# Emerging fibre components for sensors

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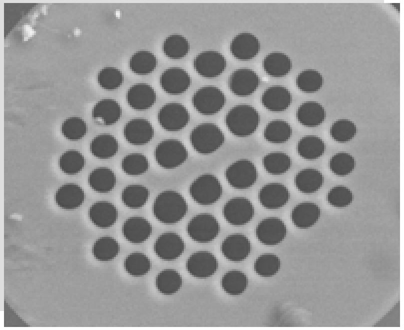
# Structured fibre hosts what do they offer?

## Structured fibre hosts: what do they offer?

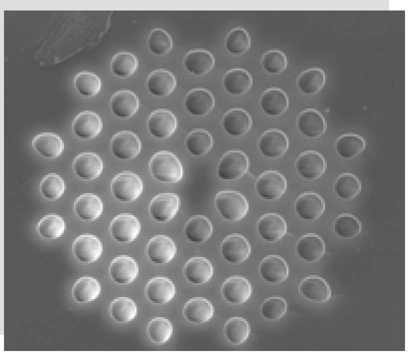
- Simple solutions? Loss, simple P sensor in polymer
- T independence – single material fibres, geometric properties, gratings
- Light collection – higher NA, astrophotonics, tapering and near field imaging
- Optical localisation - near field spectroscopy in a fibre; micro volumes; thin films
- Processing structured optical fibres
- Multiple functions, Lab-in-a-fibre

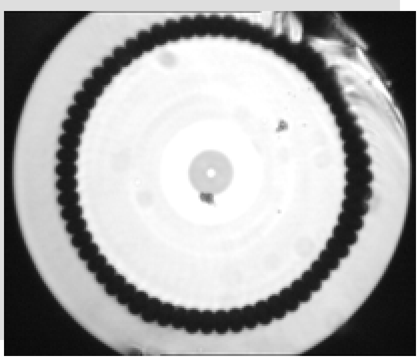
# Keep things simple!

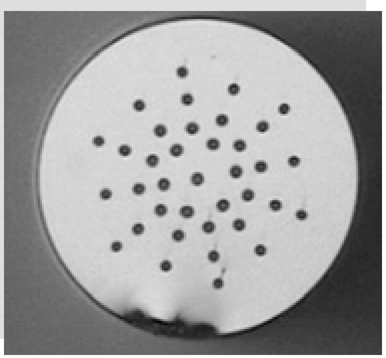


- Why structured fibres?
- Tailor design for application

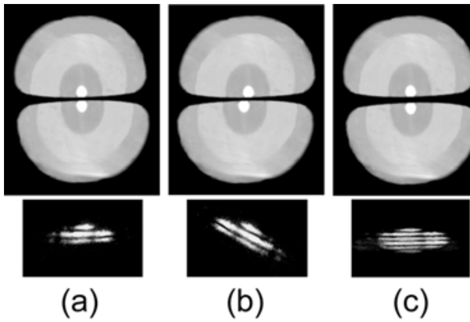
- “Complex devices”: e.g. Lab-in-a-fibre
- What is required to get there?
  - *Fabrication of custom fibres*
  - *Access to the structure*
  - *The incorporation of materials and components*
  - *Integrating multiple functionality*

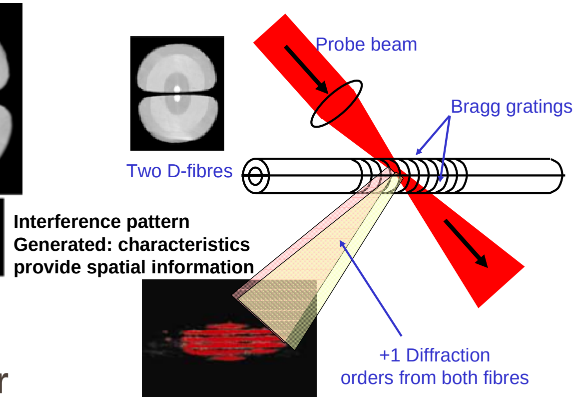




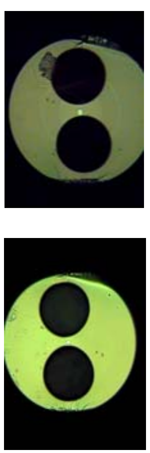


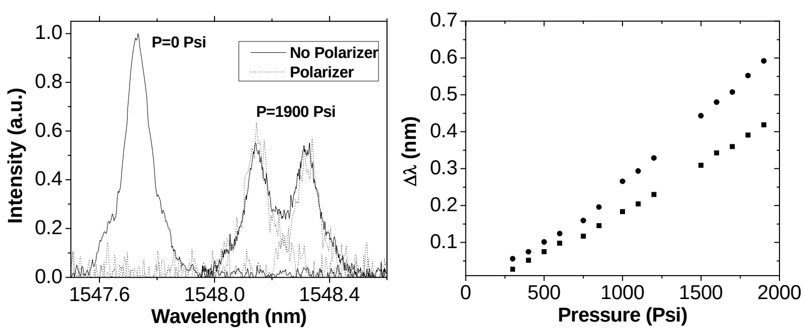
# Fabricating structure specific fibres




**nm displacement sensor**
Lateral displacement - 100nm res.
Longitudinal displacement - <10nm res.
*(Aslund et al. Opt. Express 2003)*






**Hydrostatic pressure sensor**
*(Jewart et al. OFS 2007)*

**Self aligning fibre** uses two flats on either side.
*(Michie et al. OFS 2007)*

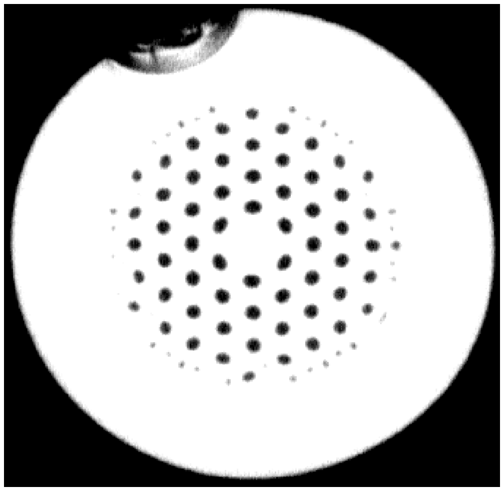
## Basic ideas around for decades!!

- **D- fibres and other shaped (e.g. canals) fibres**
  (Evanescent field sensing, core access, devices)
- **Twin/few hole fibres**
  (Sensing, poled devices)
- **Structured Optical Fibres**
  (devices, sensors, lasers, optical transport and manipulation)

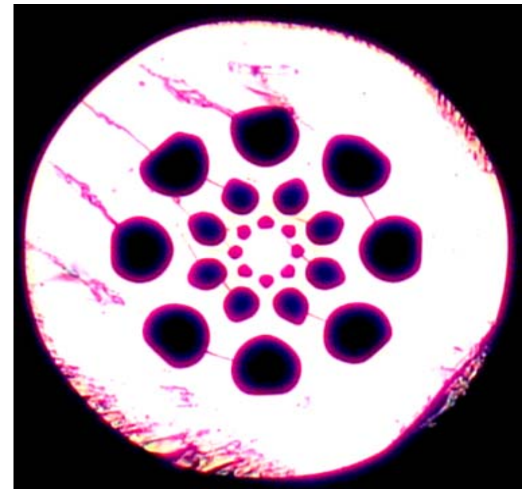
All the above remain useful. Pick fibre best suited to application – **BUT what can structured fibres do better????**

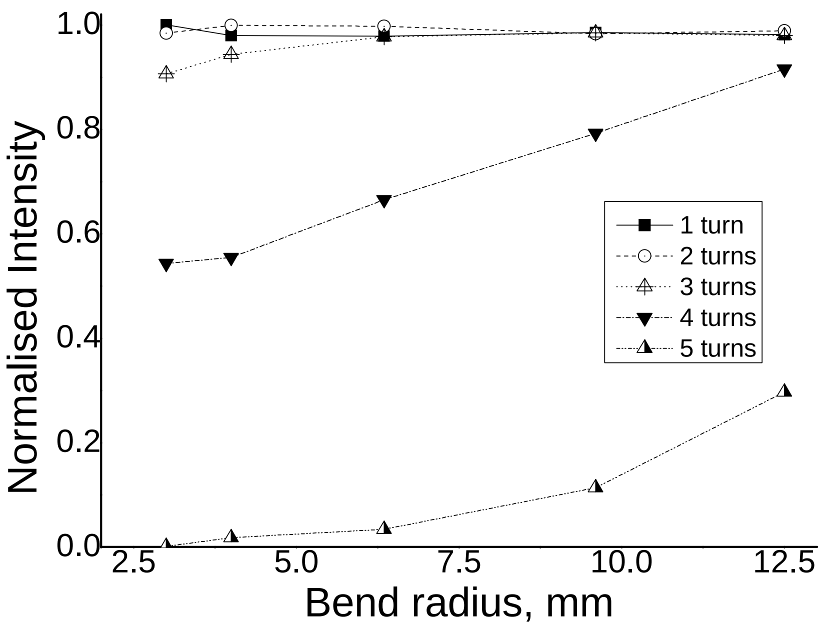
# Reducing loss

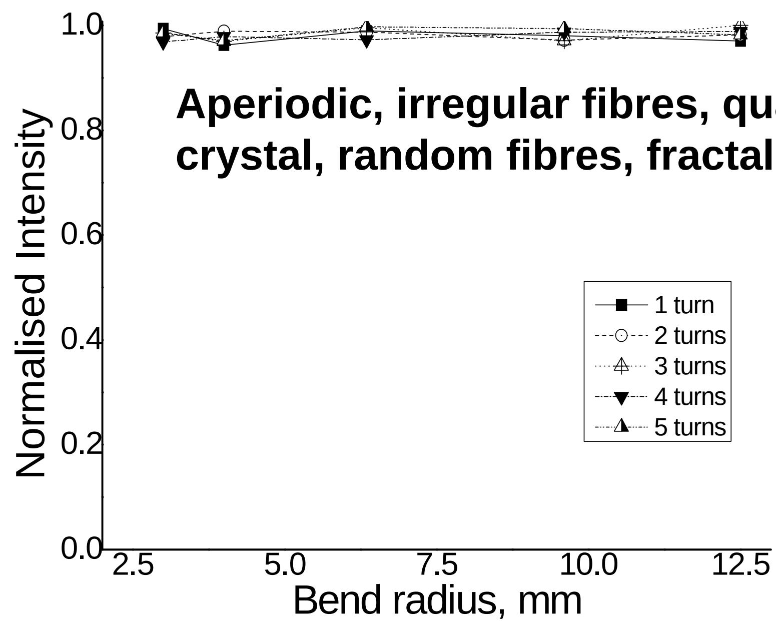
## Example: zero bend loss fibres at 1550nm



***Martelli et al. 2007***






**Aperiodic, irregular fibres, quasi crystal, random fibres, fractal fibres**

# Simple P sensor for orthodontics

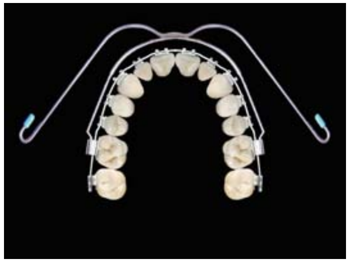
**Polymer PCF**

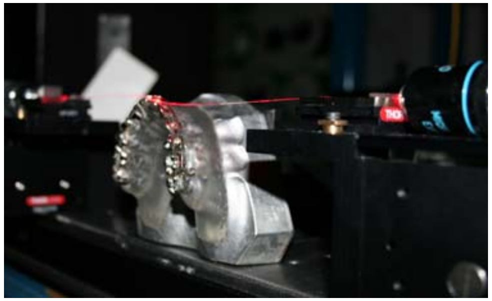
- Thought ideal for biocompatible diagnosis
  e.g. orthodontic photonics

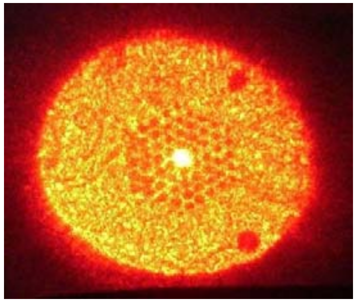
**BUT**

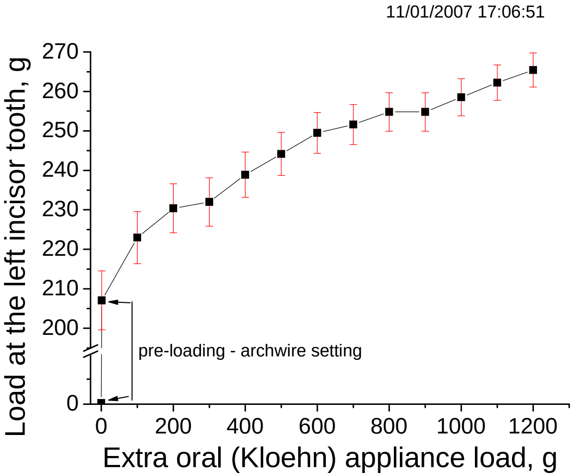
- Extremely loss; tough to cleave
- **Deforms easily**
- Could there really be a real application?

**P point sensor based on elastic deformation in polymer PCF!**





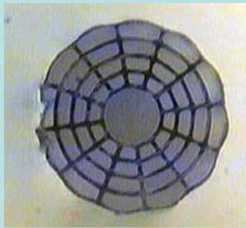





**First ever measure of orthodontic forces on periodontal ligament**

**Laser cleaving 193nm**

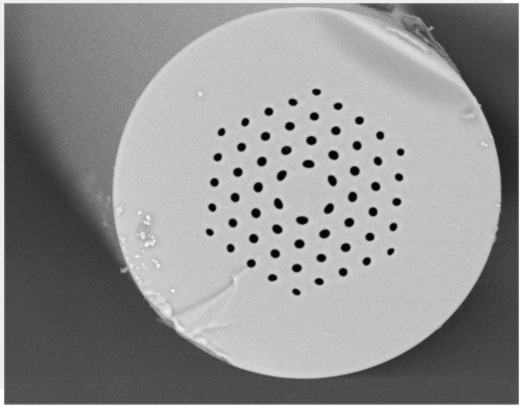
***K. Cook et al. iPL (2008) Unpublished***



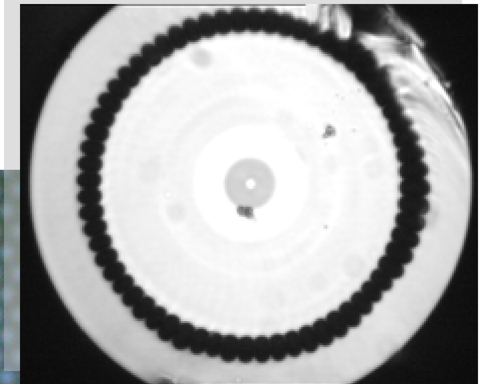
Terahertz Fresnel bandgap polymer fibre fabricated by S. Atakaramian & H. Ebendorff-Heidepriem, CEP, Adelaide University

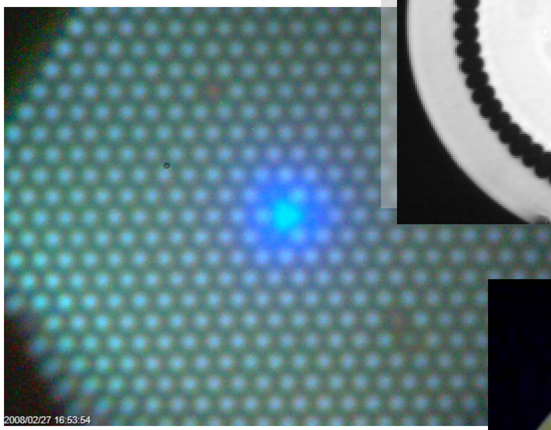
*Milczewski et al. EWOFS 2007; European J. of Glass Technology 2009*

# Temperature Independence
## - single material fibres

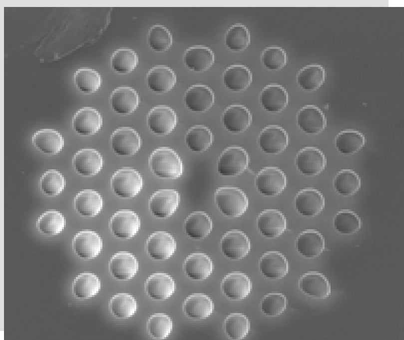


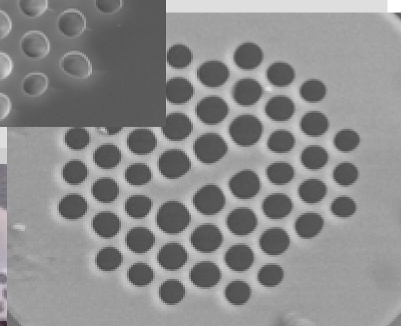
Differences in thermal expansion coefficient lead to larger T dependence

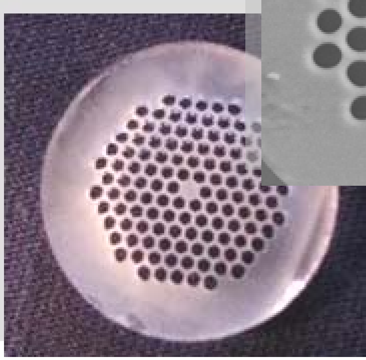


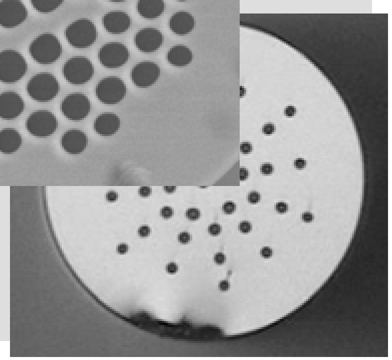



**Single material fibres**

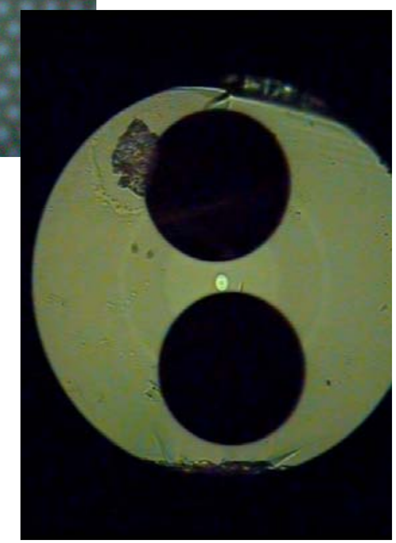






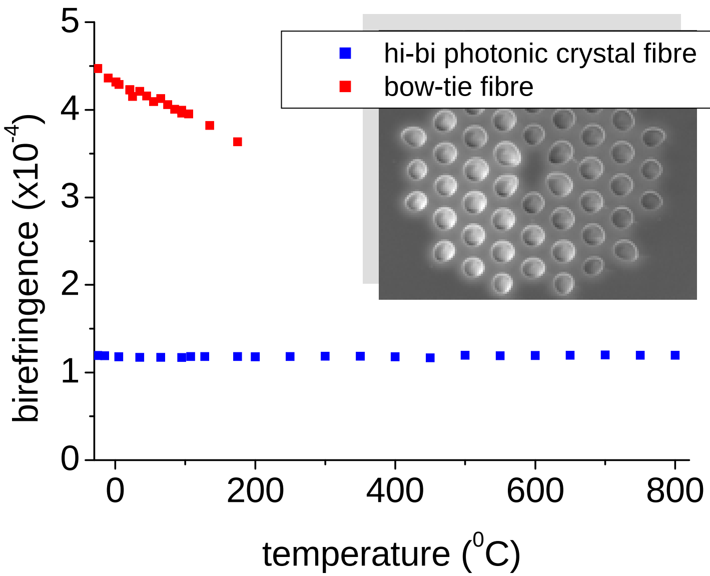


**Doped cores**

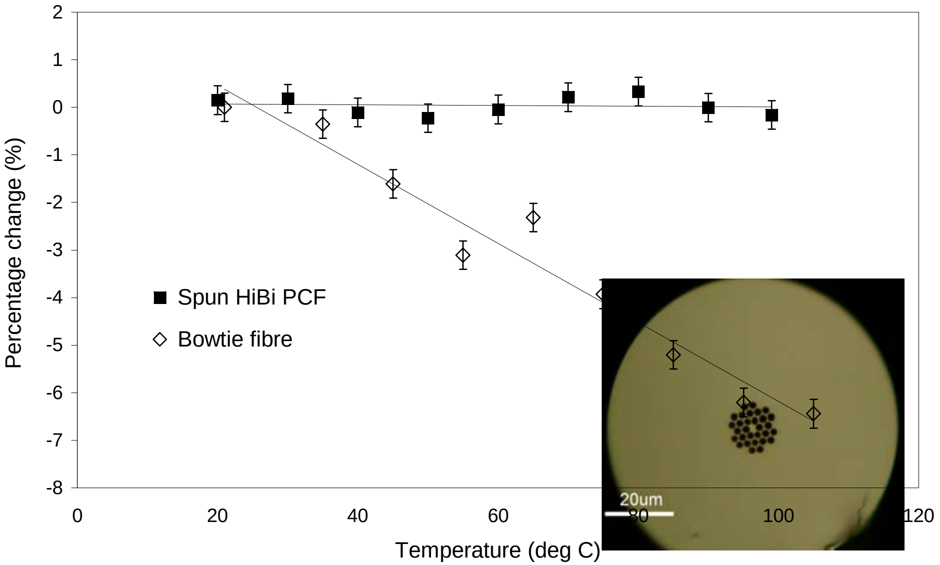


| **dopant** | $SiO_2$ | 20mol% $GeO_2$ | 12mol% $P_2O_5$ |
| --- | --- | --- | --- |
| $\alpha$ **x**$10^{-6}$ | 0.55 | 2.8 x$10^{-6}$ | 2.0x$10^{-6}$ |

# Temperature Independence
# - Form birefringence




**Linear hi-bi**




**spun hi-bi**

Elliptical Group birefringence ~2x10-3
*Order magnitude higher than stress hi-bi*

- >10x bow-tie fibre birefringence
- T insensitive
- Spin pitch ~7mm
- Small <2um core ideal for nonlinear work and gas detection
- Easy to cleave and splice
- Ideal for gyroscopes, current sensing, compact polarisers etc

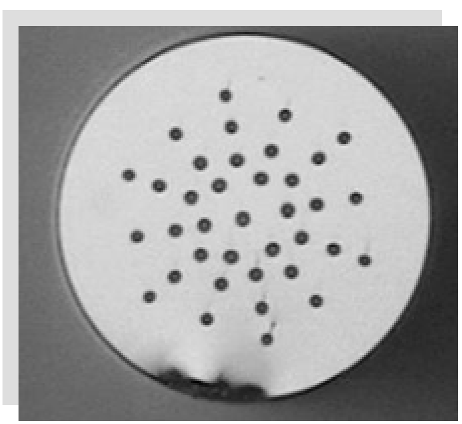
# Gratings in fibres

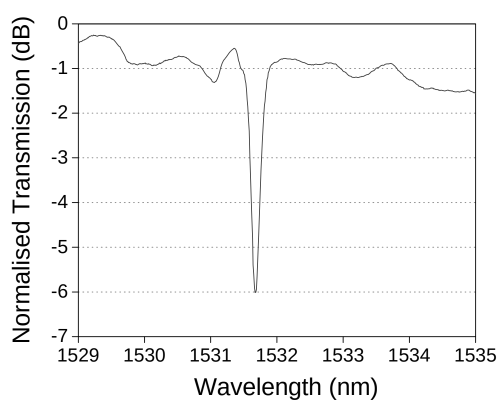
Strain and temperature:

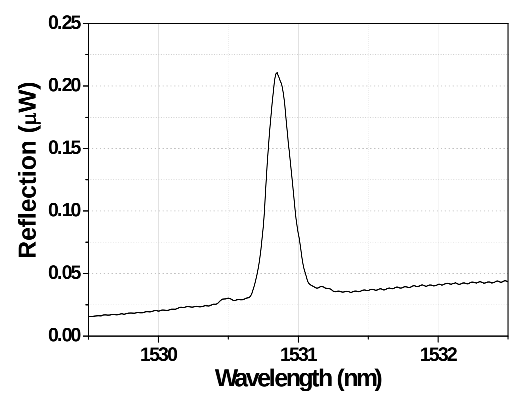
$$\frac{\Delta\lambda_{\mathbf{B}}}{\lambda_B} = \frac{\Delta n}{n} + \frac{\Delta\Lambda}{\Lambda} = (1-\rho)\varepsilon + \kappa T$$

where $\boldsymbol{\rho}$ **is the elasto-optic coefficient** of the fibre and $\boldsymbol{\kappa}$ **is the thermo-optic coefficient**. The particular expression for studying specific stain parameters introduced by pressure can be obtained by noting Poisson’s ratio.

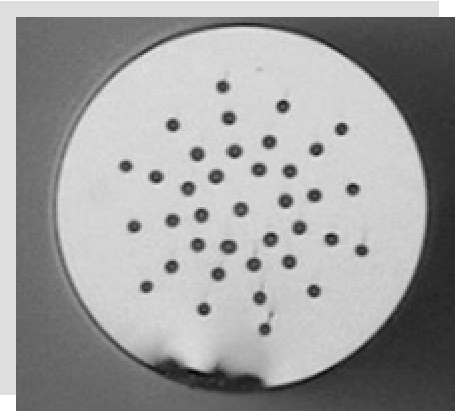
- Fibres with one or more materials have added complexity with different thermal expansion coefficients.
- Frozen in fibre stresses very sensitive to fabrication preparation (tensile or compressive possible).



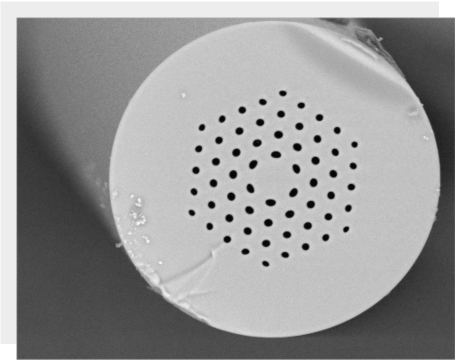


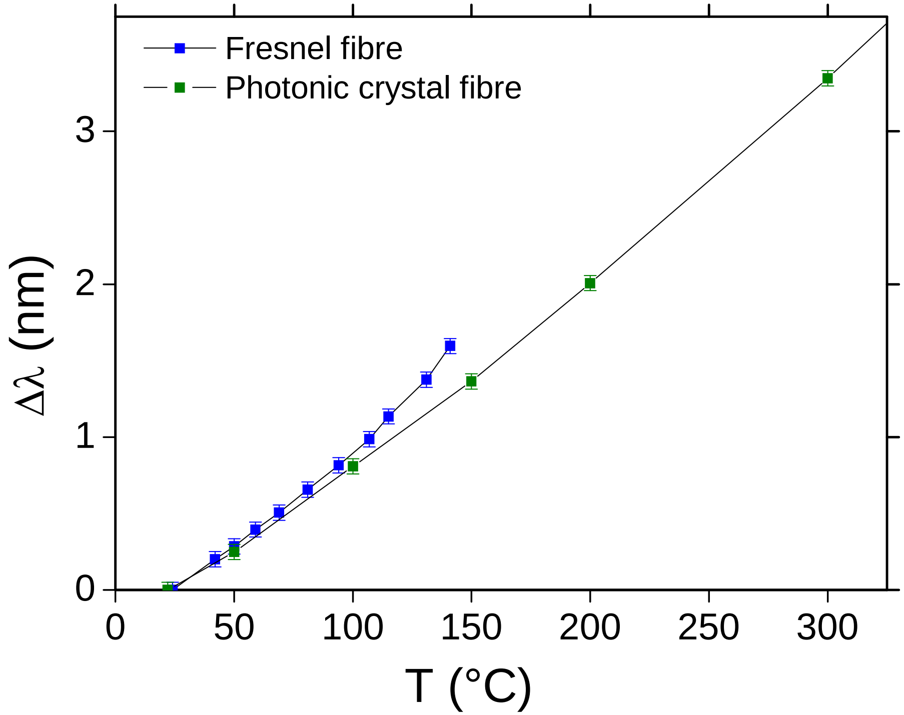
# T dependence of two structured fibre gratings



**Fresnel fibre**
**Strongly quadratic**



**Photonic crystal fibre**
**Weakly quadratic, nearly linear**



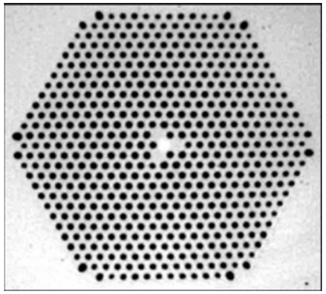

*Canning, J of Sensors 2009*

- **Radial dependence of the mode field and leakage**
- **Fresnel coupling between hole localised mode and glass ring mode also changes**
- **You can tailor a macro-property such as the effective thermooptic coefficient by design.**
- **Separate T and strain for sensors - strain dependence is linear for both.**

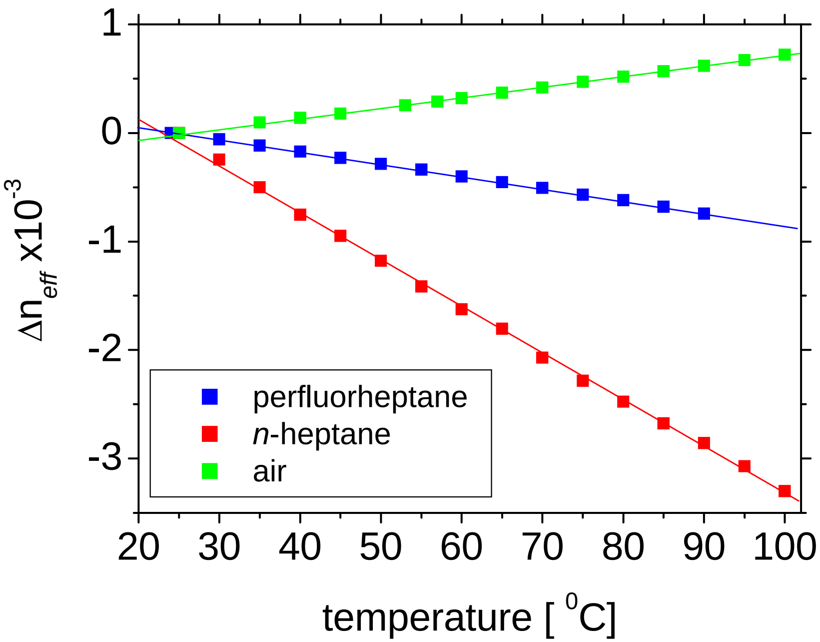
# Separating strain and T

- Single material – lower T sensitivity
- Composite material system – can adjust thermal and mechanical properties by controlling holes (Martelli et al.)
- Make all-solid PCFs with selected expansion coefficients and distribution?
- Put **materials** in the holes – can adjust thermal and mechanical properties by filling holes (Sorenson et al.)

# T insensitivity: materials in the holes



- **Change macro thermo-optic coefficient by adjusting material in holes**

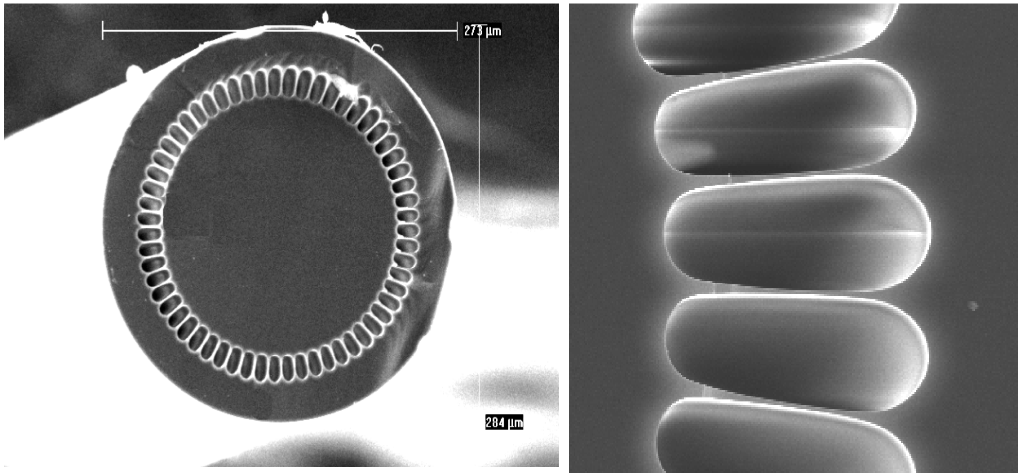



**Grating based measurements**

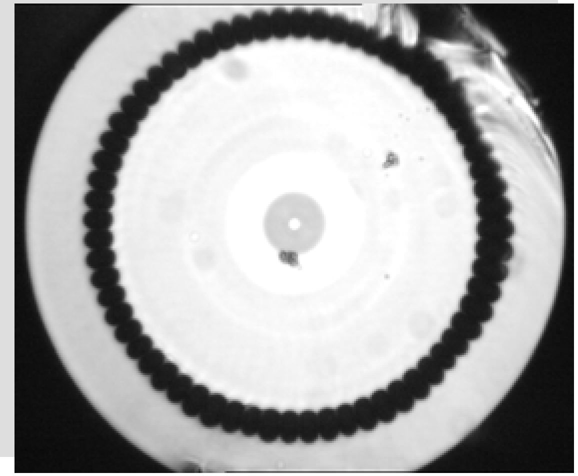
*Sørensen et al. Opt. Comm. 2006.*

- Organic liquids often have –dn/dT.
- By selecting appropriate liquids, fibre dn/dT can be made negative or even zero!
- Simple way of packaging optical components such as gratings.
- Complete separation of T from strain measurements.
- Further adjustment by playing with hole distribution (fraction of light in holes).
- Simple method for determining dn/dT

# Light Collection



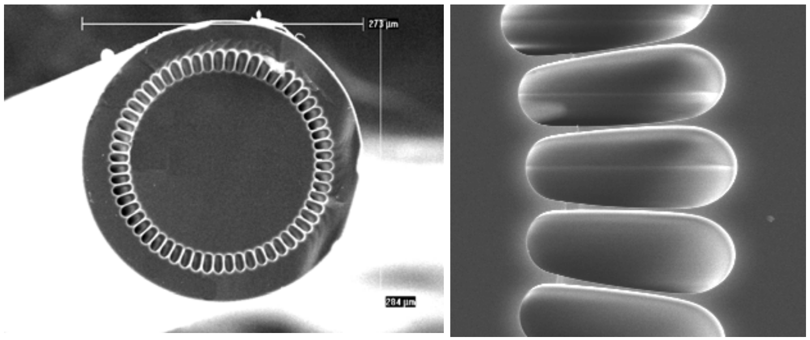

**Single material air-clad**

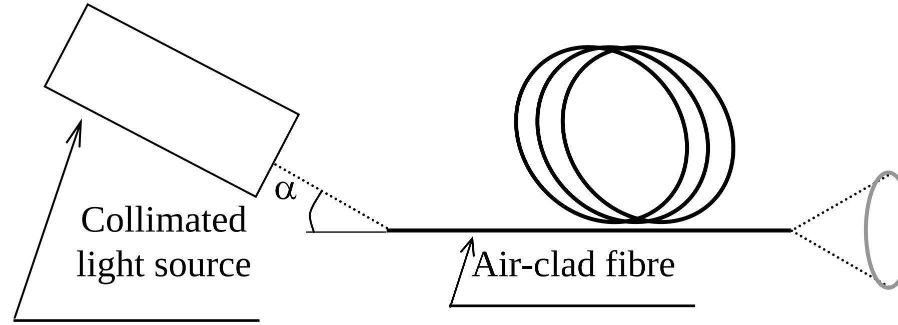


**Doped core air-clad**

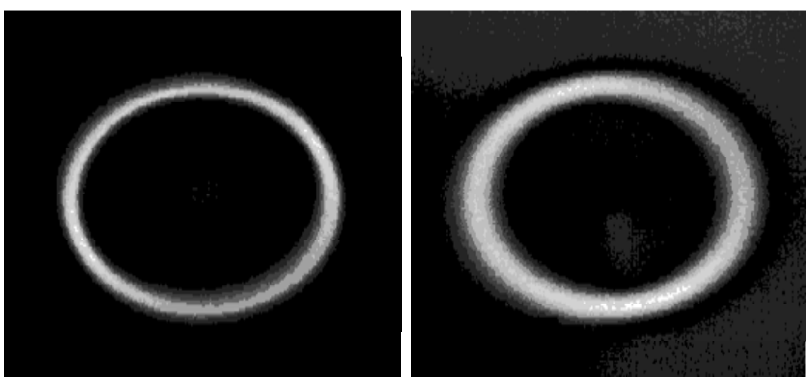
- *Patented by DiGiovanni et al 1986*
- High NA possible (>0.9 Bath University)
- Applications in astronomy, medicine, lasers, laser delivery etc

# Light Collection: air clad fibres for astrophotonics

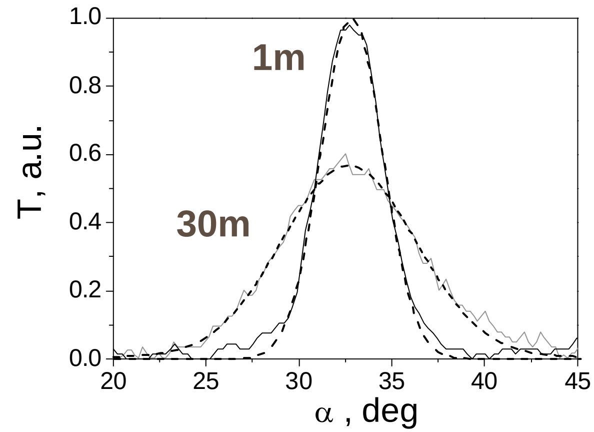





- Need for greater light collection.
- High NA air-clad fibres best
- All-silica, reduced T sensitivity, reduced radiation sensitivity
- But diffraction loss induced degradation of focal ratio degradation (FRD) occurs.

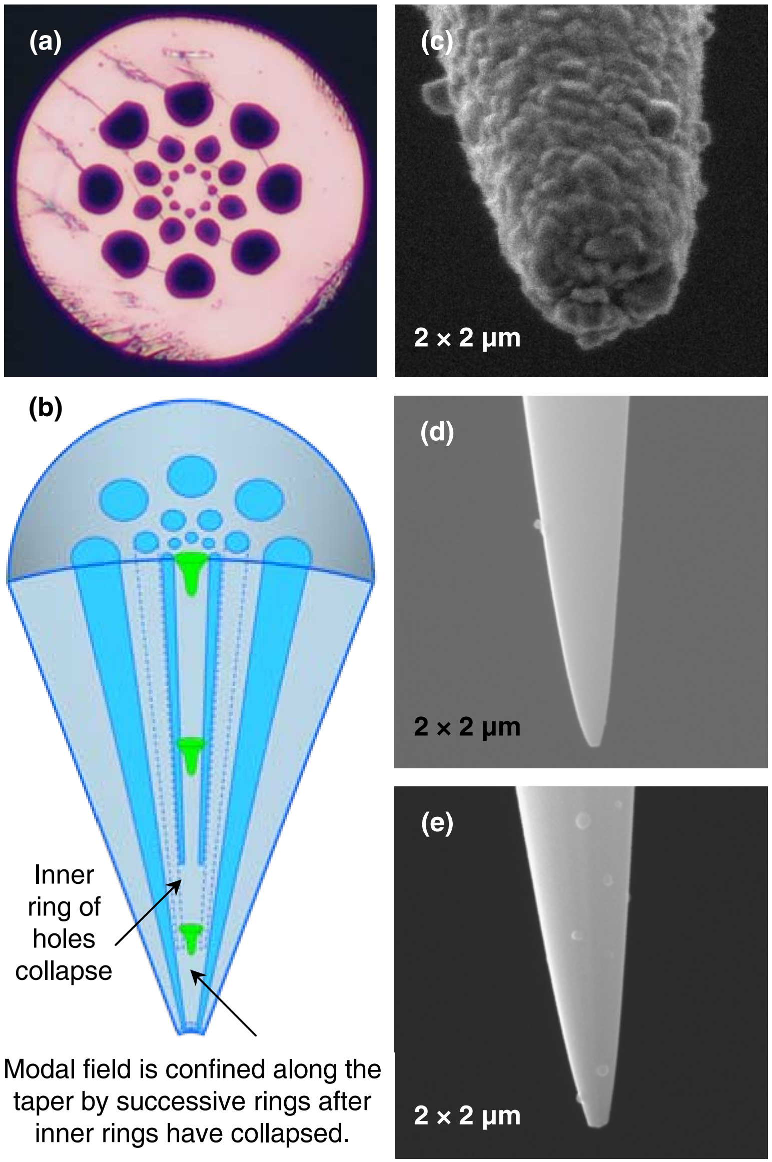


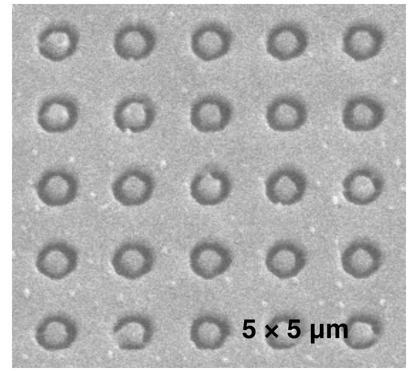
**1m** **30m**




*Aslund & Canning, Exp Astronomy. 2008*

# Light Collection: Tapering and near field imaging

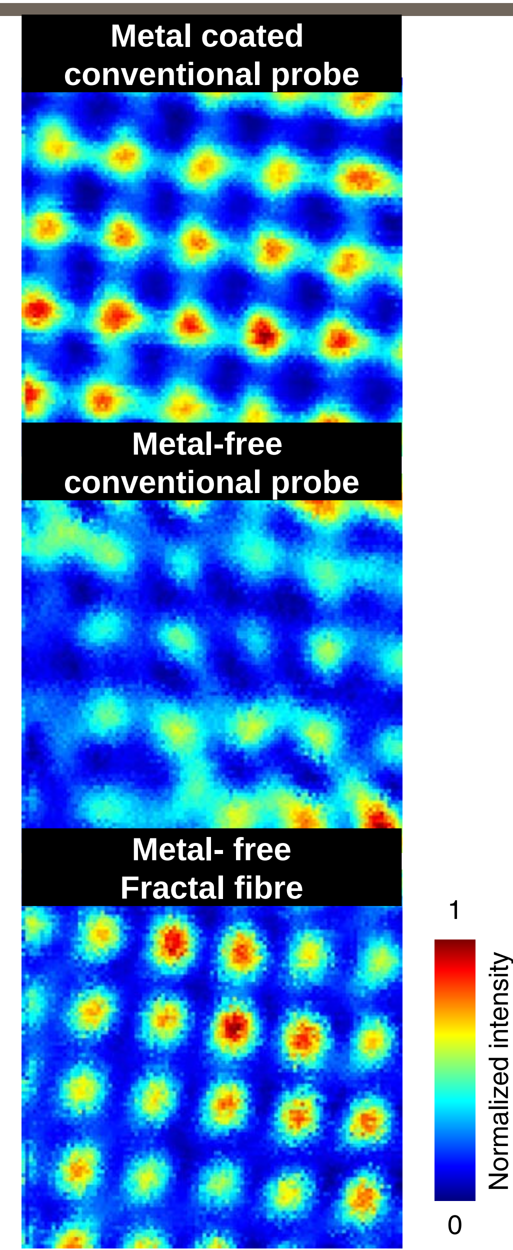



Metal-free Fresnel “fractal” probe outperforms metal coated conventional probe.

Low cost micro-diagnostics?

*Rollinson et al. Opt. Express 2008*



# Optical localisation and the near field for sensing

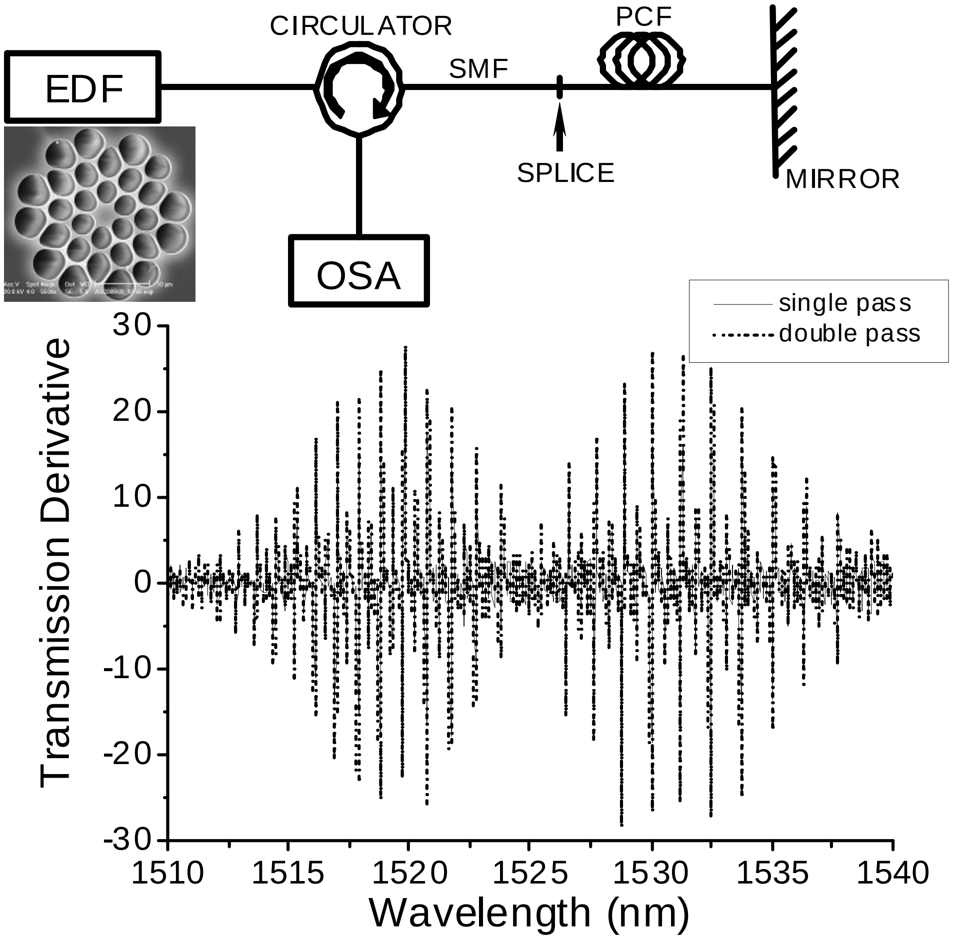



Fig. 2. All-fibre add-drop acetylene reference cell using a photonic crystal fibre (top). Spectra for both single pass an double pass of the cell are shown (bottom) [33]. (EDF – erbium doped fibre source, OSA – optical spectrum analyser, SMF – standard single mode fibre smf28, PCF – photonic crystal fibre: scanning electron microscope image of cross section shown above y-axis).

- Simple “bulk” channel detection
- Direct reference to bulk measurements makes implementation easy
- Scale sensitivity with fibre length and design.

# Optical localisation: thin films and new bands

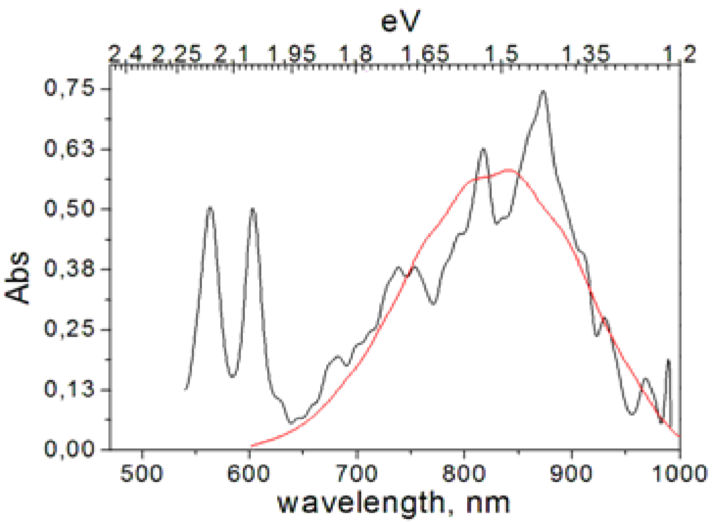
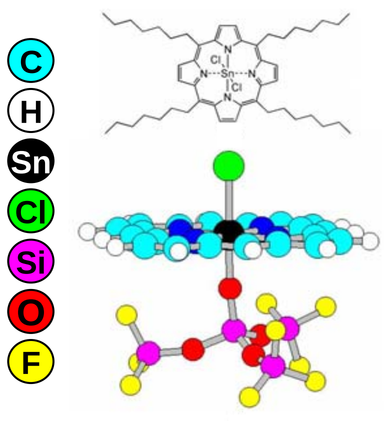


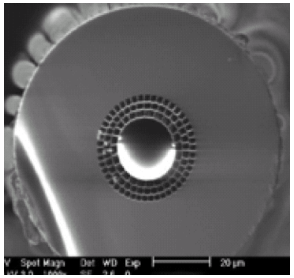

Fig. 3. Absorption measurement of PCF containing a porphyrin thin-film deposited on the surfaces of its holes in DMF: (length = 50 cm, absorption rescaled to 25 cm) the typical Q-band (559 & 599 nm) is observed along with a new near-IR band (660 - 930) nm. Numerical simulation is shown in red for a typical charge transfer band. More details can be found in [5].




- The greatest overlap is within 100nm of the surface of the holes in silica PCF.
- Use films to collect high concentrations at the surface.
- Additional field enhancement through optical impedance mismatch may improve sensitivity further.
- Porphyrin self assembly leads to specific attachment to surface.
- Postulated charge transfer bands experimentally observed for first time showing sensitivity on using near evanescent field detection.

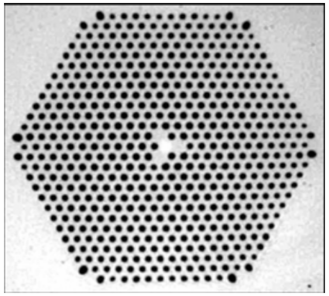
*Martelli et al. J. Am. Chem. Soc. 2008*

# Optical localisation: comparing fibre designs

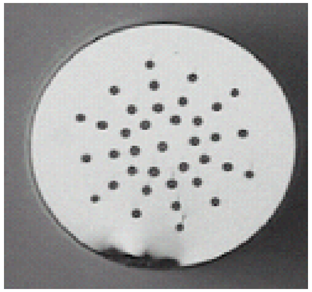


Air Bragg fibre Vienne & Deyerl *et al*, PDP25, OFC04

VS



VS



Bandgap

“Effective” index

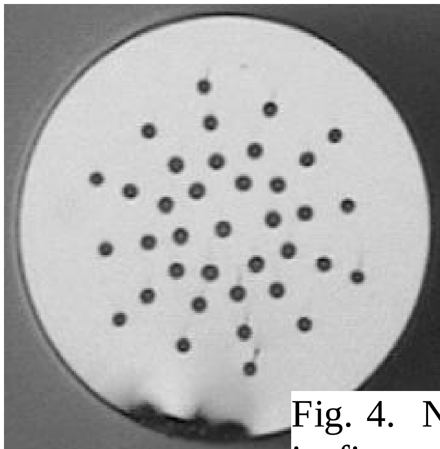
Fresnel

**Excellent overlap**
sensitive to perturbations
• index changes can shift bandgap far too much
• **cannot write gratings in air**
• higher fabrication tolerances required
• more expensive

**Reduced but good overlap possible**
less sensitive to perturbations at longer λ
• no bandgap effects at longer λ
• **easy to write gratings in core**
• easy to fabricate
• more expensive if doped core employed

**Excellent overlap in the centre**
Combines best of both worlds – diffractive properties of Fresnel fibre - bandgap
• **enough silica around the core to write gratings**
• **other issues**
• **very early development stage**

# Design fibres for optical localisation in air holes



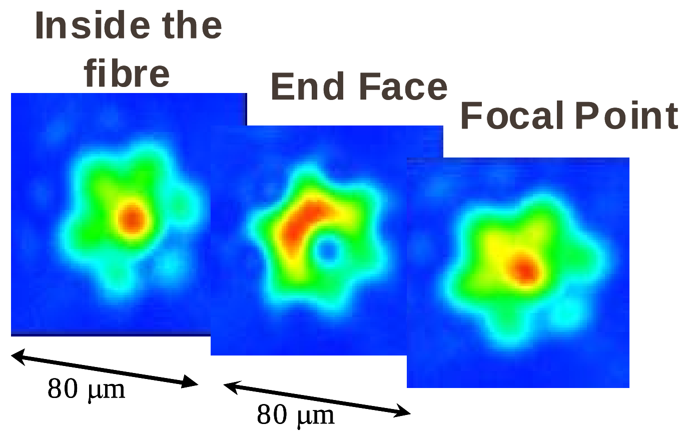
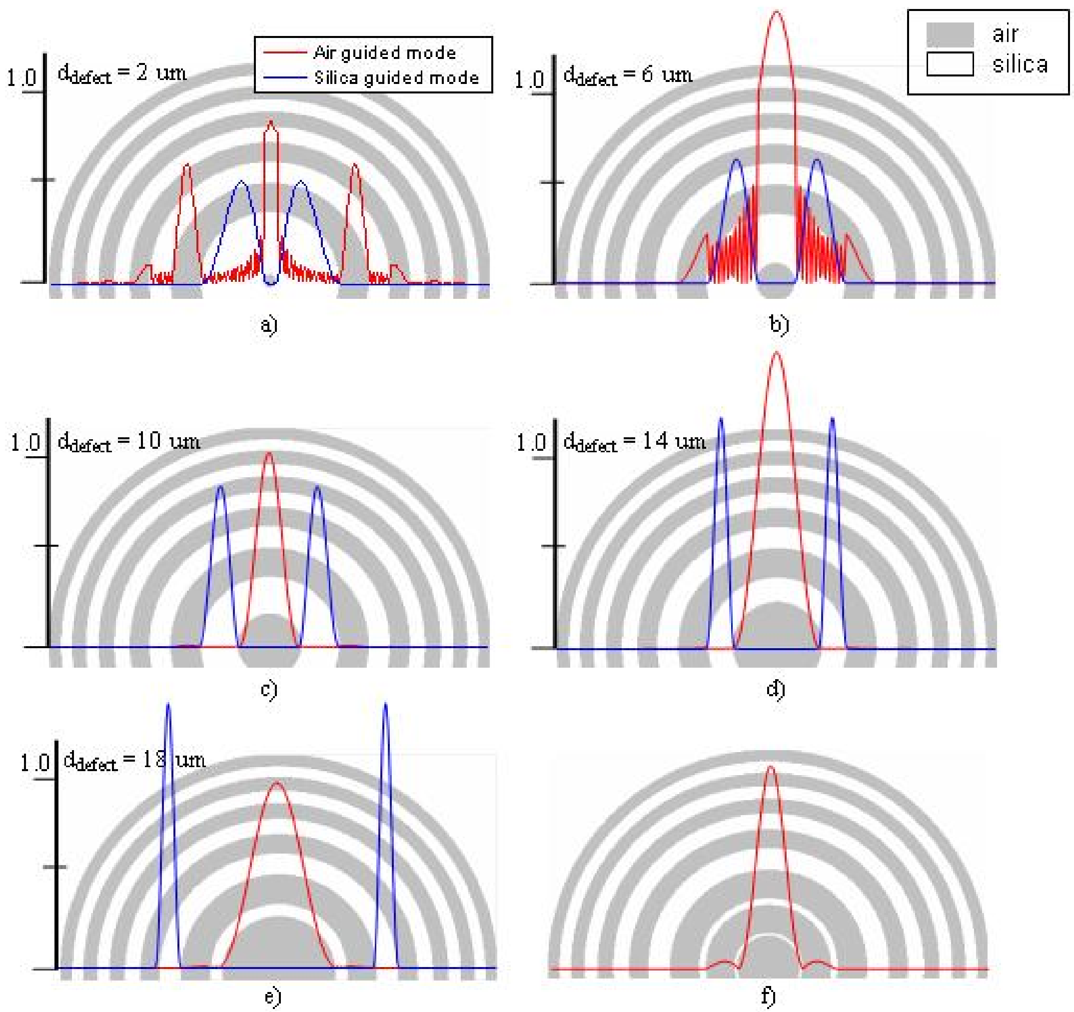



Fig. 4. Near field profile of the end of the Fresnel fibre shown in figure 1(c). The centre profile is the end face and the other profiles are imaged using an objective lens within and beyond the fibre respectively. Complex interfering supermodes are observed including one with tight optical localisation within the hole.

- Enhance the field overlap with sample under test in holes.
- Important for short devices such as those needed in biodiagnostics
- Direct reference to bulk measurements
- **1st liquid filled bandgap core optical fibre** *(Martelli et al. opt. Exp 2006.)*

# Design fibres for optical localisation




**Numerical simulation supports localised light in air holes**

**Ideal for biodiagnostics etc**

**When air hole is small, efficient localisation can still be observed –**

**Maxwell's equation support high localisation at index discontinuities**

***Martelli et al. OFS 2006***

# Processing Structured Optical Fibres

## "Standard" technologies:

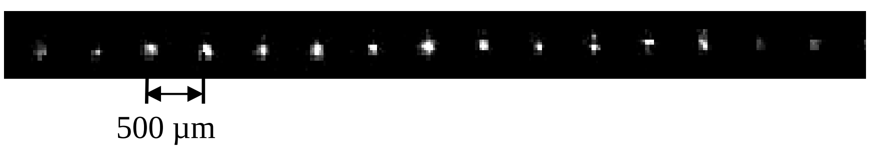
- **Laser Based**

  Both short and long period gratings
  - UV (1 & 2 photon)
  - Longer wavelengths (2-6 photon)

- **Other**

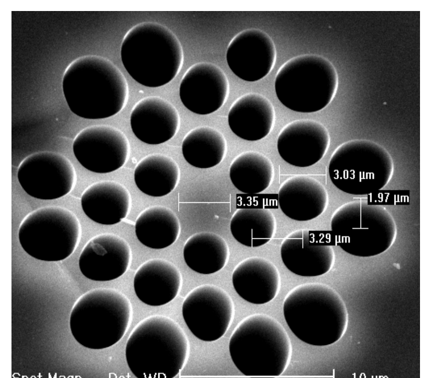
  Long period gratings
  - Long period gratings by arcing, $CO_2$ laser, ion beam etc

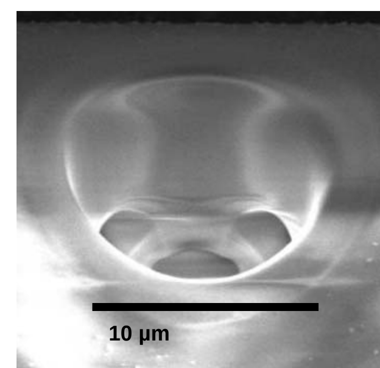
**Focus on directly written Bragg gratings written with UV and 800nm fs lasers.**




Long period gratings produced by ion beam milling

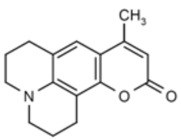
*Martelli et al. 2007*



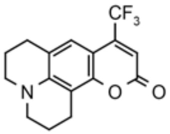



# Multiple and composite properties

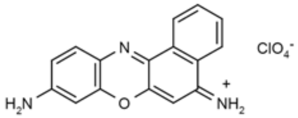
**Example: “white light” source based on 3 laser dyes**



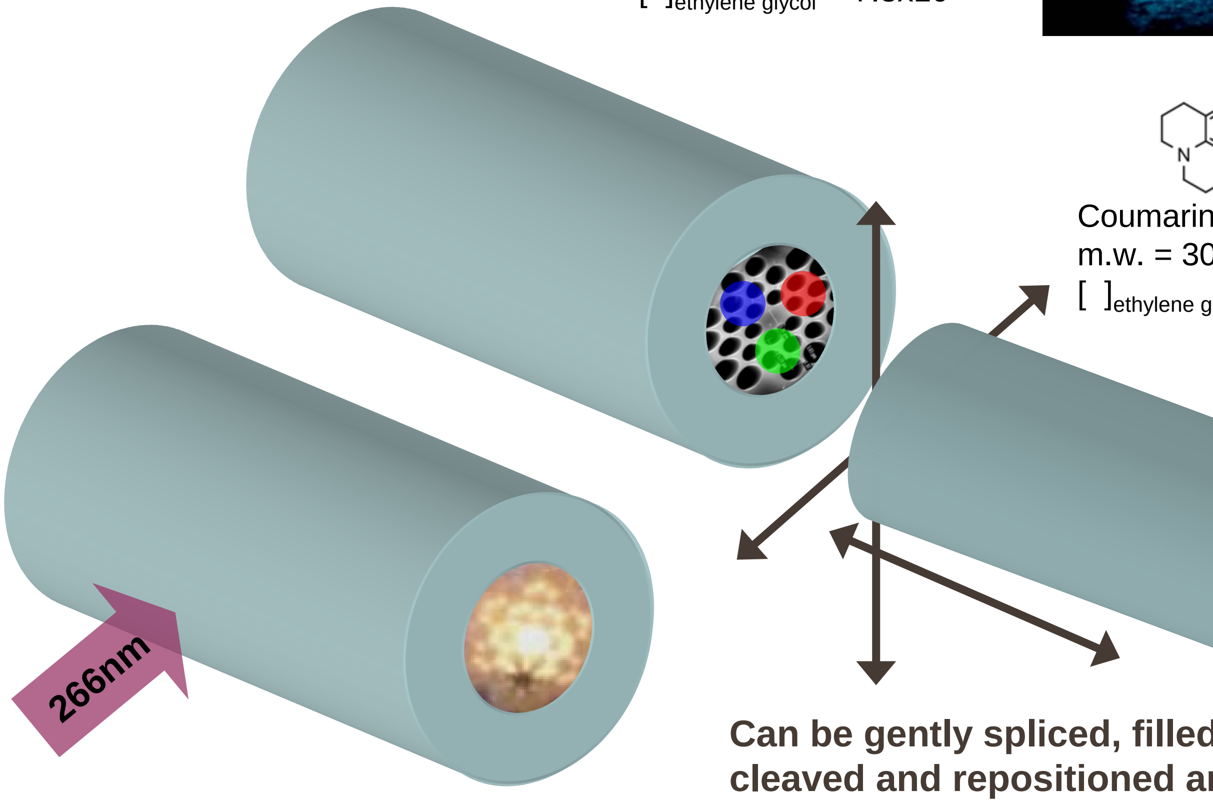

Coumarin 480
m.w. = 255.32
[ ]$_{ethylene\ glycol}$ = 7.8x10$^{-3}$




Coumarin 540a
m.w. = 309.29
[ ]$_{ethylene\ glycol}$ = 4x10$^{-3}$




Cresyl Violet 670 Perchlorate
m.w. = 361.74
[ ]$_{ethylene\ glycol}$ = 2.4x10$^{-3}$



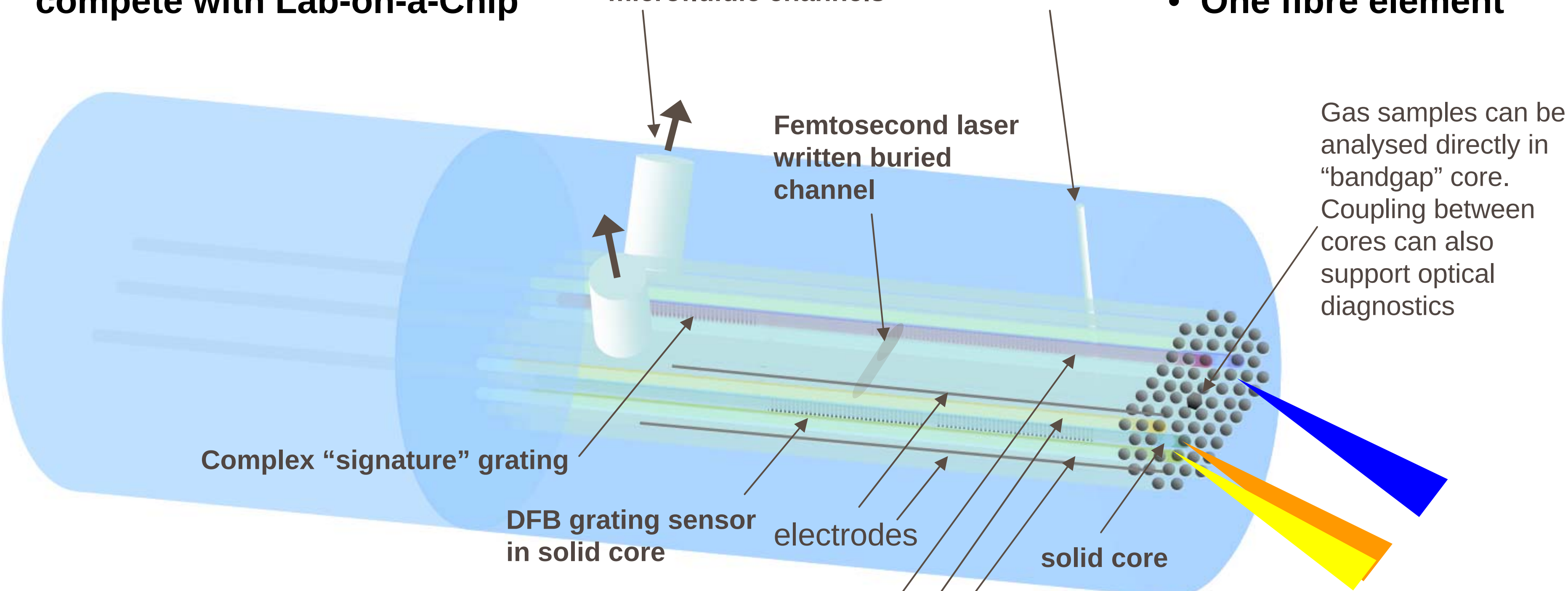

**Can be gently spliced, filled, cleaved and repositioned and respliced and filled elsewhere**

*Canning et al. Optics Express 2008*

# Lab-in-a-fibre

- **Potentially low cost, volume supply, easy integration to compete with Lab-on-a-Chip**

- **Multiple devices**
- **Multiple diagnostics**
- **One fibre element**




Channels lined with nano layers sensitive to specific chemicals. Changes in property probed by evanescent field from mode travelling in solid core, and at certain wavelengths resonant field in DFB structure.

Multiple samples under test can be drawn into holes by capillary action, pressure or electrokinetic effects using applied electric field.

• Aiming for the lab-in-a-fibre motivates the development on the way of new devices, **science** and technologies.

*(Canning ICOCN/ATF, 2006)*

# Conclusion

- Structured optical fibres form the basis for a number of new solutions and devices of potential value in sensing.
- The key integration of components with new materials is made possible by access of the evanescent field through holey channels
- Holey structure liberates the design of application specific functionality in optical fibres.

# Acknowledgments

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Australian Government

Australian Research Council

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