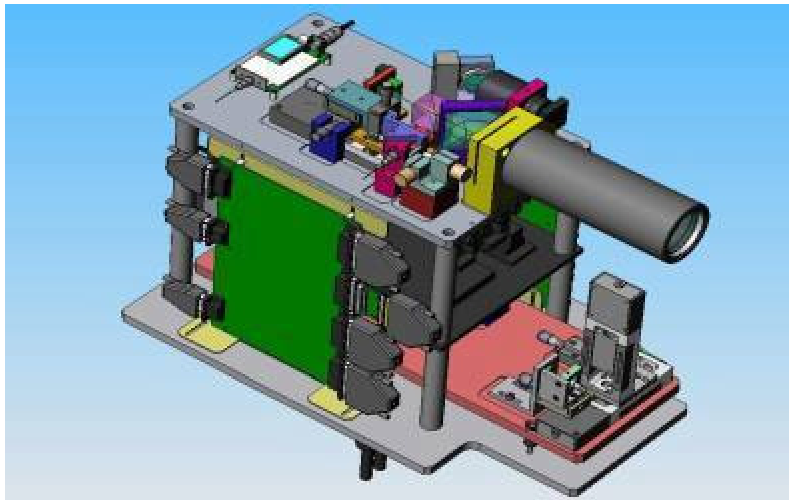
- Fibre coupled detectors
- Polarization controllers
- Variable optical attenuators



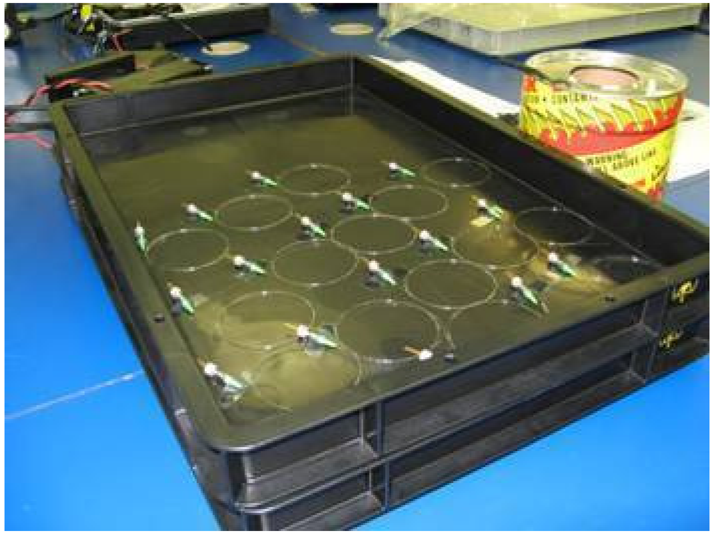


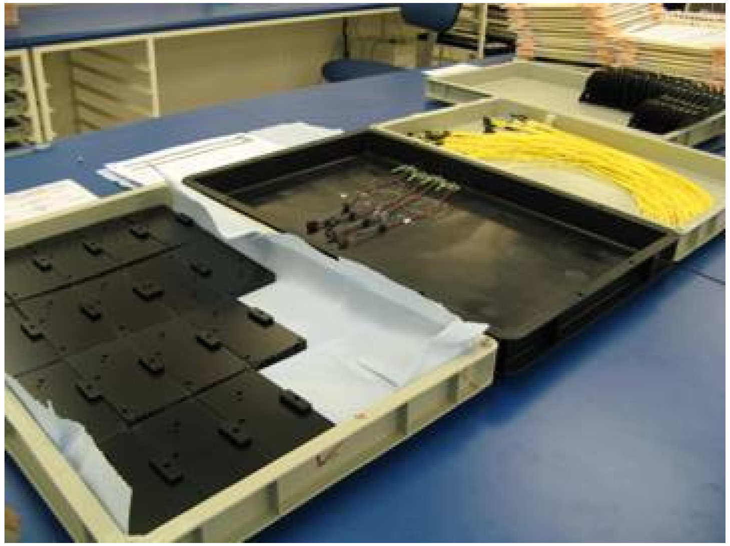
OCT Optical sub-system considerations

- Opto-mechanical design to meet footprint, fibre routing, components, PCBs
- Supply chain management of core technologies
- Extensive knowledge of passive & active components, “Intelligent Sourcing” of components
- Assembly technicians skilled in handling, routing and splicing all types of fibres & components
- Fibre and bulk optic combined (e.g. lens, prisms, filters)

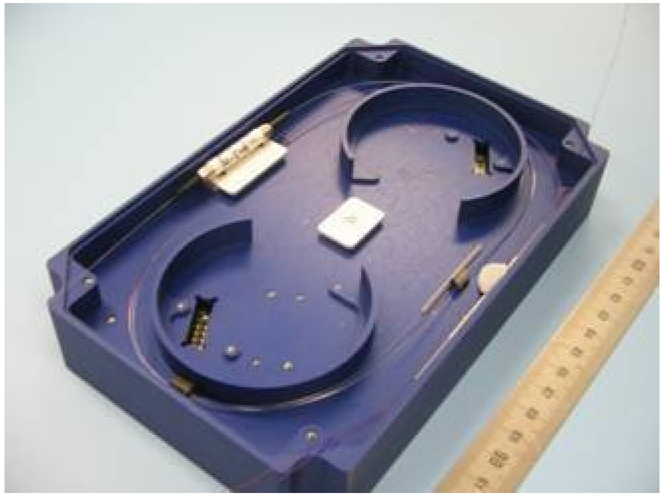


G&H Sub-assembly Facility



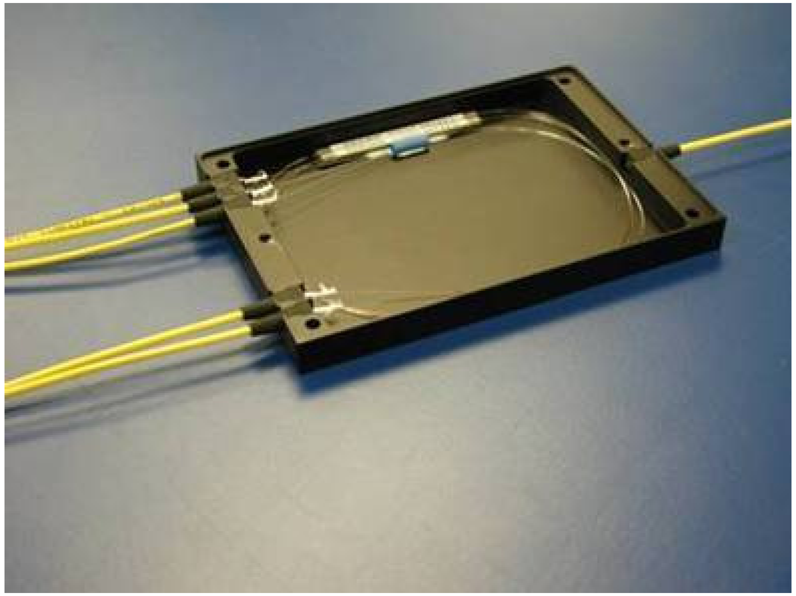


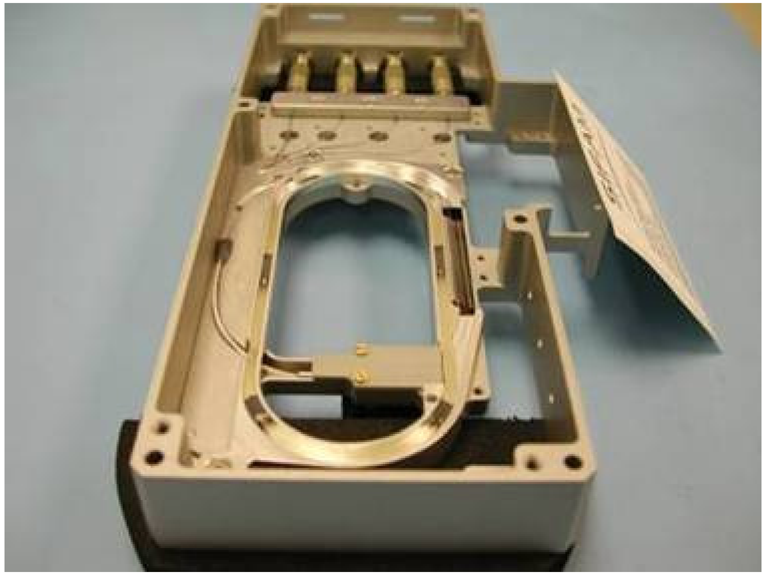
G&H Module Examples



Gooch & Housego

G&H Module Examples





Current Market

- Ophthalmology
  - Carl Zeiss Meditec
  - TOPCON
  - Optovue
  - Heidelberg Engineering
  - OPKO/OTI Canada
  - Optopol
- Other
  - Michelson Diagnostics, LightLab, Lantis Laser, Thorlabs, Volcano Corp., Bioptigen

The future

- Plurality of modalities
  – Confocal Microscopy and OCT
  – Hyperspectral imaging with OCT
- Additional wavelength bands
  – Further out into IR (2um plus)
- Wider bandwidths
  – Ultra-high resolution
- More applications
  – Material Inspection (e.g. glass)
  – Semiconductor industry