Enhanced optical nonlinearities in atmospheric air confined in Kagome hollow-core fibre

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Medium for nonlinear optics

- Crystal
  - $n_2 = 10^{-14}$ cm$^2$/W

- Liquid
  - $n_2 = 10^{-15}$ cm$^2$/W

- Silica PCF
  - $n_2 = 10^{-16}$ cm$^2$/W

- High pressure gases
  - $n_2 = 10^{-17}$ cm$^2$/W

- Atmospheric air
  - $n_2 = 10^{-18}$ cm$^2$/W

- in HC-PCF
  - $n_2 = 10^{-19}$ cm$^2$/W

Year

- 1970
- 1985
- 2000
- ?
Medium for nonlinear optics

- **Crystal**: $n_2 = 10^{-14}$ (cm$^2$/W)
- **Liquid**: $n_2 = 10^{-15}$
- **Silica PCF**: $n_2 = 10^{-16}$
- **High pressure gases**: $n_2 = 10^{-17}$
- **Atmospheric air**: $n_2 = 10^{-19}$

**References**

High peak power - intensity available
Current range GW - PW/cm²

Compact solution

Rep. rate large dynamic range
Current range kHz to GHz

C. J. Saraceno et al., Newsroom SPIE, 10.1117/2.1201503.005818 (2015)
2. Hollow-core PCF technology

New family of HC-PCF (called Kagome)

Inhibited coupling mechanism

2002
First demonstration
Benabid et al., Science 298

2007
Inhibited coupling
Couny et al., Science 318

2010
Hypocycloid core or negative curvature
Wang et al., CLEO postdeadline

2013
Record performances
Fourcade et al., CLEO postdeadline
Debord et al., Opt. Expr. 21

IC a superior alternative to PBG

Negative curvature to enhance IC

Standard core shape
Circular core

Hypocycloid core shape
Curved core
(6-cusp hypocycloid)
2. Curvature negative performances

1. Strong propagation loss decrease (17 dB/km at 1 µm)

2. Single mode operation with high PER (Gaussian-like mode, 25 dB)

3. Decrease of power overlap with silica surround to a ppm level (10000 times lower than PBG)

Breakthrough in ultrafast beam delivery

**Laser:** 1030nm center-wavelength, 500 fs pulse-duration, 1 KHz rep.rate, Max Energy=1mJ

**Fiber:** Hypocycloid-core kagome HC-PCF, 7 cells and 19 cells, lengths: 3 m and 10 m

Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber), and 20 cm (19 cell fiber)

Coupling: HC-PCF input end exposed to air. Output end: in gas/vacuum chamber or exposed to ambient air
Breakthrough in ultrafast beam delivery

Core-size = 80 µm, b-curvature parameter ~ 1
@ 1030: GVD ~ 0.55 ps/nm/km. Loss~200 dB/km
Breakthrough in ultrafast beam delivery

~ 200 µJ
~ 700 µJ
~ 400 µJ
~ 1000 µJ

C. Fourcade et al. CLEO US, Postdeadline, CTh5C.7 (2013)
Breakthrough in ultrafast beam delivery

Operating wavelength

1 μm to 800 nm
Breakthrough in ultrafast beam delivery

Laser CPA 800nm
10 mJ, 35 fs, 10 Hz

Tube inserted between lens and fiber tip
3.10^-3 mbar in cells for vacuum configuration
Breakthrough in ultrafast beam delivery

**Fiber length:** 35 cm  
**Fiber filled with:** Vacuum

**Input energy (µJ):**

- Wavelength (nm): 600 to 900
- Intensity (a.u.): 0 to 1

**Fiber length:** 35 cm  
**Fiber filled with:** Hélium 5bar

**Input energy (µJ):**

- Wavelength (nm): 600 to 900
- Intensity (a.u.): 0 to 2500
Breakthrough in ultrafast beam delivery

Fiber length: 35 cm
Fiber filled with: Vacuum

Wavelength (nm)

Intensity (a.u.)

Input energy (µJ)

Fiber length: 35 cm
Fiber filled with: Hélium 5bar

Wavelength (nm)

Norm (Log(Intensity))

2.6 mJ
81 GW
**Breakthrough in ultrafast beam delivery**

- **C. Fourcade et al. CLEO US, Postdeadline, CTh5C.7 (2013)**

- 1 mJ energy handling (*1000/ PBG fiber*)
- 80% transmission coefficient
- Single mode guidance
- 10 m-long He-filled hollow-core
- 600 fs pulse duration preserved
- Output intensity up to 30 TW/cm²


- 2.6 mJ energy handling – 30 fs input pulses
- 81 GW input peak power (*54/ previous work*)
- Few mode guidance
- 60% transmission coefficient
- 35 cm-long He-filled hollow-core
- Output intensity up to 1.1 PW/cm²

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**Graph:**

- Input/Output
- 30 TW/cm²
- > 1 PW/cm²

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**Figure:**

- Input energy (µJ) vs. Output energy (µJ) graph showing the relationship between input and output energies.
Nonlinear effects in molecular gases

Previous IC Kagome design

HC-PCF

GC 2

GC 1

$\text{H}_2$

Transform the AMBIENT AIR to a nonlinear platform

- 1000 $\mu$J energy -
  > 1 PW/cm$^2$ peak int.
  > 10 GW peak power (2013-2015)

$\times$ 1000 energy-level increased in inhibited coupling HC-PCF

- 1 $\mu$J energy -
  10 TW/cm$^2$ peak intensity
  0.07 GW peak power (2007-2015)

High harmonic generation

Raman comb generation

Supercontinuum generation
**Experimental set-up**

**Yb-laser source 1.36mJ (Amplitude Systemes)**

**Laser:** 1030nm center-wavelength, 1 KHz rep.rate, Max Energy=1.36mJ

Two output regimes made from the system: **300 ps** and **600 fs** pulses

**Fiber:** Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m

Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)

Coupling: HC-PCF input and output end exposed to ambient air

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**Output 1**

- 300 ps
- IC Fiber #1
- PBS
- λ/2
- Lens
- λ/4

**Output 2**

- 600 fs
- IC Fiber #2
- PBS
- λ/2
- λ/2
- Lambda/4
- Lens
- Lambda/4
Experimental set-up

- **UV/Mid-IR guidance**
- **50 dB/km at the laser pump**
- **Single mode - 42 µm MFD**
- **Filled at atmospheric air**

**Laser:** 1030nm center-wavelength, 1 KHz rep.rate, Max Energy=1.36mJ
Two output regimes made from the system: 300 ps and 600 fs pulses

**Fiber:** Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m
Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)
Coupling: HC-PCF input and output end exposed to ambient air
Raman comb generation

- 1.03 mJ energy transmitted
- 75% transmission coefficient
- 300 THz wide Raman comb
- ~ 70 THz tooth-spacing (vibrational Raman response of N₂ molecules)
- Spectral broadening at high energy (rot sideband S6)

Measured output spectrum vs input energy
Experimental set-up

Input energy: 1.36 mJ
Input peak power: 2.13 GW
Input peak intensity: 154 TW/cm$^2$

**Experimental Diagram:***
- Oscillator and CPA
- Lens
- PBS
- λ/2
- λ/4
- Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)
- Coupling: HC-PCF input and output end exposed to ambient air

**fiber**
- Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m

**Lasers**
- 1030 nm center-wavelength, 1 KHz rep. rate, Max Energy=1.36 mJ

**Output regimes**
- Two output regimes made from the system: 300 ps and 600 fs pulses

**Fiber**
- Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m

**Fiber positioning**
- Coiled with ~10 cm coil-radius (7 cell fiber)

**Coupling**
- HC-PCF input and output end exposed to ambient air

**IC Fiber #2**
- UV/Mid-IR guidance
- 50 dB/km at the laser pump
- Single mode - 42 μm MFD
- Filled at atmospheric air
- Anomalous dispersion
Supercontinuum generation

- Strong broadening in all the detected transmission bands
- ~ PHz wide SC / single mode
- Average record energy spectral density of 150 nJ/nm

- ×100 current laser SC sources -
SC broadening dynamics

Step 1: laser pump

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps²/km
Step 2: 3\textsuperscript{rd} harmonic generation

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps\textsuperscript{2}/km
SC broadening dynamics

Step 3: FWM process

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps$^2$/km
Step 4: cascade of FWM in all bands

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps$^2$/km
Step 5: high order soliton formation

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps$^2$/km

+ multi-resonant radiations
Step 6: high order soliton formation

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps$^2$/km

+ multi-resonant radiations
Step 7: broadening through fission of higher-order soliton

Nonlinear length: 4.5 mm, Dispersion length: 228 m
Soliton order > 200, GVD: 2.8 ps/nm/km, $\beta_2$: -1.6 ps$^2$/km

$\Rightarrow$ Several fundamental solitons and their associated radiations
CONCLUSIONS

- **Ultra broad and ultra low-loss** inhibited coupling Kagome HC-PCFs
  - UV/Mid-IR guidance
  - 50 dB/km loss level at 1 µm
  - Truly single-mode operation (42 µm MFD)
  - Ultra-low optical overlap with the silica surround

- **Breakthrough** in optical fiber delivery of ultrafast lasers

- **Strong nonlinear broadening became possible** at milli-joule energy regime in HC-PCFs at **atmospheric air**

First demonstration of Raman comb in HC-PCFs from air

PHz wide SC generation with record energy density of 150nJ/nm
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