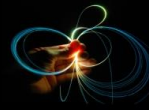




# Specialty Optical Fibres and Devices for the Internet of Things

**Gilberto Brambilla**

Optoelectronics Research Centre  
Southampton, United Kingdom



# A "smart" world

## Air Pollution

Control of CO<sub>2</sub> emissions of factories, pollution emitted by cars and toxic gases generated in farms.

## Forest Fire Detection

Monitoring of combustion gases and preemptive fire conditions to define alert zones.

## Wine Quality Enhancing

Monitoring soil moisture and trunk diameter in vineyards to control the amount of sugar in grapes and grapevine health.

## Offspring Care

Control of growing conditions of the offspring in animal farms to ensure its survival and health.

## Sportsmen Care

Vital signs monitoring in high performance centers and fields.

## Structural Health

Monitoring of vibrations and material conditions in buildings, bridges and historical monuments.

## Quality of Shipment Conditions

Monitoring of vibrations, strokes, container openings or cold chain maintenance for insurance purposes.

## Smartphones Detection

Detect iPhone and Android devices and in general any device which works with Wifi or Bluetooth interfaces.

## Perimeter Access Control

Access control to restricted areas and detection of people in non-authorized areas.

## Radiation Levels

Distributed measurement of radiation levels in nuclear power stations surroundings to generate leakage alerts.

## Electromagnetic Levels

Measurement of the energy radiated by cell stations and WiFi routers.

## Traffic Congestion

Monitoring of vehicles and pedestrian affluence to optimize driving and walking routes.

## Smart Roads

Warning messages and diversions according to climate conditions and unexpected events like accidents or traffic jams.

## Smart Lighting

Intelligent and weather adaptive lighting in street lights.

## Intelligent Shopping

Getting advices in the point of sale according to customer habits, preferences, presence of allergic components for them or expiring dates.

## Noise Urban Maps

Sound monitoring in bar areas and centric zones in real time.

## Waste Management

Detection of rubbish levels in containers to optimize the trash collection routes.

## Smart Parking

Monitoring of parking spaces availability in the city.

## Golf Courses

Selective irrigation in dry zones to reduce the water resources required in the green.

## Water Leakages

Detection of liquid presence outside tanks and pressure variations along pipes.

## Vehicle Auto-diagnosis

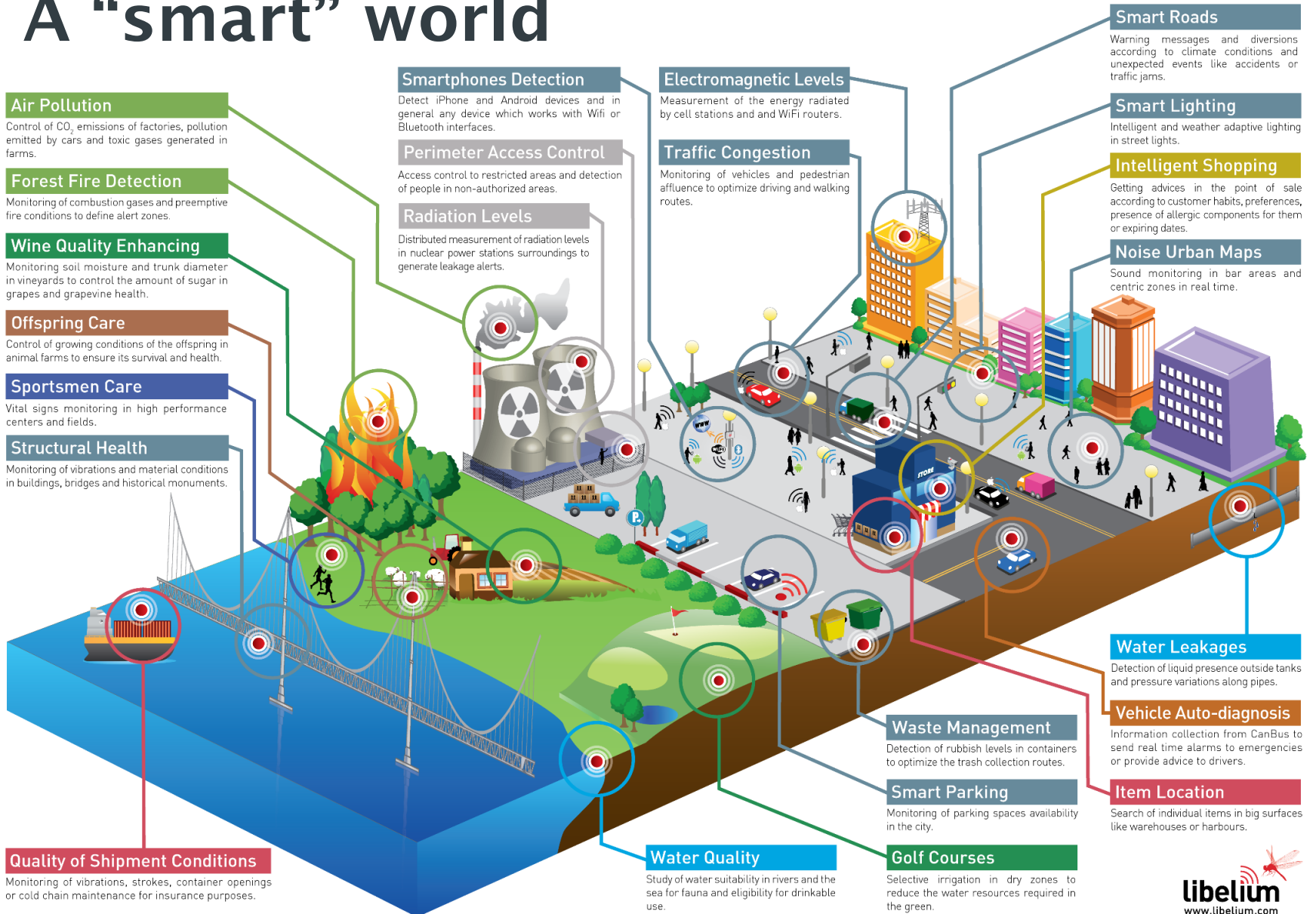
Information collection from CanBus to send real time alarms to emergencies or provide advice to drivers.

## Item Location

Search of individual items in big surfaces like warehouses or harbours.

## Water Quality

Study of water suitability in rivers and the sea for fauna and eligibility for drinkable use.





# The Internet of Things Moves In

The 2014 U.S. edition of Deloitte's Global Mobile Consumer Survey reveals that smartphone owners overindexed in their desire for Internet of Things (IoT) solutions for the home and car.

Would find value in smart HOME solutions



Would find value in connected CAR solutions

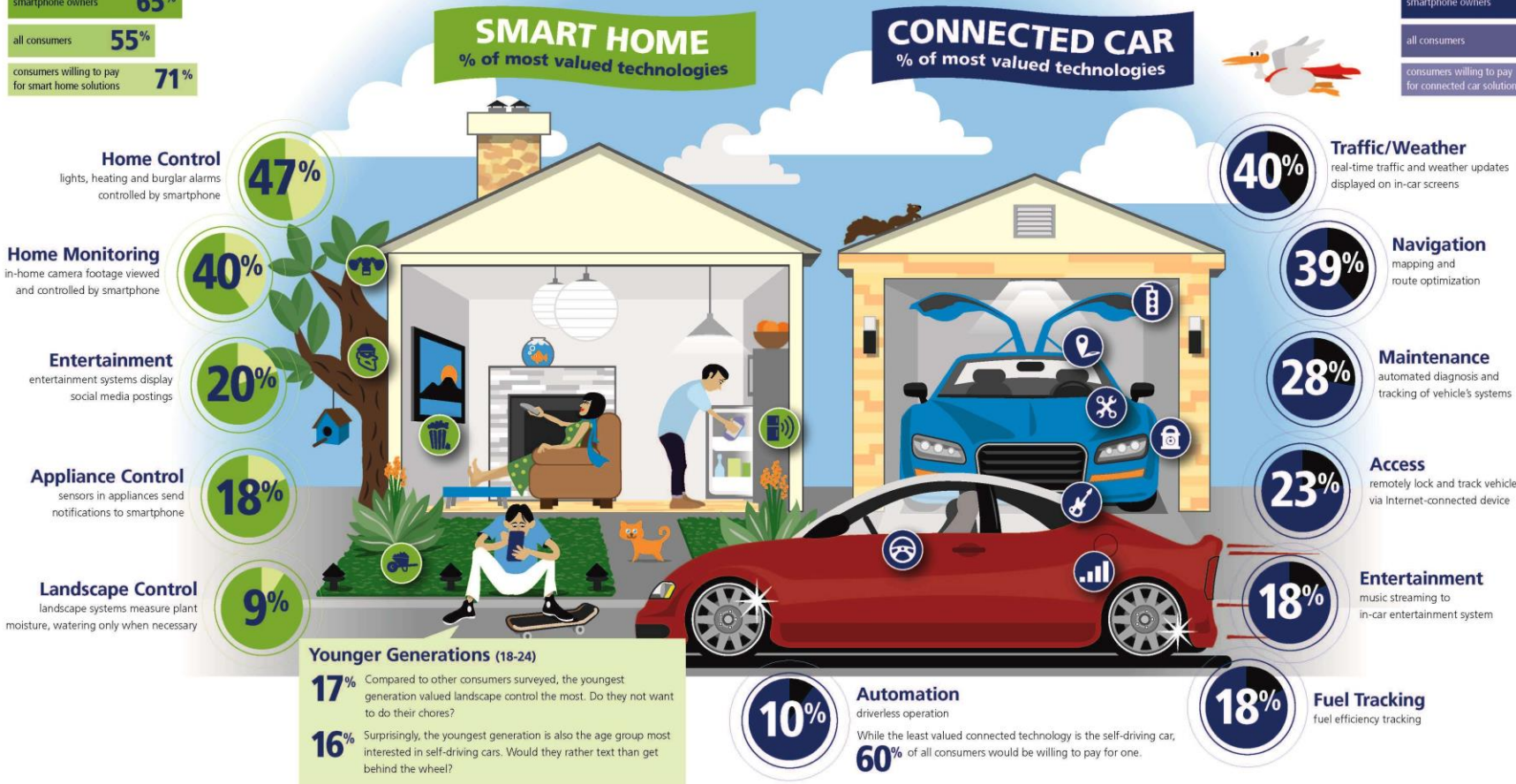
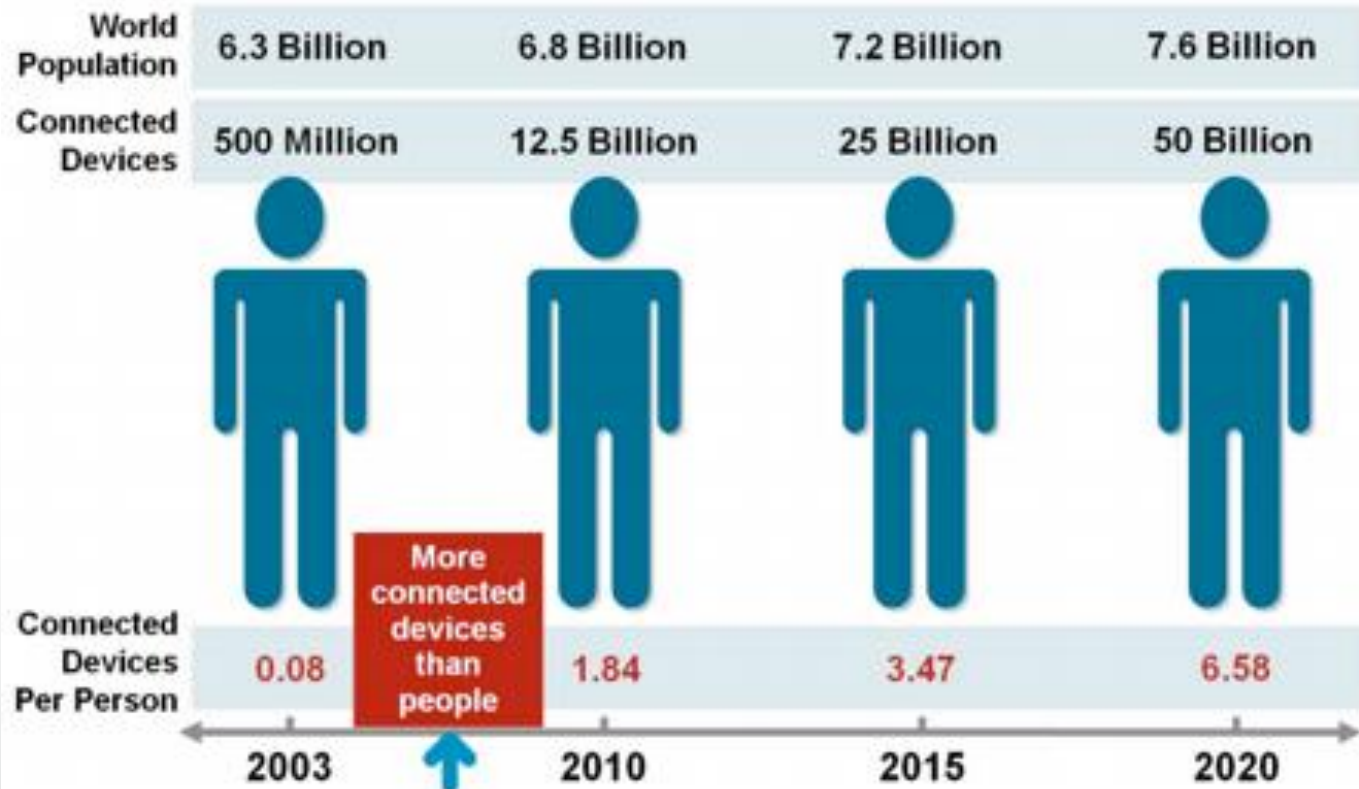




Figure 1. The Internet of Things Was "Born" Between 2008 and 2009



Source: Cisco IBSG, April 2011



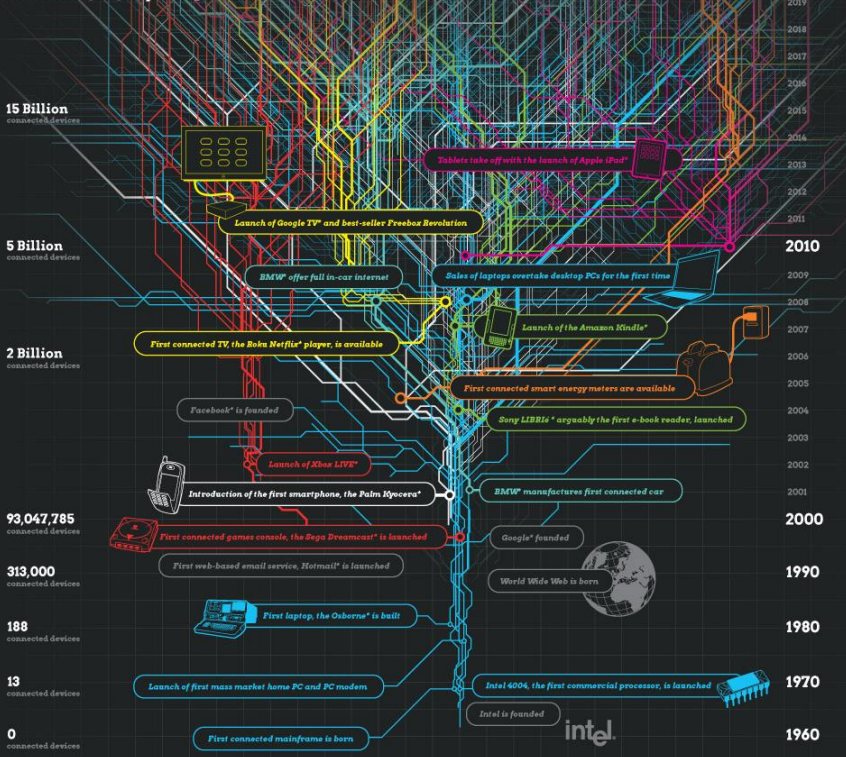
## The Internet of Things

The Internet is evolving, again. Every day billions of people connect to the Internet through billions of devices – PCs, smartphones and TVs to name just a few. While the PC remains at the centre of this evolution, Internet connectivity is now embedded into cars, fitness equipment, factory robots and vending machines. This smarter, connected world has the potential to change how we live.

Here, Intel has produced a quick snapshot of how the number of connected devices has exploded since the birth of the Internet and the PC, as well as a glimpse forward to 2020. The Internet may already be huge, but it's about to get a lot bigger.

- Mainframes, PCs & Laptops
- Smart TVs
- Tablets
- Smartphones
- E-book Readers
- Smart Energy Meters
- Games Consoles
- Automotive

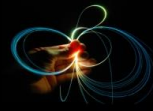
**31 billion devices** / connected to the internet  
**& 4 billion people** by 2020



**80%** of all PCs shipped today  
have Intel\* Inside

The data referenced in this document came from a variety of sources. For a full list please visit: [www.intel.co.uk/internetofthings](http://www.intel.co.uk/internetofthings)  
Intel is a trademark of Intel Corporation in the United States and other countries. \*Other names and brands may be claimed as the property of others.





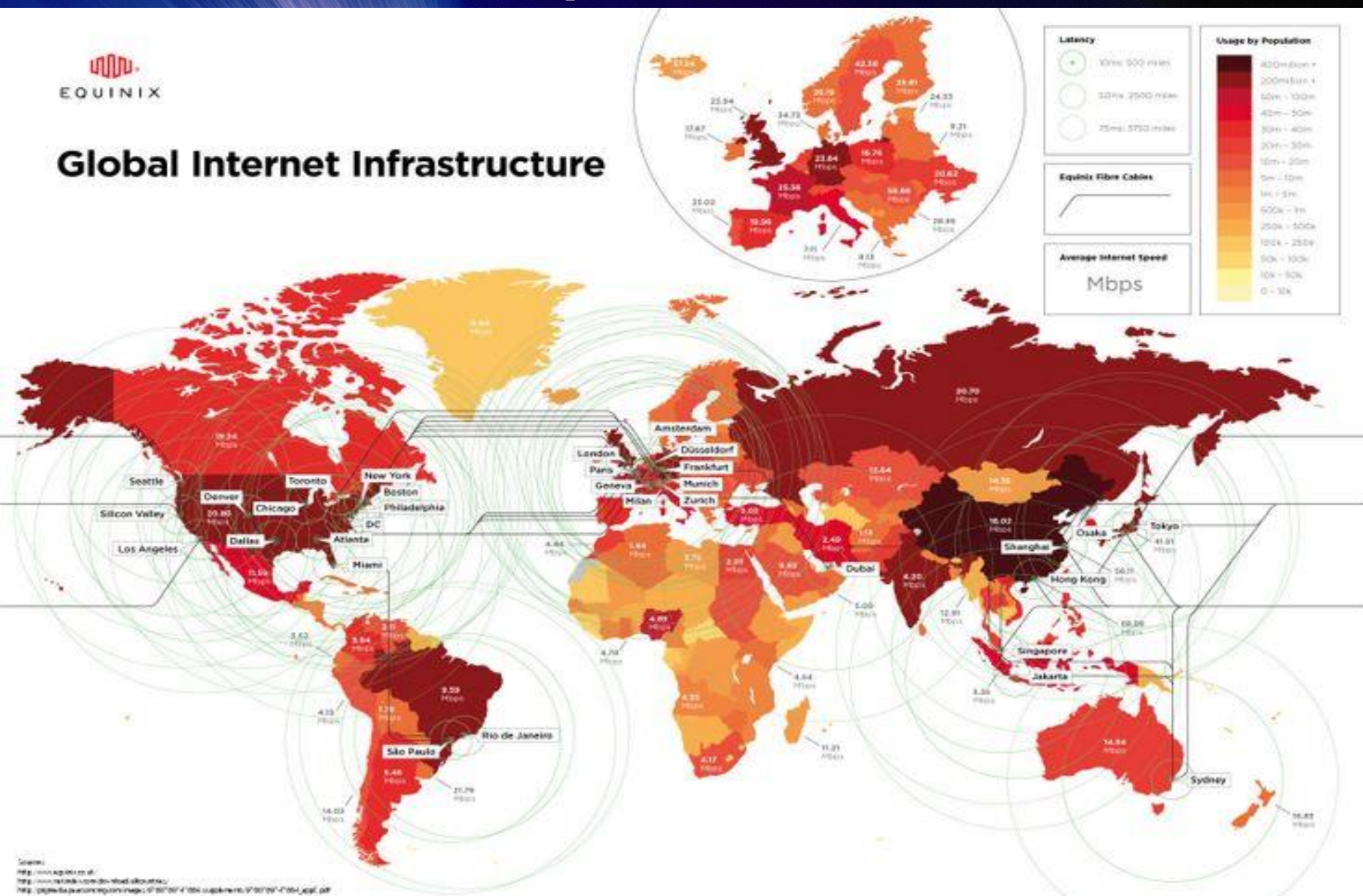
# 50T Gbit Internet

Optical fibres constitute the  
backbone of the Internet

# >1M km: A truly interconncted world



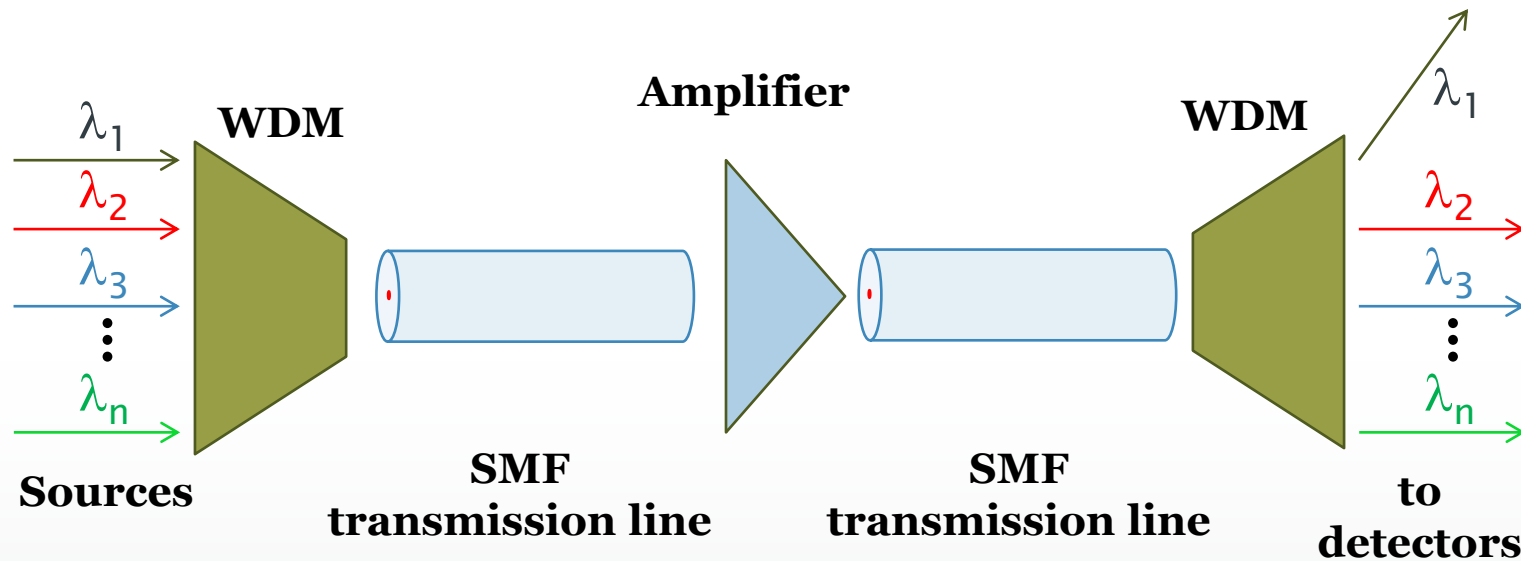
## Global Internet Infrastructure



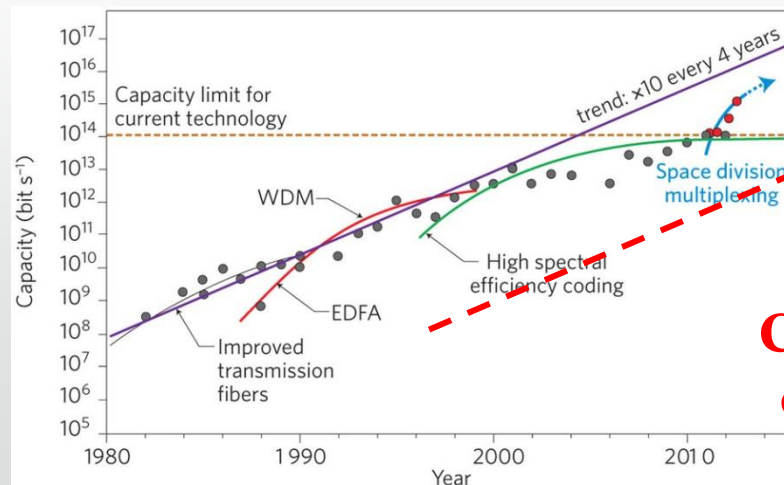
Source:  
http://www.equinix.com  
http://www.equinix.com/press-releases/2014/04/01/equinix-reveals-1-7-million-km-of-fiber-optic-cable  
http://www.equinix.com/press-releases/2014/04/01/equinix-reveals-1-7-million-km-of-fiber-optic-cable.pdf



# Introduction: the “capacity crunch” issue



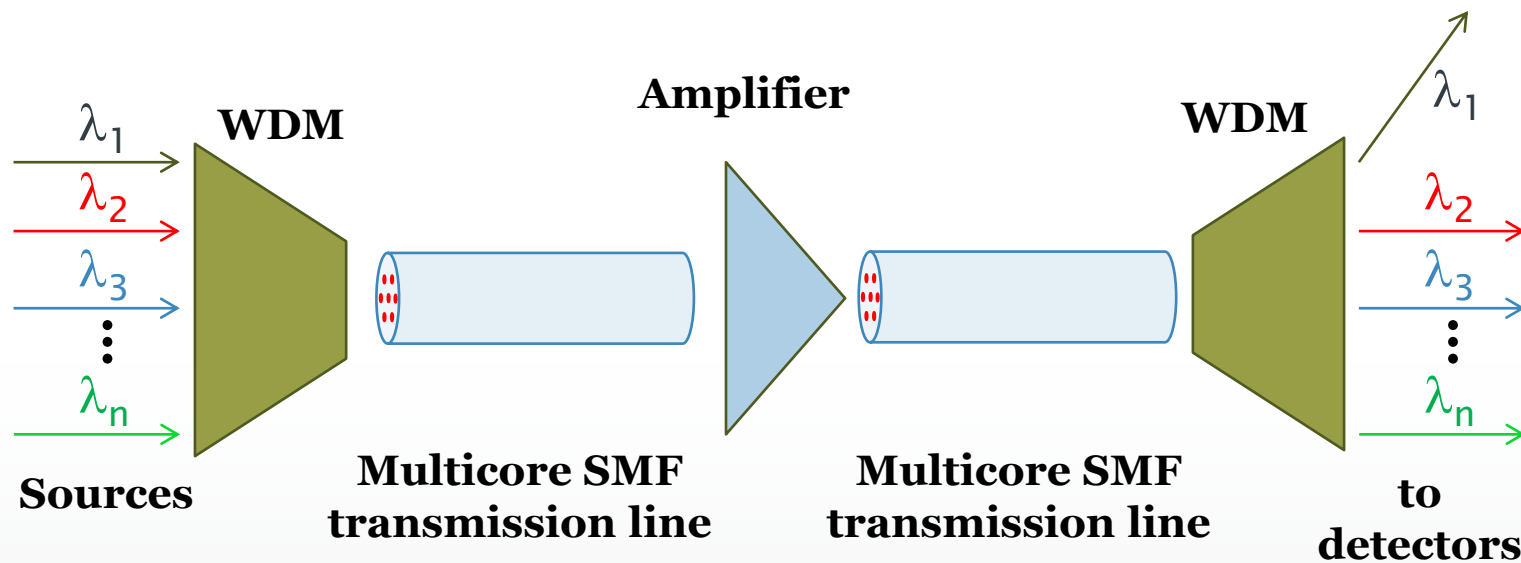
**Not enough**



**2017:  
Capacity  
crunch**



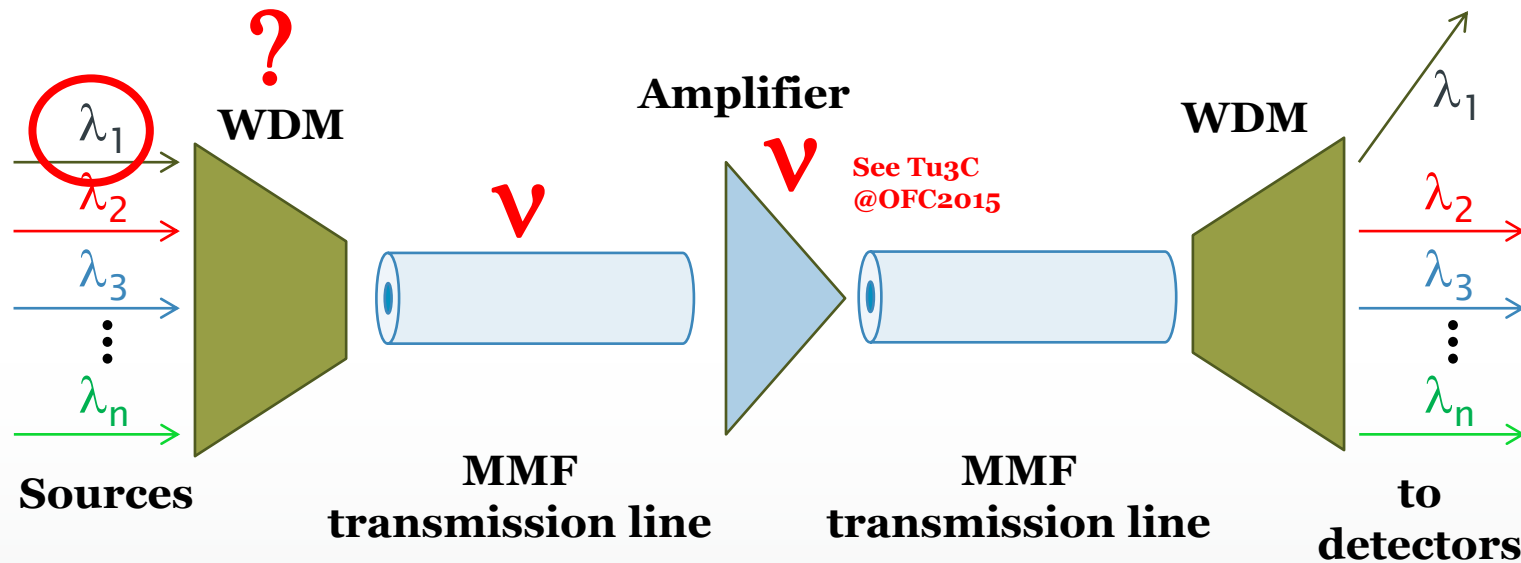
# Introduction: Space Division Mux



**N cores: capacity x N**



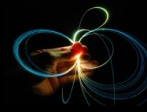
# Introduction: Mode Division Mux



$$\lambda_1 \rightarrow = \left\{ \begin{array}{l} \underline{LP_{01}(\lambda_1)} \rightarrow \\ \underline{LP_{11}(\lambda_1)} \rightarrow \\ \underline{LP_{02}(\lambda_1)} \rightarrow \\ \vdots \\ \underline{LP_{mn}(\lambda_1)} \rightarrow \end{array} \right.$$

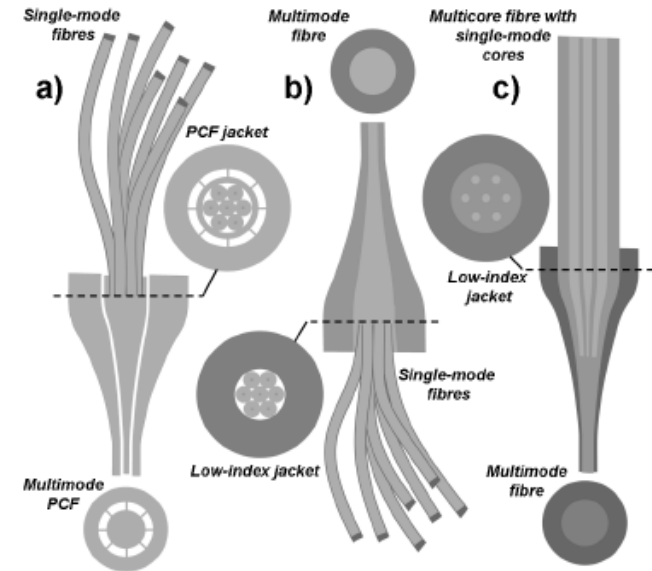
**N modes: capacity x N**

**WDM??**

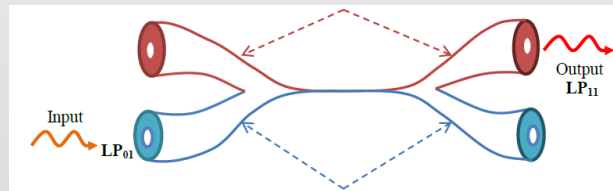
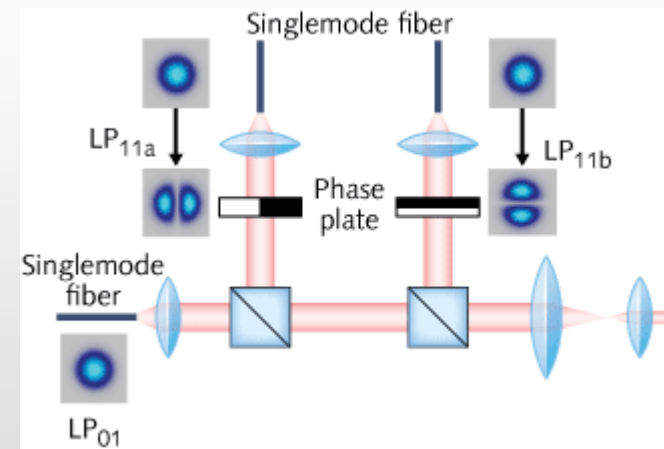


# Introduction: MDM

- Modal Mux/Demux: Photonic lantern many modes simultaneously
- Phase plate: free space launching, alignment issues
- Can we have all fiberised solution?



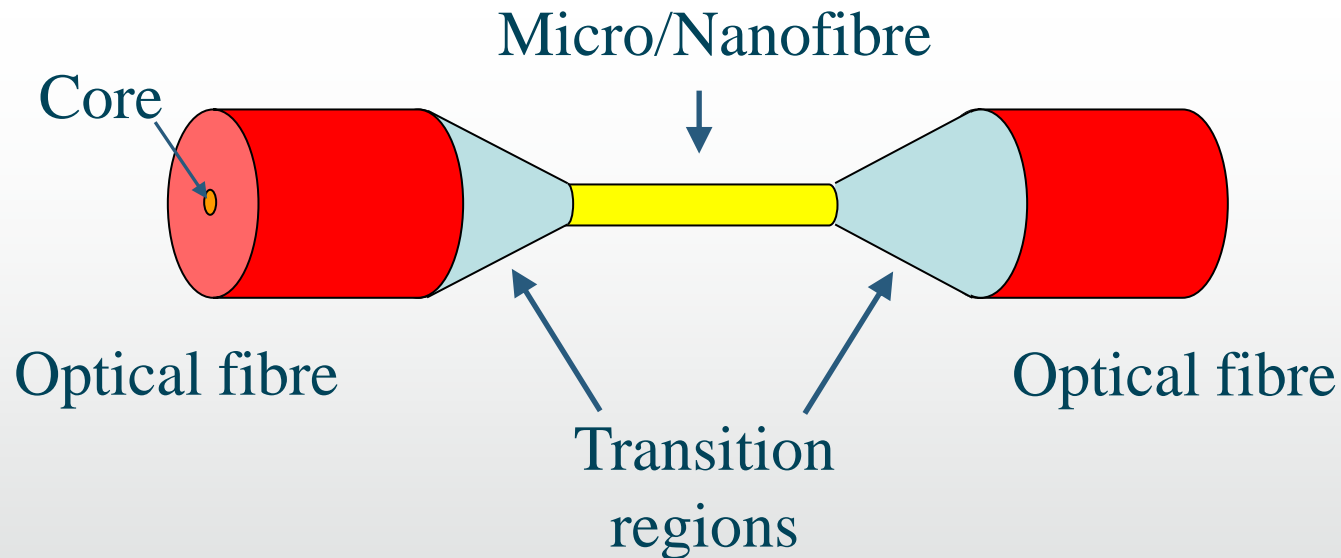
S.C. Leon-Saval, Opt. Expr. 18(8), 8430 (2010)





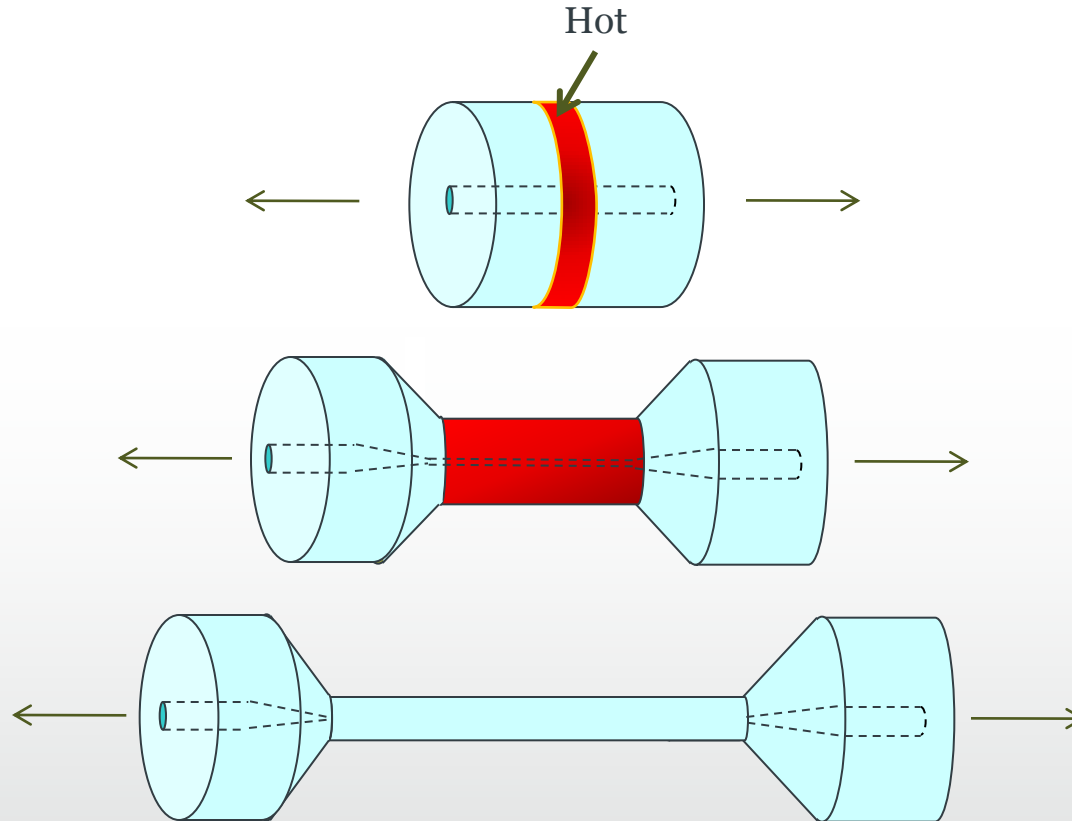
# Optical Microfibres

OM are optical fibre tapers  
They have a size orders of magnitude smaller than OFs

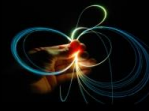




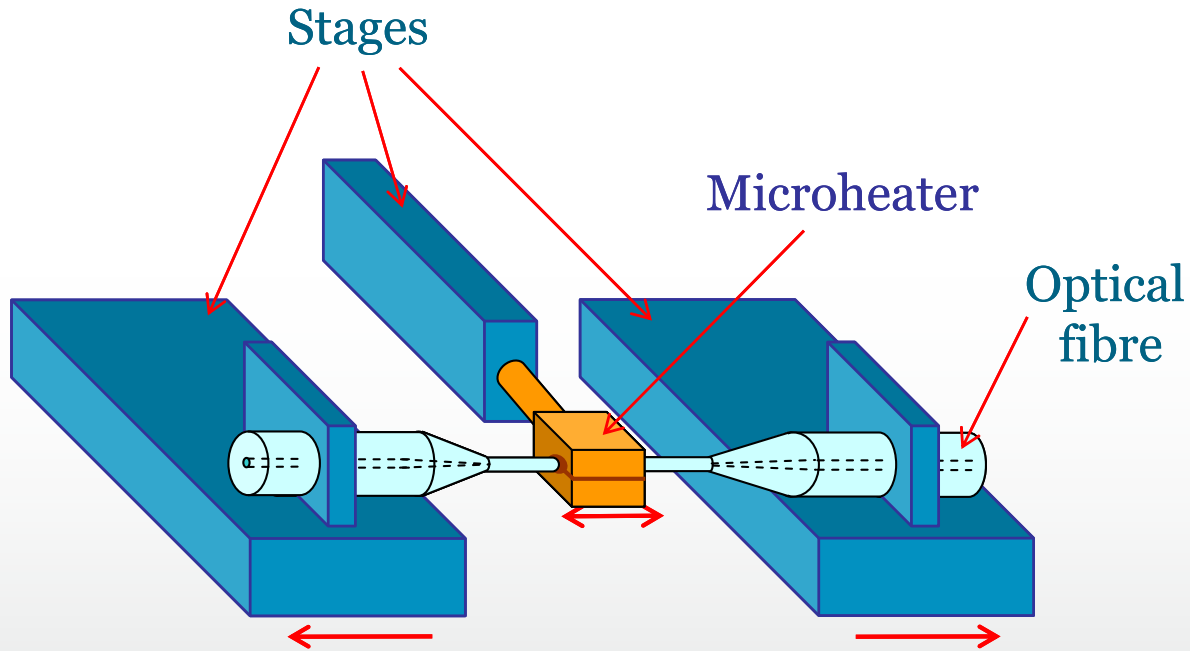
# Fabrication (1): mass conservation



Mass conservation: elongating fibres above  $T_s$ , diameter decreases

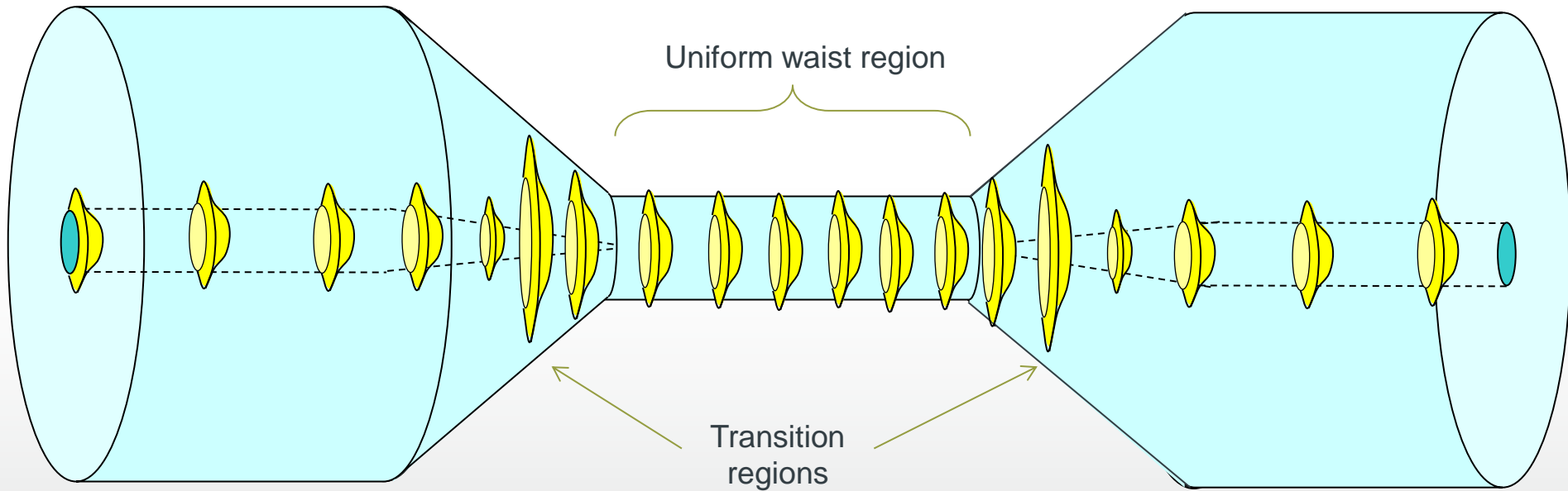


# Fabrication (2): microheater



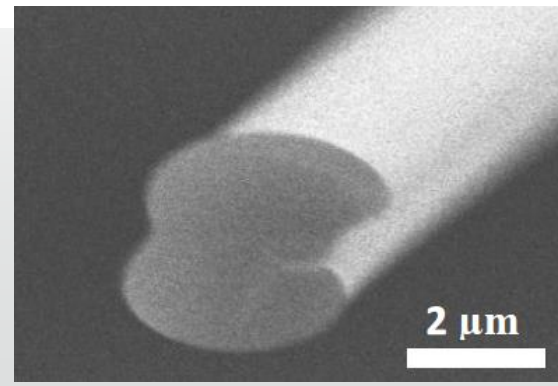
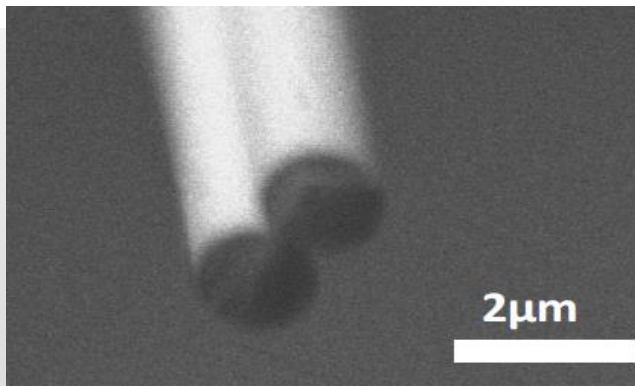
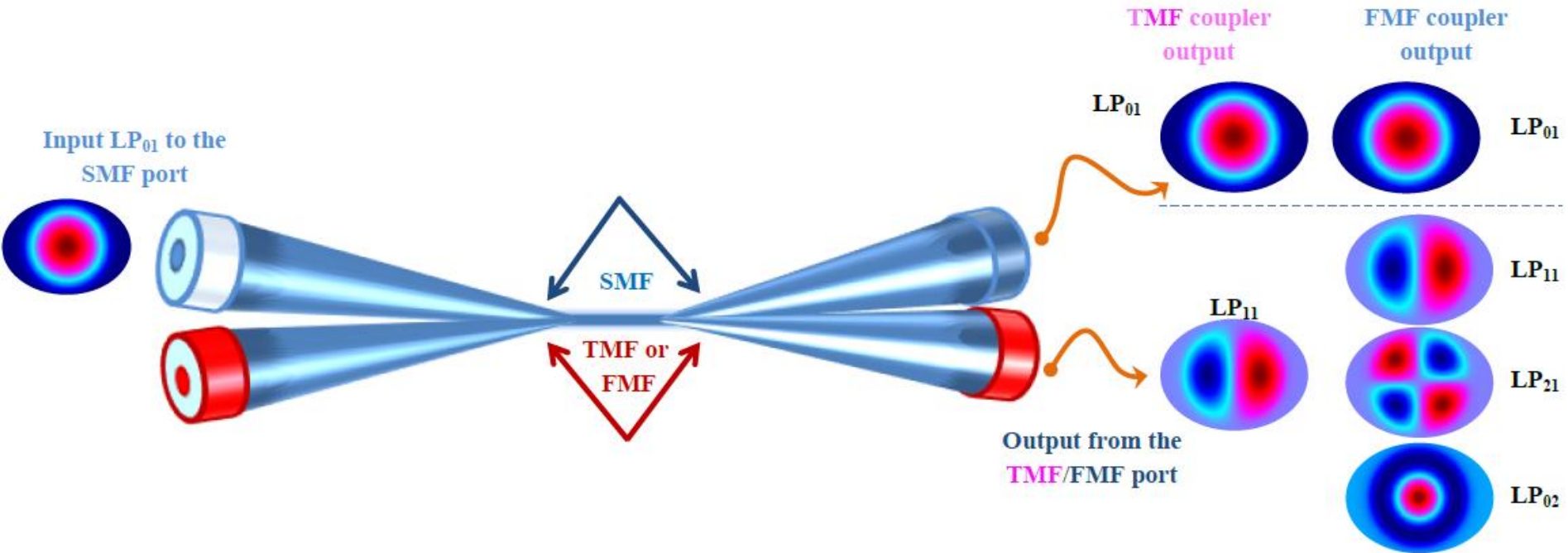


# Mode Propagation





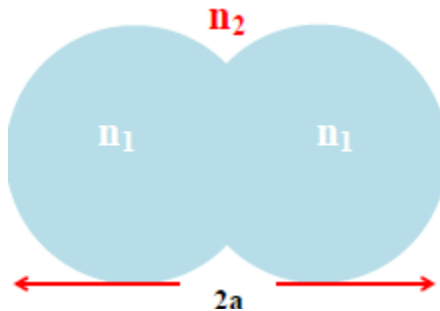
# Weakly-fused multimode coupler



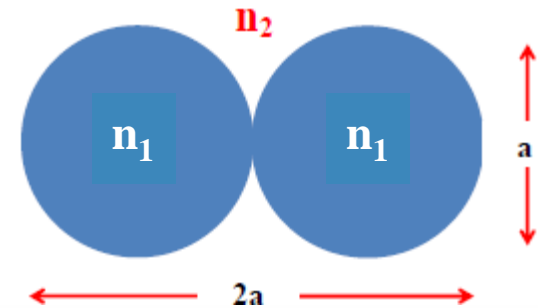


# Weakly-fused coupler

Strongly fused coupler



Weakly fused coupler



Power coupling for **symmetric** coupler

$$P = \frac{1}{2} [1 + \cos(C_x + C_y) \cdot L \cos(C_x - C_y) \cdot L]$$

$$C_x + C_y = \frac{3\pi\lambda}{32n_2a^2} \left[ \frac{1}{(1 + \frac{1}{V})^2} + \frac{1}{(1 + \frac{n_2^2}{n_1^2} \frac{1}{V})^2} \right]$$

$$C_x - C_y = \frac{3\pi\lambda}{16n_2a^2} \frac{1}{V} \left( 1 - \frac{n_2^2}{n_1^2} \right)$$

$$P = \frac{1}{2} [1 + \cos(C_x + C_y) \cdot L \cos(C_x - C_y) \cdot L]$$

$$C_x + C_y = \frac{2^{7/2}(n_1^2 - n_2^2)^{1/2} U_\infty^2}{n_1 a \sqrt{\pi} V^{5/2}}$$

$$C_x - C_y = \frac{2^{5/2}(n_1^2 - n_2^2)^{1/2} U_\infty^2}{n_1^3 a \sqrt{\pi} V^{7/2}}$$

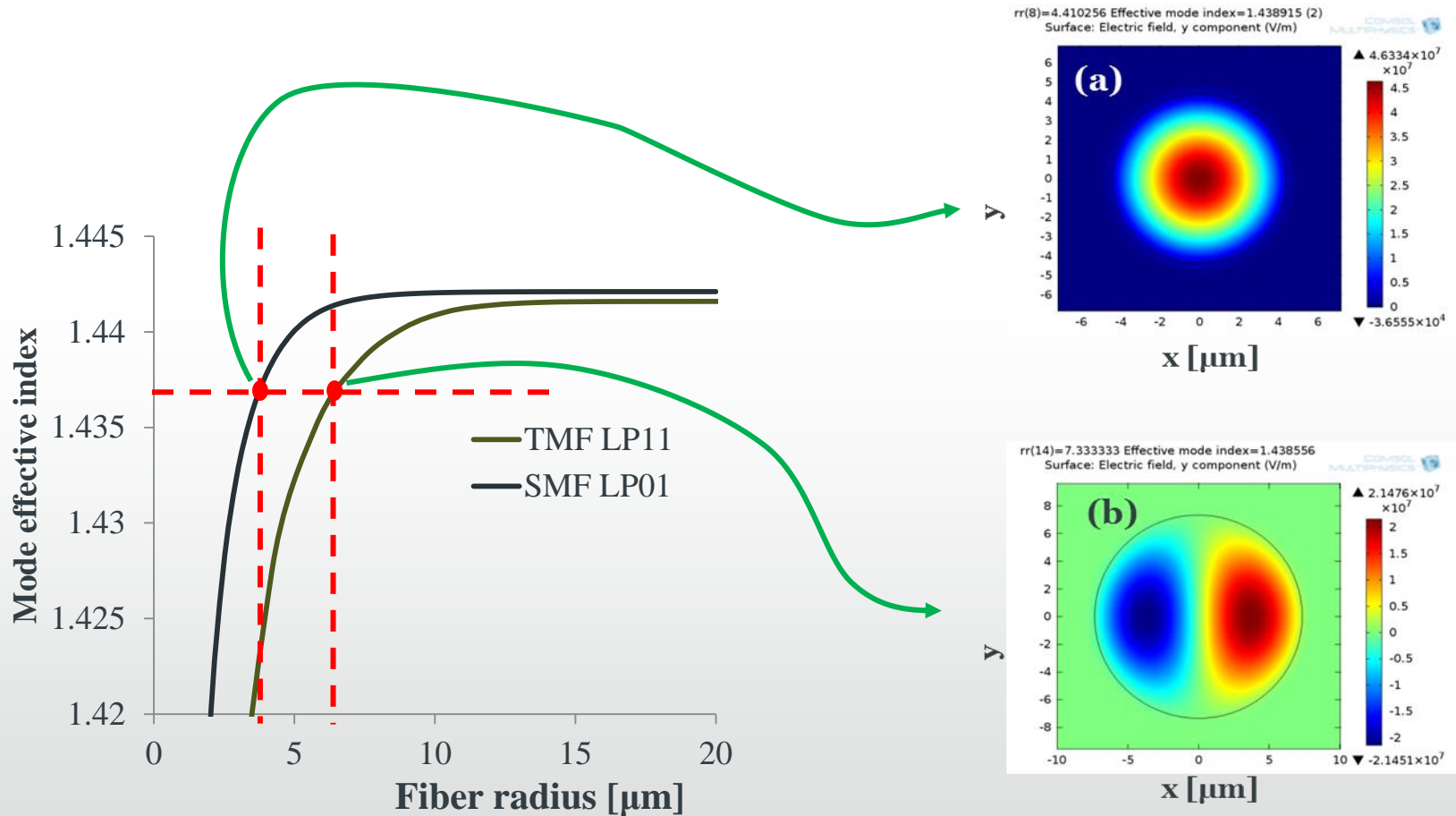
Weakly fused coupler can be treated as two axisymmetric waveguides in contact!

The two waveguides need to phase match to maximise coupling: same  $\beta$   $\rightarrow$  same  $n_{\text{eff}}$



# Phase matching

- Microfibres in air

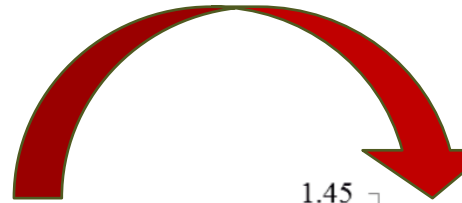
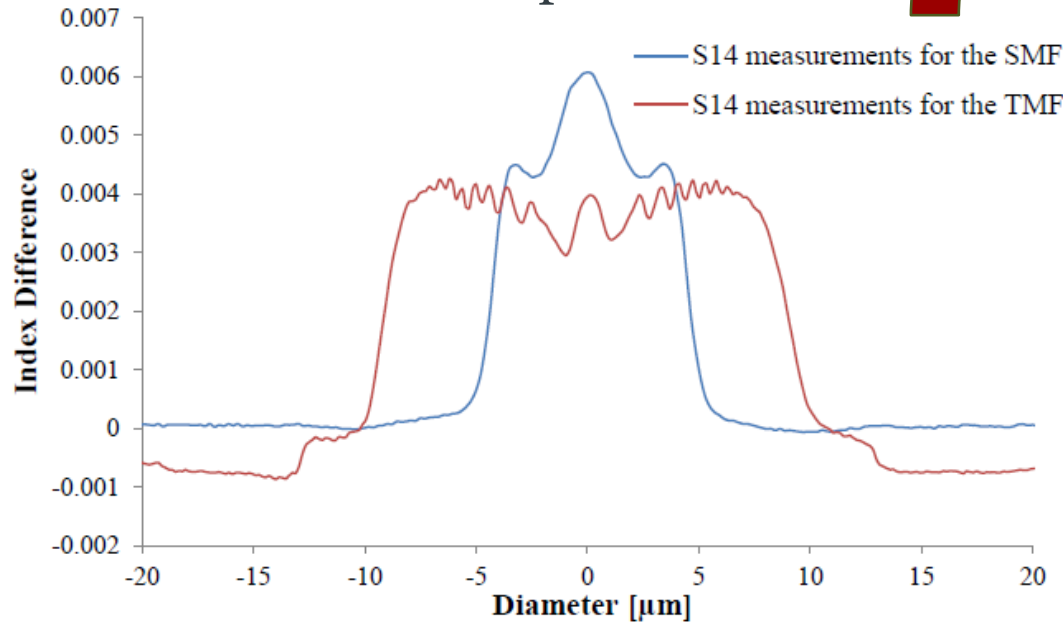


$d_{SMF} < d_{MMF} \rightarrow$  SMF needs pretapering!

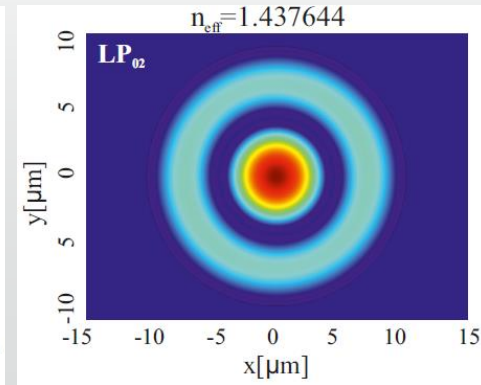
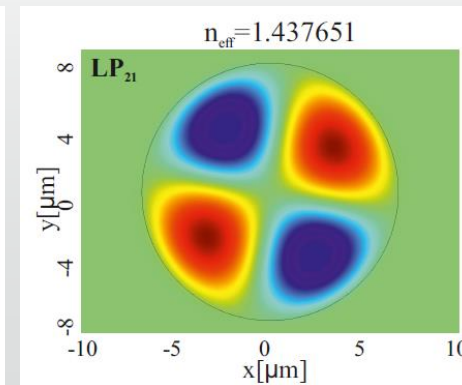
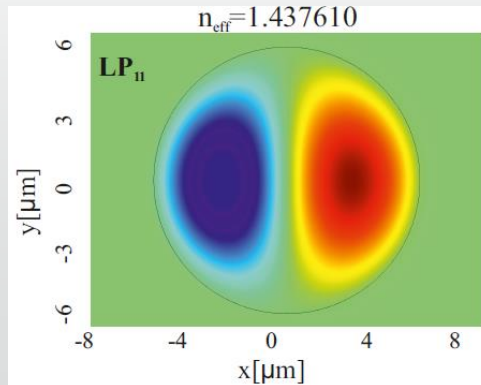
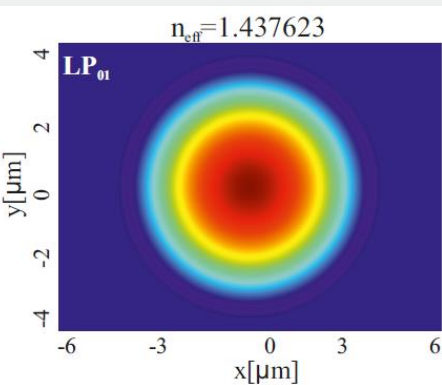
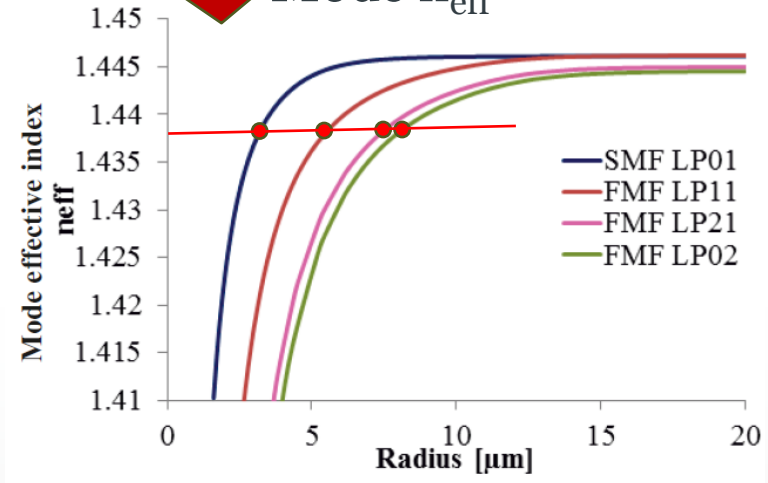


# Four mode fibres

RI profile



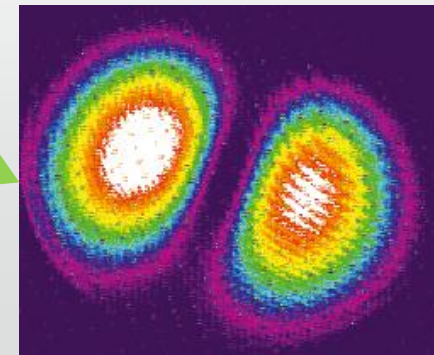
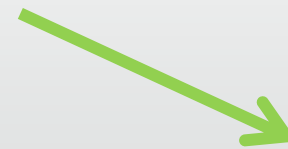
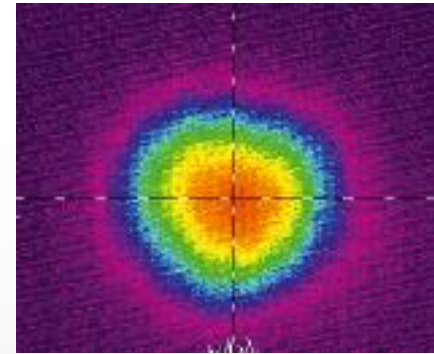
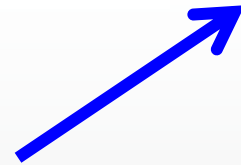
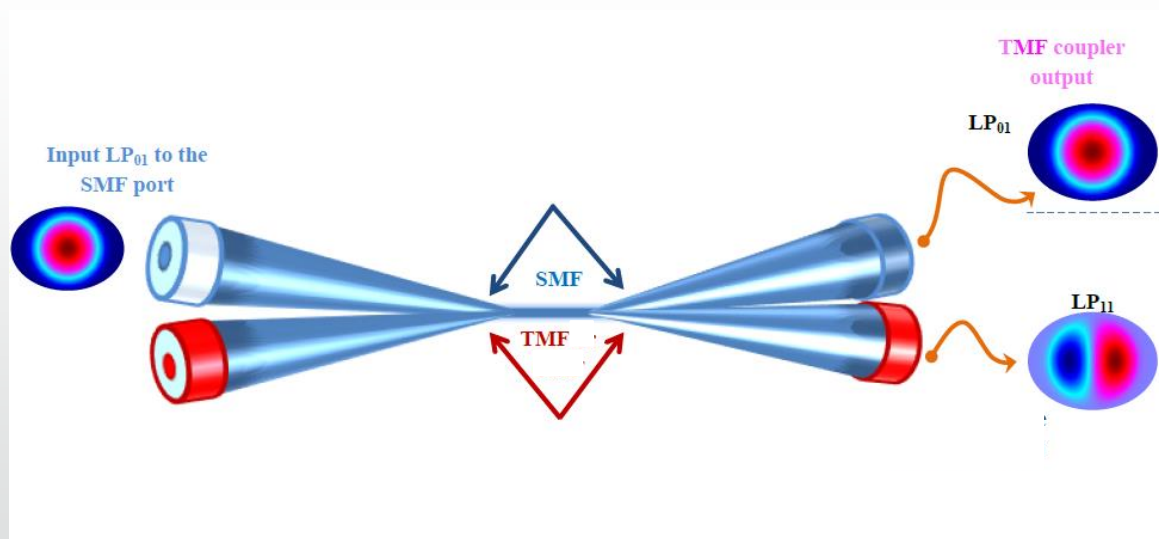
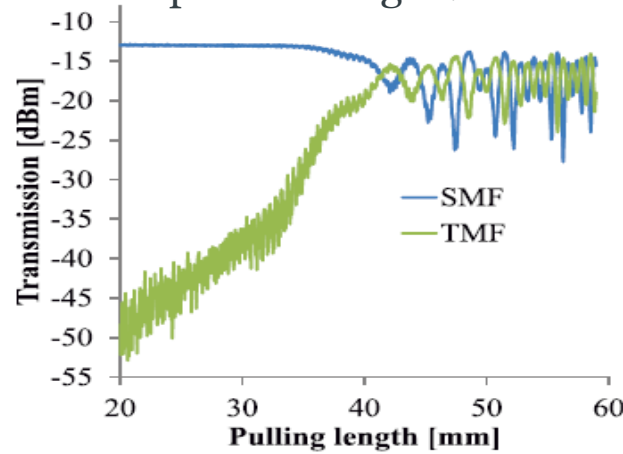
Mode  $n_{\text{eff}}$





# TMF Coupler

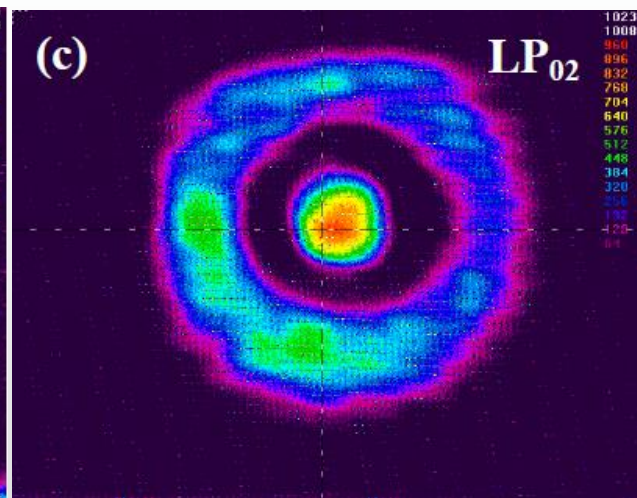
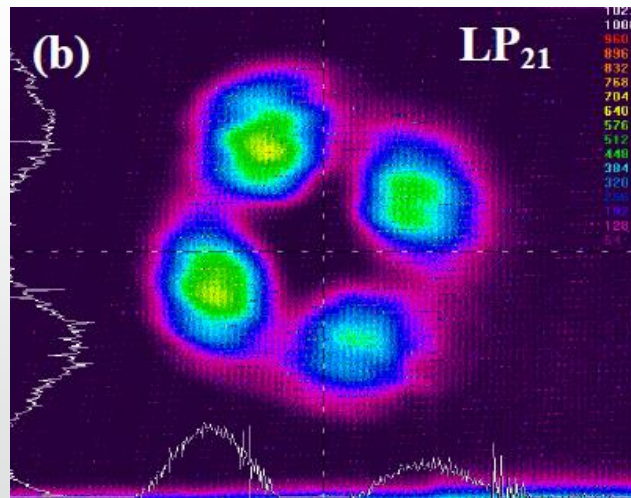
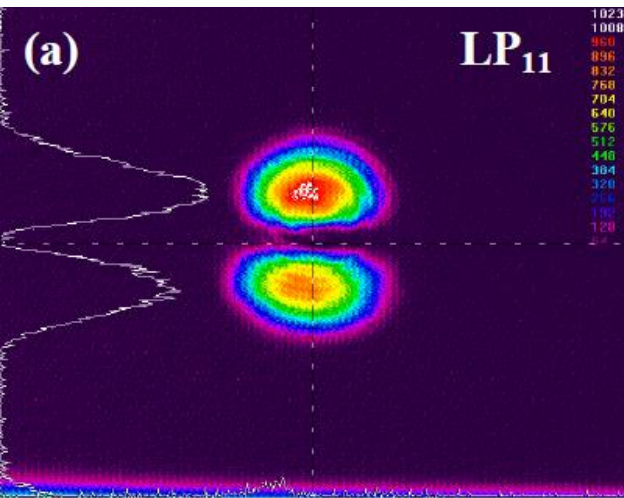
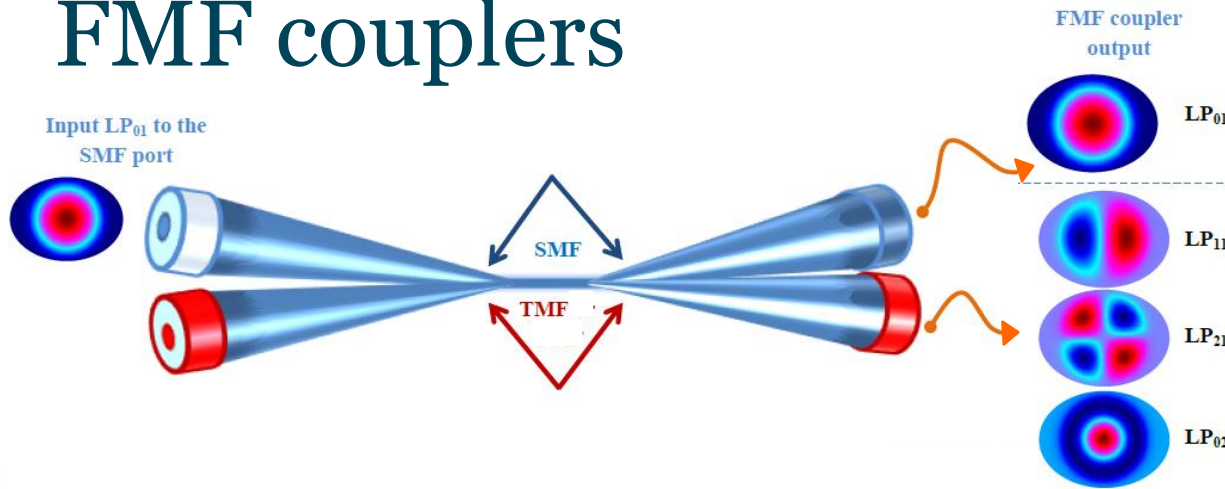
Power output from SM and MM ports during fabrication



Spectral purity >95%

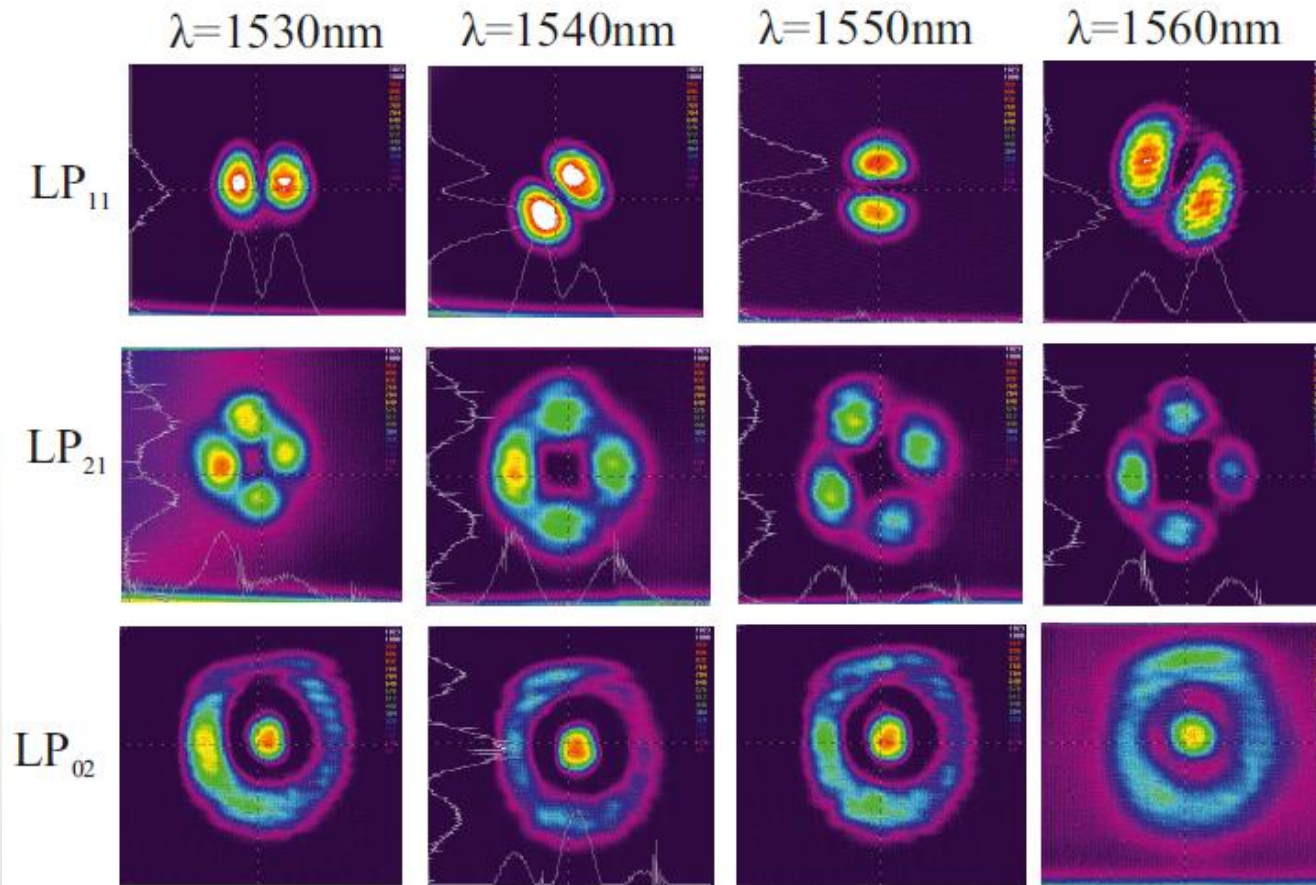


# FMF couplers





# Broadband operation



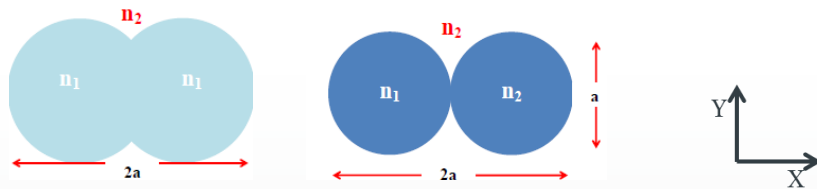
Broadband operation is strongly dependent on couple diameter.  
Larger fibre diameters allow for broadband operation.



# Polarization discrimination

For circularly symmetric waveguides high order modes are degenerate.

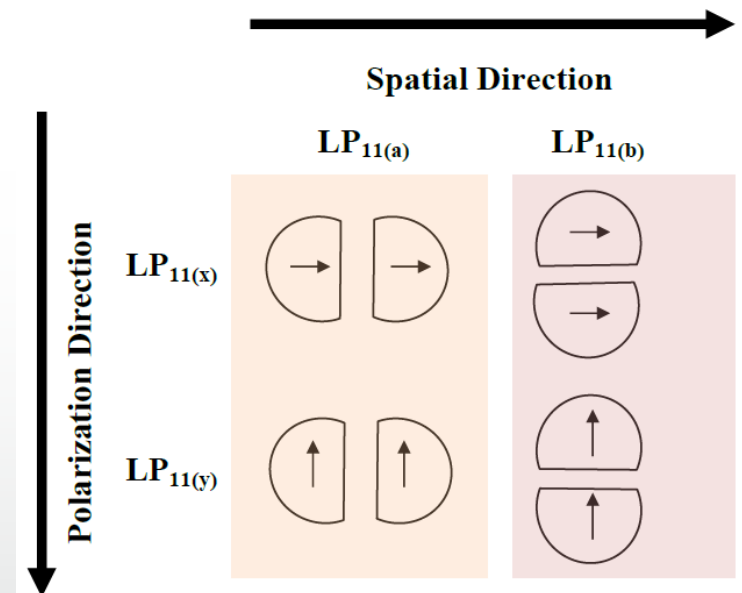
Couplers have  $\epsilon=0.5$ .



Propagation constants in orthogonal  
directions X and Y are significantly different



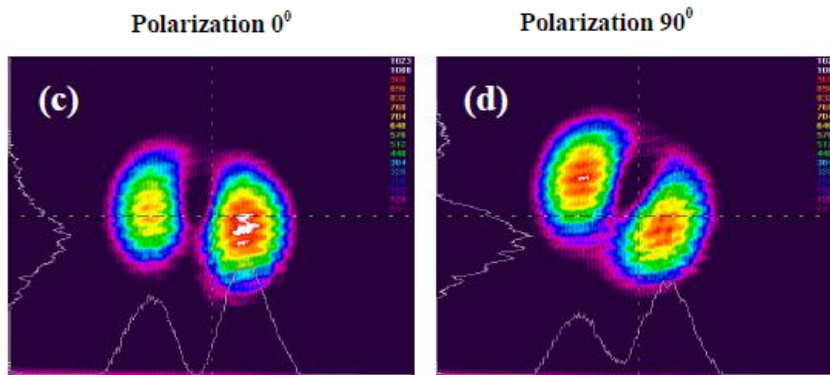
can be discriminated



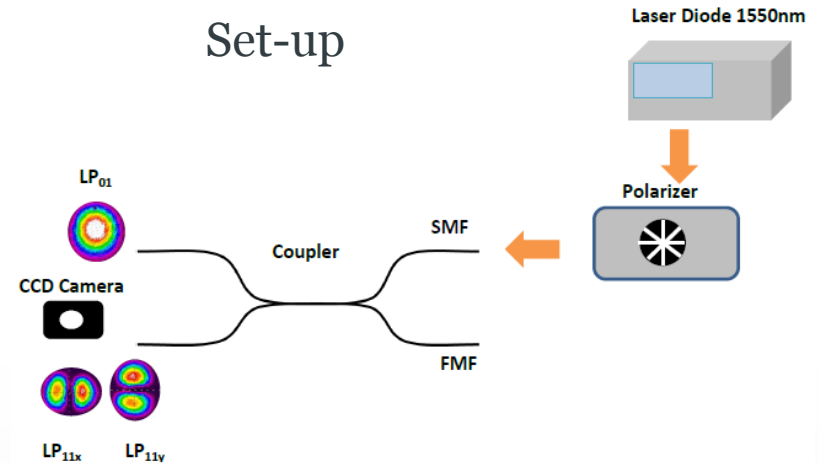


# Polarization discrimination (2): experiment

$L=50\text{mm}$ ,  $\epsilon \sim 0.5$



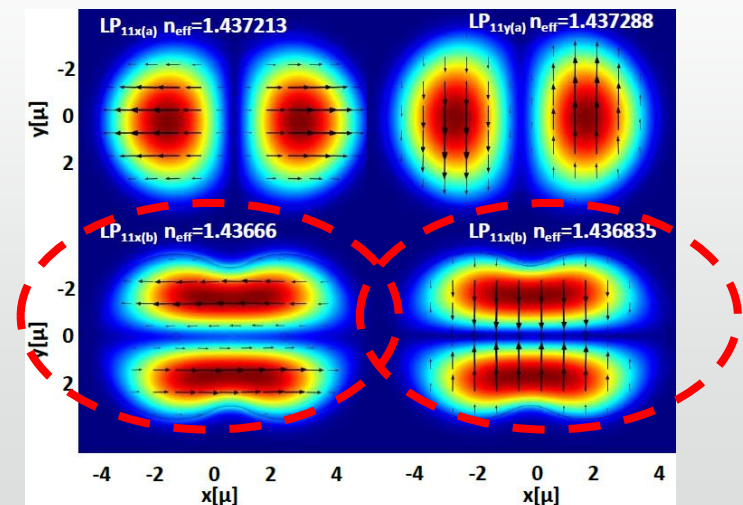
Set-up

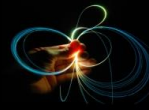


Coupler discriminates  $LP_{11(a)}$  from  $LP_{11(b)}$

Launch	Output
$0^\circ$	$LP_{11x(a)}$
$90^\circ$	$LP_{11x(b)}$

Coupler selectively excites  $LP_{11(b)}$





# Conclusions

- IOT requires more and more data to be carried through the fibre backbone system
- Novel fibres (multicore and multimode) have been proposed to overcome the growth bottleneck
- In modal multiplexing add drop multiplexers are the greatest challenge, yet.
- Weakly-fused couplers can be the solution and provide large asymmetry and discriminate different components of high order mode  $LP_{11(a)}$  from  $LP_{11(b)}$



# Acknowledgements



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D.J. Richardson, D.N. Payne