Microstructured optical fibres:

Opportunities & challenges

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Topics

- Introduction to PCF
- Compound glass PCF
- Hybrid two-glass structures
- Optomechanical structures
- Twisted fibres
- Final comments
Elounda, Crete: Summer 1995

Optimistic subtitle: "Photonic bandgaps by the km"
Some of the latest structures


new ways to guide light

Roberts et al, Opt. Exp. 13 (236-244) 2005

- 70 μm
- 20.5 μm
- 115 μm

1 dB/km at 1550 nm

fused silica
Hollow core 1 dB/km

2.8 million bounces per km (20 µm core, 1550 nm)

0.35 µdB/bounce (reflectivity 0.99999992)

all angles, all polarisation states

new mirror every time
Typical attenuation spectrum

Roberts et al, Opt. Exp. 13 (236-244) 2005
Loss peaks caused by surface states


Fraction of light in glass changes dramatically with wavelength of the light

735nm

746nm

820nm
Low loss mid IR silica fibre


core diameter 
~100 µm

loss (dB/km)
34 dB/km

wavelength (nm)

HCl lines

high loss band
Guidance mechanisms: summary

- **Total internal reflection**
  - core index must be higher than cladding index

- **Photonic band gap (PBG)**
  - core index not important (can be lower than cladding)
  - core resonance must coincide with PBG in the cladding
  - losses as low as 1 dB/km

- **Low leakage structures (ARROW** and kagome)**
  - core light anti-resonant with cladding states, i.e., not phase-matched
  - some light leaks into cladding, typical losses 1 dB/m

** anti-resonant reflection optical waveguides
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Xin Jiang
**Why bother with compound glasses?**


- Higher nonlinearity & refractive index
- Extended window of transparency (e.g., into the mid-IR)
- Higher rare-earth solubility

<table>
<thead>
<tr>
<th></th>
<th>Silica SiO₂</th>
<th>Chalcogenide AsGeSeTe</th>
<th>Tellurite TeO₂-based</th>
<th>Lead-silicate SF₆</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass transition temperature (°C)</td>
<td>1175</td>
<td>245</td>
<td>300</td>
<td>423</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.46</td>
<td>2.9</td>
<td>1.9-2.3</td>
<td>1.81</td>
</tr>
<tr>
<td>$n_2$ (m²/W)</td>
<td>$10^{-20}$</td>
<td>$10^{-17}$</td>
<td>$10^{-19}$</td>
<td>$10^{-19}$</td>
</tr>
<tr>
<td>Window of transparency (µm)</td>
<td>0.2-2.3</td>
<td>4-11</td>
<td>0.4-5</td>
<td>0.3-2.5</td>
</tr>
</tbody>
</table>
Viscosity control is key to fibre drawing

- hollow core soft-glass PCF difficult because of:
  - steep viscosity gradient with temperature
  - reactivity or thermal instability

![Graph showing temperature vs. log viscosity for different materials](image)

- **Tellurite**
- **Germanate**
- **Fused silica**

**Convenient viscosity range**
When things go wrong


Serious structural distortion in hollow-core SF6 PCF
When things go better


Increasing internal pressure during drawing
Transmission losses


Transmission (dBm)

-60
-75
-90
-100
-110
-120

Loss (dB/m)

-10
-20
-30
-40
-50
-60
-70
-80
-90
-100

Wavelength (nm)

700
800
900
1000
1100

Pitch 7.6 µm

Bulk glass loss

~2 dB/m

0.74 dB/m
Finite element modelling

Finite element modelling


• 20 µm
• 20 cm length
• launch LP_{11} mode
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Hybrid glass-glass structures

- Pressure-assisted melt-filling technique:
  - low-melting-point glasses in a fused silica host matrix
  - strand diameters as narrow as 200 nm

- Viscosity: 5 Pa.s
- Temperature: 665°C
- Pressure: 50 bar
Hybrid glass-glass structures

- Pressure-assisted melt-filling technique:
  - low-melting-point glasses in a fused silica host matrix
  - strand diameters as narrow as 200 nm
- Overcomes viscosity and process incompatibility of silica and non-silicate optical glasses
- Unique waveguiding devices with:
  - high core-cladding index-contrast
  - high optical non-linearity
  - wide transparency windows into the mid infrared
- Very small quantities of filling material required:
  - protected from environmental contact
  - ultra-high cooling rates possible
  - difficult-to-handle or reactive optical glasses can be used
Hybrid chalcogenide-silica fibre


chalcogenide glass $\text{Ga}_4\text{Ge}_{21}\text{Sb}_{10}\text{S}_{65}$
(unsuitable for fibre drawing)

- index contrast reversed:
  photonic bandgap guidance

1.45 μm

silica host

5 μm
Transmission spectrum

![Diagram of transmission setup with labels: OBJ, sample, iris, MM fiber, OSA. Graphs showing dBm and dB/cm vs. wavelength. Peaks and valleys indicate transmission and attenuation levels.]

Transmission

Attenuation
Modes in chalcogenide strands


confocal microscope
Supercontinuum in $\text{Ga}_4\text{Ge}_{21}\text{Sb}_{10}\text{S}_{65}$ core


- $\text{Ga}_4\text{Ge}_{21}\text{Sb}_{10}\text{S}_{65}$ strand:
  - diameter 1.6 µm
  - length ~10 mm
  - ZDW 1500 nm

- **Er fibre laser**
  - 1550 nm
  - 100 MHz
  - 60 fs
Numerical modelling: As$_2$S$_3$ strand

zero dispersion wavelength

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Stripe waveguide in fibre: 1974


80 dB/km at 600 nm

50 µm

10 µm
Fabricating nanowebs


capillaries  jacket

preform

vacuum

heat & draw

nanoweb-fiber
Dual nano-web fibre


- two suspended air-clad silica nanowebs
- long optomechanical interaction length
Optomechanical self-channelling


- optomechanical nonlinear refractive index
- formation of self-channeled guided beams
- highly non-local nonlinearity
Guiding dual-nanoweb fiber

- fabricated by stack-and-draw technique
- web thickness 440 nm, spacing 550 nm, width 22 μm
- slightly convex thickness profile
Interferometric set-up

Lorentzian response


294 $\text{W}^{-1}\text{m}^{-1}$

20,000 times larger than Kerr effect at resonance

$\gamma_{\text{OM}}$ ($\text{W}^{-1}\text{m}^{-1}$)

$\Omega$ (MHz)

14 $\text{W}^{-1}\text{m}^{-1}$

$\pi/2$ phase
Measurements at different pressures

Dual nanoweb structure

- Higher optomechanical nonlinearity possible by thinner and longer webs
- Dynamic nonlinearities > 20,000 times greater than Kerr effect
- Gas stiffness & damping affect resonances
- Q factor enhancement in evacuated fiber
- Possible applications as a highly sensitive static or dynamic fiber pressure sensor
- Ultimate goal: self-channelling
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Solid core PCF (1995)

Knight et al., Opt. Lett. 21, 1547 (1996)

\[ n_{\text{core}} > n_{\text{cladding}} \]

hollow channels

silica glass

\(~100 \mu m\)
Twisted solid-core PCF

- twist rate
  \[ \alpha = \frac{2\pi}{L} \]
- pitch \( L \) is much greater than inter-hole spacing
- angle between hollow channels and axis increases with radius
Transmission spectra

$L = 581 \, \mu m$

inter-hole spacing
$\sim 3 \, \mu m$

$L = 462 \, \mu m$
Twist rate versus resonant wavelength

Wong et al: Science 337, 446 (2012)

\[ n_{SM} \rho^2 \alpha = l \frac{\lambda}{2\pi} \]

Dip positions

Mode order

Twist rate (rad/mm)

Wavelength (µm)
Twisted solid-core PCF

Wong et al: Science 337, 446 (2012)

Twist rate
\[ \alpha = \frac{2\pi}{L} \]

Top-view

radius

\[ \sin \phi = \frac{\rho \alpha}{\sqrt{1 + (\rho \alpha)^2}} \approx \rho \alpha \]

\[ n_{SM} \rho^2 \alpha = \frac{l}{2\pi} \frac{\lambda}{2} \]

mode order
Consistent mode orders

Wong et al: Science 337, 446 (2012)

\[
\frac{1}{\lambda} = \left( \frac{1}{2\pi n_{SM} \rho^2 \alpha} \right) \cdot l
\]

Fits obtained for \( n_{SM} \rho^2 = 54.6 \ \mu m^2 \)
FE Modelling: Axial Poynting vector

pitch 461 µm
FE Modelling: Axial Poynting vector

pitch 461 µm

1/λ (µm⁻¹)

0 1 2 3 4 5 6 7 8

mode order, l

10.8 rad/mm
18.4 rad/mm

d c b a
FE Modelling: Axial Poynting vector

pitch 461 µm
FE Modelling: Axial Poynting vector

pitch 461 µm
Twisted fibres

• Leaky ring-shaped resonances form in the twisted cladding of helical photonic crystal fibre
• Complex filtering characteristics possible by varying the pitch along the fibre
• Twisting during fibre drawing allows extremely long lengths to be produced
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Final comments

Requirements

- Hollow core PCF made from "soft" glasses needs more development:
  - high power delivery of IR radiation, e.g. 10 microns, not yet available
  - losses can be orders of magnitude lower than the bulk glass
- New techniques for producing nano-scale glass fibre structures
  - flow-focusing?
  - new kinds of extrusion?
- Optical glasses with other properties, e.g., magneto-optical, UV transparent, are highly desirable

Applications

- Lab-in fibre:
  - (photo)chemistry using PCF as a microfluidic channel that guides light
- Optomechanics
  - hollow core PCF for laser manipulation of particles & cells
  - intense nonlinear optoacoustic modulation driven by light
- Nonlinear optical devices
  - exquisite control of ultrafast nonlinear optics in gases (e.g., tunable deep UV light)
  - supercontinuum generation from compact pump lasers
- Nanowire plasmonics
  - devices based on metallic nanowire arrays