Recent Advances in the Development of Highly Nonlinear Microstructured Fibres

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Thanks and credits

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- M. L. V. Tse
- A. Camerlingo
- M. N. Petrovich
- J. Y. Y. Leong
- P. Horak
- F. Parmigiani
- P. Petropoulos
- T. M. Monro
- W. H. Loh
- D. J. Richardson
Background

• A large variety of all-optical processing functionalities can be implemented in an optical fibre by exploiting its $\chi^{(3)}$ nonlinearity:

  - Wavelength conversion
  - Demultiplexing
  - Regeneration
  - Clock recovery
  - Parametric amplification
  - Pulse compression
  - Supercontinuum generation

• Different requirements, but all generally benefit from high effective fibre nonlinearity:

  \[ \gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{\text{eff}}} \]

  - Low operational power and short fibre lengths

• Microstructured Optical Fibres (MOFs) provide a way to achieve tight confinement (low $A_{\text{eff}}$) in glasses with high $n_2$
Glass choice

- MOFs, often single material, allow the use of a broad range of glasses →
- Besides a high $\gamma$, efficient nonlinear processes also require a tailored group velocity dispersion ▼

- Different glasses require different amount of waveguide dispersion to achieve the target →
Outline

- High $\gamma$ fibres and tapers;
- Dispersion flattened MOFs (silica);
- High $\gamma$ and dispersion flattened MOFs (non silica);
- Nonlinearity in large mode area, multimode fibres;
- Conclusion and outlook.
High $\gamma$ fibres

Target: achieve the highest possible nonlinearity

- **Bi$_2$O$_3$–based glass step index fibres**

  \[ \Phi = 1.72 \mu m; \quad n_1 = 2.22; \quad n_2 = 2.13; \quad \gamma \sim 1360 W^{-1}km^{-1} \]
  \[ D = -250 ps/nm/km \]
  \[ \alpha = 1.9 \text{ dB/m} \ (0.8 \text{ dB/m}) \]

- **Nano–tapered As$_2$Se$_3$ fibres**

  \[ \Phi = 1.2 \mu m; \quad \gamma \sim 68000 W^{-1}km^{-1} \]
  \[ D \sim 0 \text{ ps/nm/km} \]

\[ \Phi = 0.95 \mu m; \quad \gamma \sim 93000 W^{-1}km^{-1}; \quad D \sim 250 \text{ ps/nm/km} \]

\[ \Phi = 1.2 \mu m; \quad \gamma \sim 68000 W^{-1}km^{-1} \]
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\[ \Phi = 0.95 \mu m; \quad \gamma \sim 93000 W^{-1}km^{-1} \]
  \[ D \sim 250 \text{ ps/nm/km} \]

Suspended core/Wagon wheel

- Similar to air−suspended rod configuration
- Maximum nonlinearity for diameter smaller than wavelength
- Fabricated in various glasses:
  - Schott SF57:
    \[ d \approx 1\,\mu m; \gamma = 1860\, W^{-1}\, km^{-1} \]
  - Tellurite:
    \[ d \approx 2.1\,\mu m; \gamma = 280\, W^{-1}\, km^{-1} \]
  - Bismuth oxide:
    \[ d \approx 0.53\,\mu m; \gamma = 5400\, W^{-1}\, km^{-1} \]

- Limited dispersion control
- Large dispersion slope
Vector effects $\rightarrow$ higher nonlinearity!

- The effective fibre nonlinearity $\gamma$ is usually derived via use of the weak guidance and homogeneous x-section approximations;
- Both these assumption break down in waveguides with sub-wavelength features and high index materials because of non-negligible $z$-component of electromagnetic fields;

- New definition proposed:

$$\gamma^\nu = \frac{2\pi}{\lambda} \frac{n^2}{\Delta A_{\text{eff}}}$$

$$A_{\text{eff}} = \frac{\int (e^\nu \times h_{\nu}^*) \cdot \hat{z} dA}{\int |(e^\nu \times h_{\nu}^*) \cdot \hat{z}|^2 dA}$$

$$\overline{n}^2 = \frac{k(\varepsilon_0/\mu_0)}{3} \int n^2(x,y) n_2(x,y) [2|e^\nu|^4 + \left|e_{\nu}^2\right|^2] dA$$

Courtesy of Dr Shahraam Afshar, Univ. Adelaide

S. Afshar et al. OE 17, 2298 (2009)
Outline

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• Dispersion flattened MOFs (silica);

• High $\gamma$ and dispersion flattened MOFs (non silica);

• Nonlinearity in large mode area, multimode fibres;

• Conclusion and outlook.
Dispersion flattened MOFs at 1550 nm

W. Reeves et al. OE 10, 609 (2002).
11 rings of holes

W. Reeves et al. OFC (2003), FI3.
13 rings of holes:

- ~ 600 capillaries
- $\gamma \sim 3 \text{ W}^{-1}\text{km}^{-1}$


(full vector FEM sims)
Many designs to reduce complexity...

Poletti et al, OE 13, 3728 (2005)  
Saitoh et al, OE 13, 8365 (2005)

Dispersion (ps/nm/km)

- Ultra-broadband flatness theoretically achievable;

- BUT: pretty low nonlinearity:
  \[ \gamma \sim 10 \text{ W}^{-1} \text{ km}^{-1} \quad \gamma \sim 4 \text{ W}^{-1} \text{ km}^{-1} \quad \gamma \sim 12 \text{ W}^{-1} \text{ km}^{-1} \]
... and extremely tight fabrication tolerances

Errors in the dimension of the first ring of holes ($d_1$) introduce severe third order dispersion contribution;

$$\Rightarrow 1-2\% \text{ max deviation from target values required}$$

Differently sized holes expand or compress differently during fibre draw

$$\Rightarrow$$

Size precompensation is needed, but difficult to achieve structural and dispersion targets!

Target

Easier design at 1050 nm

1050nm TARGET:
\[ \Lambda = 1.5 \mu m; \frac{d}{\Lambda} = 0.41 \]

Larger targeted \( \frac{d}{\Lambda} \) AND shorter wavelength

6 rings of holes (all equal) are enough to generate negligible confinement loss.

\[ A_{\text{eff}} = 4.4 \mu m^2 \]
\[ \gamma = 29.4 W^{-1} km^{-1} \]

Dynamics of SC in fibres with 2 ZDW

- Decreasing the anomalous dispersion region.
- Decreasing in SC bandwidth.
Outline

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High $\gamma$, dispersion flattened fibres

- Same idea but using glasses, with higher $n_2$:
- e.g. Schott SF57:  $n = 1.8$
  $n_2 = 4.1 \times 10^{-20} \text{ m}^2/\text{W}$

Best design:
$\Lambda = 1.38 \mu\text{m}; d/\Lambda = 0.46$

5 rings of holes: negligible confinement loss
$\gamma \sim 470 \text{ W}^{-1}\text{km}^{-1}$ @ 1550 nm

Issue: Temperature gradient inside preform and rapid change of viscosity with temperature make fabrication of soft glass fibres with many rings of holes – even all equal – extremely difficult
Structured Element approach


Jacketing tube

7-hole cladding Preform

6-hole core Preform

Target: \( \Lambda = 1.31 \mu m \)
\( d = 0.48 \Lambda \)

<table>
<thead>
<tr>
<th>Wavelength (( \mu m ))</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
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<tr>
<td>D at 1550 nm [ps/nm/km]</td>
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<td>Nonlinear parameter [1/Wkm]</td>
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<tr>
<td>measured</td>
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<tr>
<td>Fibre 1</td>
<td>4</td>
<td>2</td>
<td>170</td>
<td>172</td>
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<tr>
<td>Fibre 2</td>
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<td>246</td>
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<td>Fibre 3</td>
<td>55</td>
<td>49</td>
<td>414</td>
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</tbody>
</table>

\( \rightarrow DS \sim 0.2 \text{ ps/nm}^2/\text{km}; \alpha = 3.2 \text{ dB/m} \)

Double cladding approach

- 3 inner rings to control the dispersion;
- Large outer holes to reduce confinement loss

**Extruded Schott SF57 preform**

(note the hole size pre-compensation)

X. Feng et al. CLEO-EU 2009, CE3.4

**Microstructure parameters:**

- inner cladding: $\Lambda_1=1.60 \, \mu m$, $d_1/\Lambda_1=0.35-0.5$;
- outer cladding: $d_2/\Lambda_2=0.85$

From modelling: negligible confinement loss

**Modelling results @ 1.55μm:**

$\gamma = 310 \, W^{-1}km^{-1}$,
$D = -18.3 \, ps/nm/km$,
$DS = 0.08 \, ps/nm^2/km$

**Measurement results @ 1.55μm:**

$\gamma = 270 \, W^{-1}km^{-1}$,
$D = -17 \, ps/nm/km$,
$DS < 0.10 \, ps/nm^2/km$,
Loss = $3.0 \pm 0.1 \, dB/m$
All solid, high index contrast 1-D approach

- Two compatible glasses
- Extrusion of stacked polished disks
- Control of thickness allows dispersion control

\[
\text{Schott SF6: } n=1.76, n^2 = 22 \times 10^{-20} \text{ m}^2/\text{W};
\]

\[
\text{Schott LLF1: } n=1.53, n^2 = 6 \times 10^{-20} \text{ m}^2/\text{W}
\]

X. Feng et al. CLEOEU 2009, CE3.4

Modelling results @ 1.55mm:
\[
\begin{align*}
\gamma &= 130 \text{ W}^{-1}\text{km}^{-1}, \\
D &= 13.3 \text{ ps/nm/km}, \\
\text{DS} &= 0.16 \text{ ps/nm}^2/\text{km}
\end{align*}
\]

Measurement results @ 1.55μm:
\[
\begin{align*}
\gamma &= 120 \text{ W}^{-1}\text{km}^{-1}, \\
D &= 12.5 \text{ ps/nm/km}, \\
\text{DS} &\sim 0.15 \text{ ps/nm}^2/\text{km}, \\
\text{Loss} &= 0.8 \pm 0.2 \text{ dB/m}
\end{align*}
\]
Nonlinear liquid filled MOF

- Silica hollow MOF
- Core selective filling: Carbon disulfide (CS₂)

Transmission (%)

@1.55μm

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>$n_2 \times 10^{20}$ [m²/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>1.44</td>
<td>2.3</td>
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<tr>
<td>CS₂</td>
<td>1.59</td>
<td>320</td>
</tr>
</tbody>
</table>

Poletti et al, PTL 20, 1449 (2008)

- Inverse design to optimise dispersion flatness;
- Optimum structure: $\Lambda = 1.36$ μm; $d/\Lambda = 0.75$
- 65% of the optical power in the liquid
  - $\gamma = 6776$ W⁻¹km⁻¹
  - $D \sim 0$; $DS \sim 0$ at 1550 nm
## Summary

<table>
<thead>
<tr>
<th>Core material</th>
<th>$\gamma$ [1/Wkm]</th>
<th>$D$ [ps/nm/km]</th>
<th>DS [ps/nm$^2$/km]</th>
<th>Core size [µm]</th>
<th>Loss [dB/m]</th>
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<tbody>
<tr>
<td>(target)</td>
<td>526</td>
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<td>0</td>
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<td>SF57</td>
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<td>250</td>
<td>23</td>
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<td>414</td>
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<td>(target)</td>
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<td>SF6</td>
<td>120</td>
<td>12.5</td>
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<td>0.8</td>
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<td>CS2</td>
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<td>1.0</td>
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<td>Nonlinear fibres at 1550 nm</td>
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<td><strong>Raman Pulse broadening</strong></td>
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<td><strong>Self similarity</strong></td>
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<td><strong>FWM</strong></td>
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<td><strong>Soliton dynamics</strong></td>
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<td><strong>Modulation instability</strong></td>
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<thead>
<tr>
<th>Fibre Types</th>
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<tbody>
<tr>
<td>Chalcogenide nano-tapers</td>
</tr>
<tr>
<td>Soft glass SIFs</td>
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<td>Suspended core soft glass MOFs</td>
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<tr>
<td>Highly nonlinear silica MOFs</td>
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<td>Dispersion flattened silica MOFs</td>
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<td>Silica HNLFs</td>
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<tr>
<td>Silica SIF</td>
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</table>

**References:**
- T. Nagashima et al. ECOC 2006, We 1.3.2
- X. Feng et al. CLEOEU 2009, CE3.4
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• Conclusion and outlook.
Nonlinearity in large mode area fibres

- Constant increase in ultrashort pulsed laser peak demands for fibres with larger and larger mode area;
- Various schemes to maintain good beam quality above a few 1000s μm²; in practice it is difficult to maintain strict single-mode guidance.
  - Can we STUDY numerically MM nonlinear effects?
  - Can we AVOID them?
  - Can we EXPLOIT them?

\[ \text{High peak powers} \quad \text{Ultrashort pulse durations} \]

\[ \text{Multimode GNLSE} \quad \text{Multimode waveguides} \]
Multimode GNLSE

- Expand laser field in fibre modes
  \[ E(x, y, z, t) = \sum_{n} F_n(x, y) A_n(z, t) \]

- Derive set of coupled differential equations for temporal mode amplitudes (equivalent to the single-mode NLSE)

\[
\frac{\partial A_p(z, t)}{\partial z} = i(\beta_0^{(p)} - \beta_0)A_p(z, t) - (\beta_1^{(p)} - \beta_1)\frac{\partial A_p(z, t)}{\partial t} + i \sum_{n \geq 2} \frac{\beta_n^{(p)}}{n!} \left( i \frac{\partial}{\partial t} \right)^n A_p(z, t) \\
+ i \frac{n_2 \omega_0}{c} \sum_{l,m,n} \left\{ \left(1 + i \tau_{plmn}^{(1)} \frac{\partial}{\partial t} \right) Q_{plmn}^{(1)}(\omega_0) 2A_l(z, t) \int d\tau R(\tau) A_m(z, t - \tau) A_n^*(z, t - \tau) \right. \\
+ \left. \left(1 + i \tau_{plmn}^{(2)} \frac{\partial}{\partial t} \right) Q_{plmn}^{(2)}(\omega_0) A_l^*(z, t) \int d\tau R(\tau) A_m(z, t - \tau) A_n(z, t - \tau)e^{2i\omega_0\tau} \right\} 
\]

- Dispersion
- Kerr and Raman nonlinearity
- Mode overlap factors (incl. polarisation)
- Self-steepening

\[ R(\tau) = (1 - f_R)\delta(\tau) + \frac{3}{2} f_R h(\tau) \]

\[ Q_{plmn}^{(1)} \sim \int dx \, dy \, [F_p^* \cdot F_l][F_m \cdot F_n^*] \]

\[ Q_{plmn}^{(2)} \sim \int dx \, dy \, [F_p^* \cdot F_l^*][F_m \cdot F_n] \]

\[ \tau_{plmn}^{(1,2)} = \frac{1}{\omega_0} + \left\{ \frac{\partial}{\partial \omega} \ln \left[ Q_{plmn}^{(1,2)}(\omega) \right] \right\}_{\omega_0} \]

Multimode supercontinuum

- Launch only fundamental mode: sech with $T_0 = 100$ fs

$L=3 \ \mu m$, 7 modes $L=10 \ \mu m$, >100 modes

- Power transfer to mode $LP_{02}$ only: same symmetry as $LP_{01}$!
  $\Rightarrow 10^{-5}$ conversion efficiency

- 15 times larger pulse energy, but factor $\sim 10^4$ more energy in higher order modes!

- Analytic stationary solution for 2 modes: $P_2 \approx \frac{\gamma_2^{2111}}{\Delta \beta^2} P_1^3$

- Larger fibre has smaller phase mismatch (dispersion of all modes approaches bulk material dispersion) $\Rightarrow$ increased energy transfer

Conclusion and outlook

• Nonlinear glasses have allowed enormous increase in achievable nonlinearity from MOFs: \( \gamma \sim 10^3 - 10^5 \text{ W}^{-1}\text{km}^{-1} \) → efficient NL effects in metre or sub-metre length fibres;

• Fibres with \( \gamma \sim 500 \text{ W}^{-1}\text{km}^{-1} \) and flat broadband dispersion are now within reach; → all-optical processing applications;

• Next focus should be on improving fabrication techniques and reducing losses: currently, conventional HNLF still have better \( \gamma/\alpha \) ratio;

• Nonlinearities in MM fibres represent both an exciting opportunity and a fundamental limitation for high power applications. Further understanding required…