Hollow core photonic crystal fibre: Novel light guidance and myriad of gas-photonic applications

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GPPMM: GAS-PHASE PHOTONIC & MICROWAVE MATERIALS

GPPMM expertise

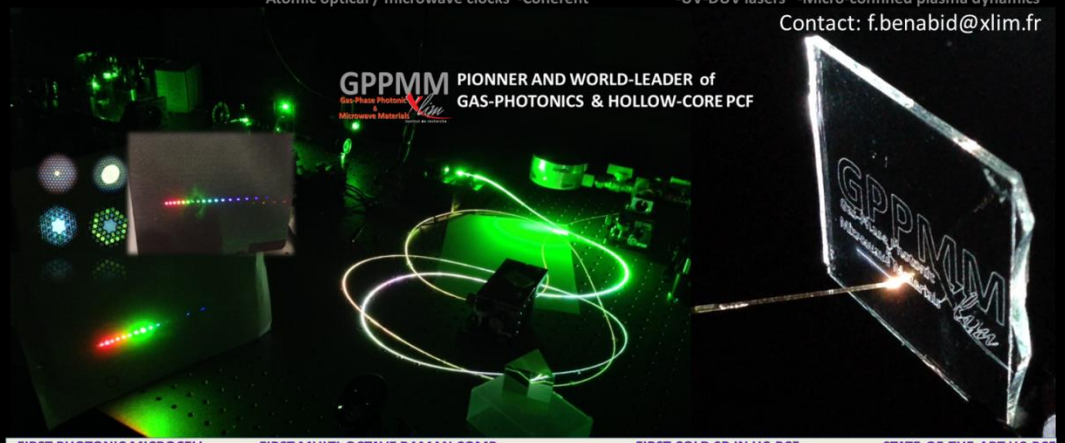
Fiber photonics
-Design and fabrication of PCF -Fiber components

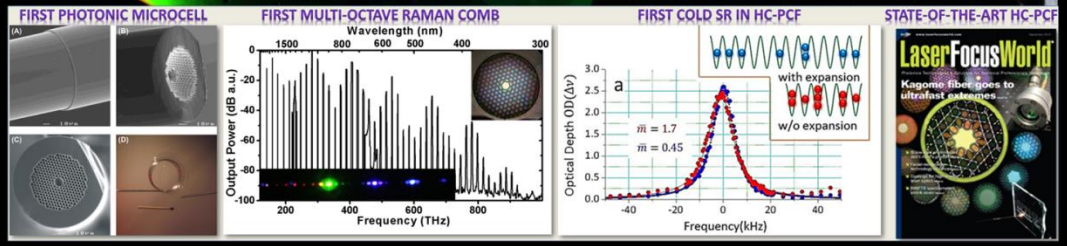
Gas nonlinear opitcs
Frequency conversion -Ultra-broad comb generation
-Pulse compression & High field photonics

Atom optics & laser metrology
Atomic optical / microwave clocks -Coherent

Plasma photonics
-UV-DUV lasers -Micro-confined plasma dynamics

Contact: f.benabid@xlim.fr





End of August 2011 *September 2011*

Permanents
F. Benabid, F. Gerome, J.M. Blondy, C. Restoin, D. Cros

Post-docs
B. Debord, E. Elinova, A. Benoit

PhD students
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Past members
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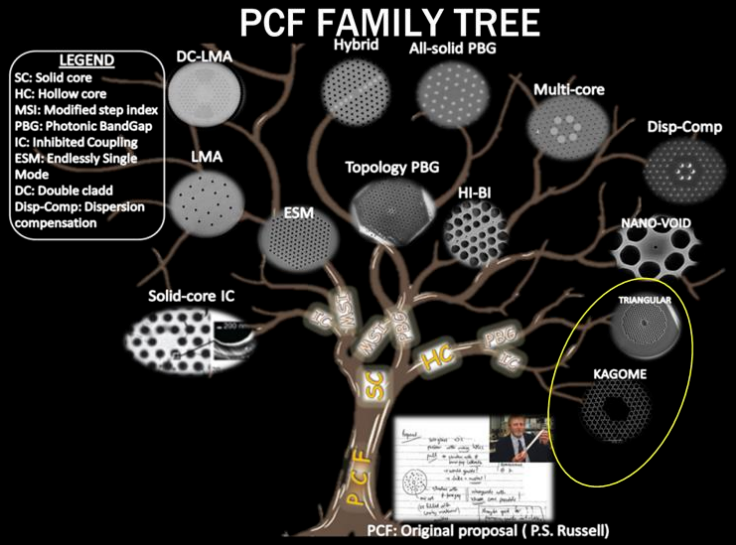
Collaborators
L. Vincetti, A. Huzakou

BACKGROUND: Towards GAS PHOTONICS

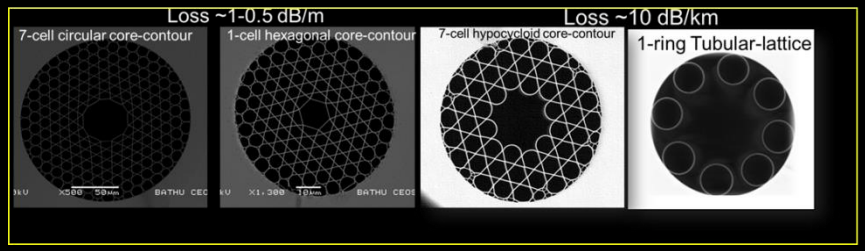
GPPMM: building block technology



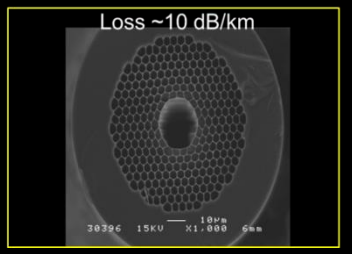
*F. Benabid, et al., **Science,** 298, 399-402 (2002).*
P. St. J. Russell, ***Science*** 299, 358–362(2003)
*F. Benabid, et al., **Nature,** 434(2005).*
*F. Benabid, **Phil. Tran. R. Soc. A**, 364, 3439-3462 (2006).*
*F. Benabid and J. P. Roberts, **JMO** 58, 87-124 (2011)*

Science & technology of fibre photonics

IC guiding HC-PCF

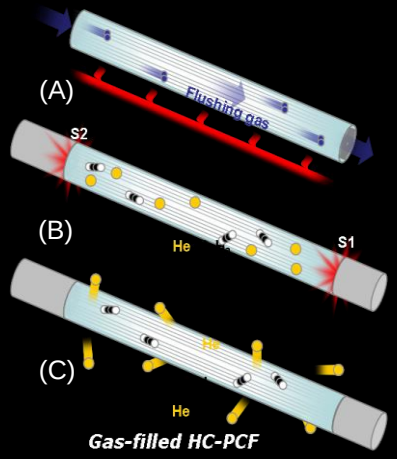


19-cell PBG guiding HC-PCF



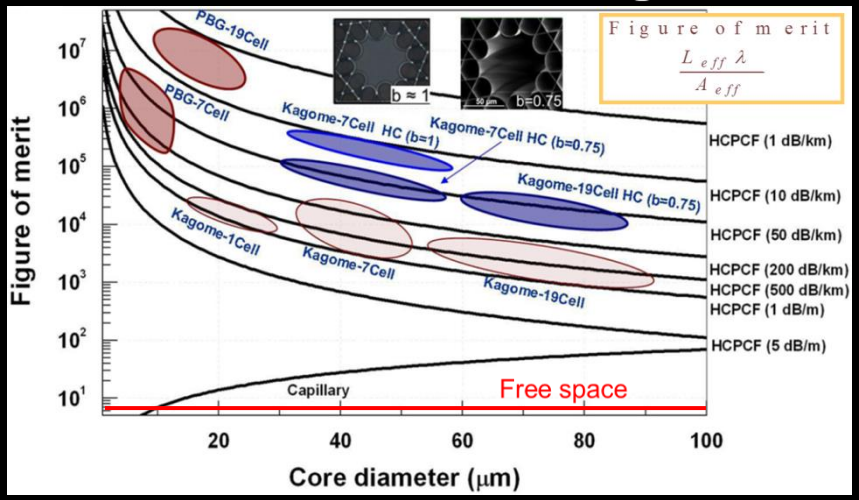
Gas-Phase photonic materials

Photonic Microcell



Gas-filled HC-PCF

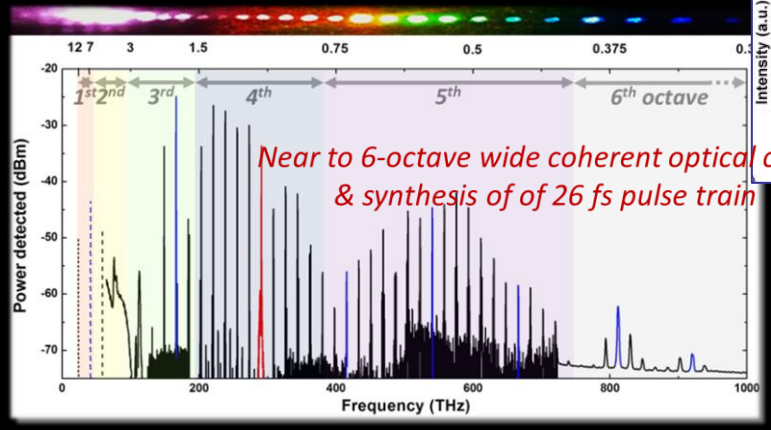
Ultra-enhancement of gas-laser interaction strength



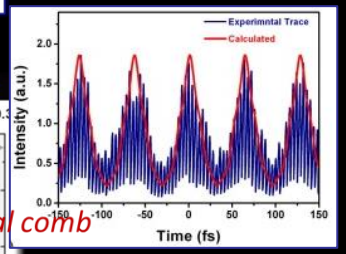
HC-PCF goes extreme: *Taming the photons*

The extremely broad

A. Benoît, *et al. Opt.Express*, *23*(11), 14002-14009 (2015)



Near to 6-octave wide coherent optical comb & synthesis of of 26 fs pulse train



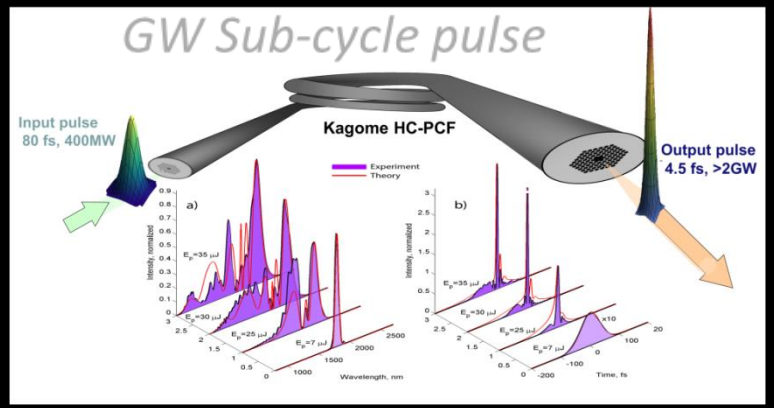
The extremely energetic

B. Debord et al. Opt. Express 21, 25509-25516 (2013)

Fiber-laser-pen: delivering Milli-Joule femtosecond pulse

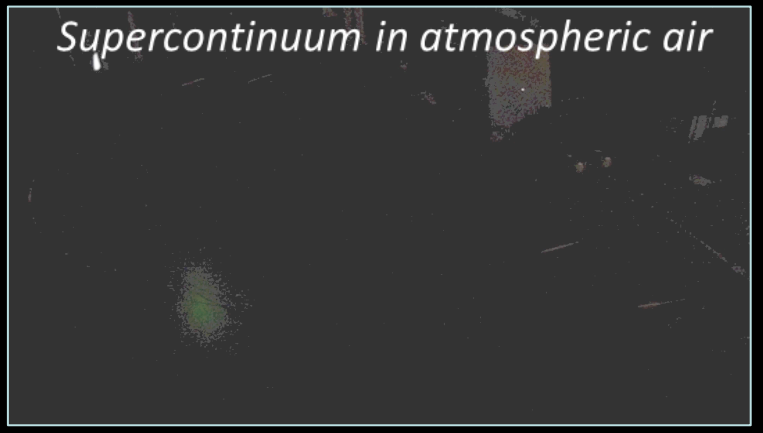
The extremely intense & short

T. Balciunas *et al*. Nature Comm. 6, 6117 (2015)



The extremely NLO efficiency

B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)



HC-PCF goes extreme: *Gas media in all phases*

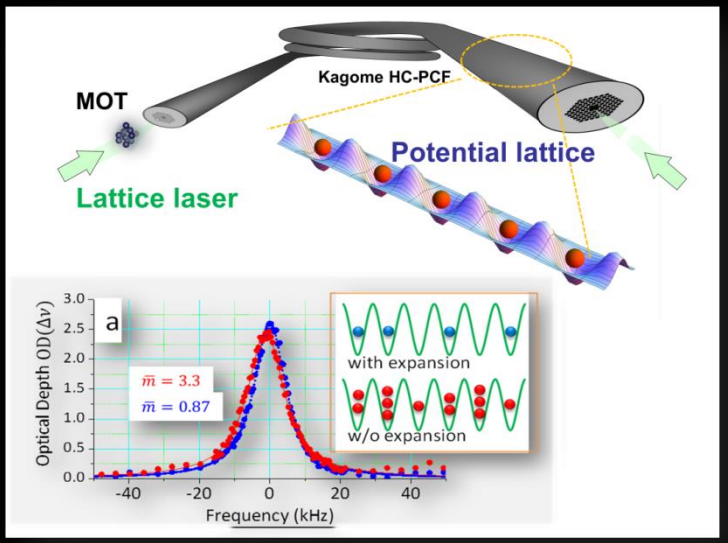
The extremely hot

B. Debord et al. Opt. Express 22,10735-10746 (2014)

Highly ionised and hot (~1000K) gas in Kagome HC-PCF

The extremely cold

S. Okaba et *al*. Nature Comm. 5, 4096 (2014)

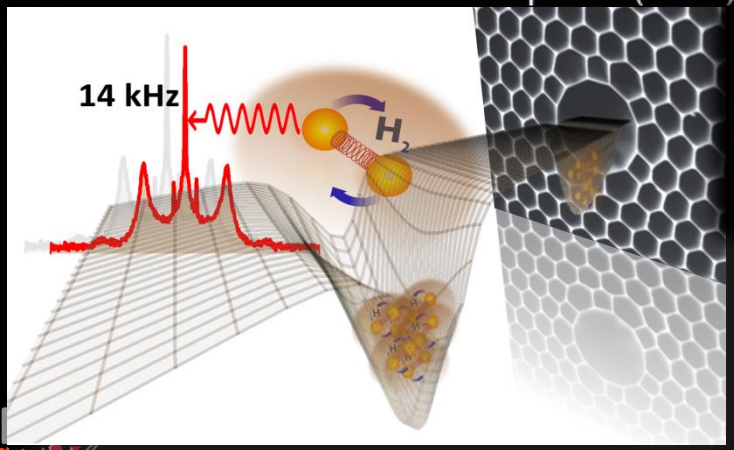


1D chain of cold (~μK) Sr not feeling the wall-heat

The extremely deep

Molecular gas-structuring

M. Alharbi et *al*. Nature Comm. In press (2016)

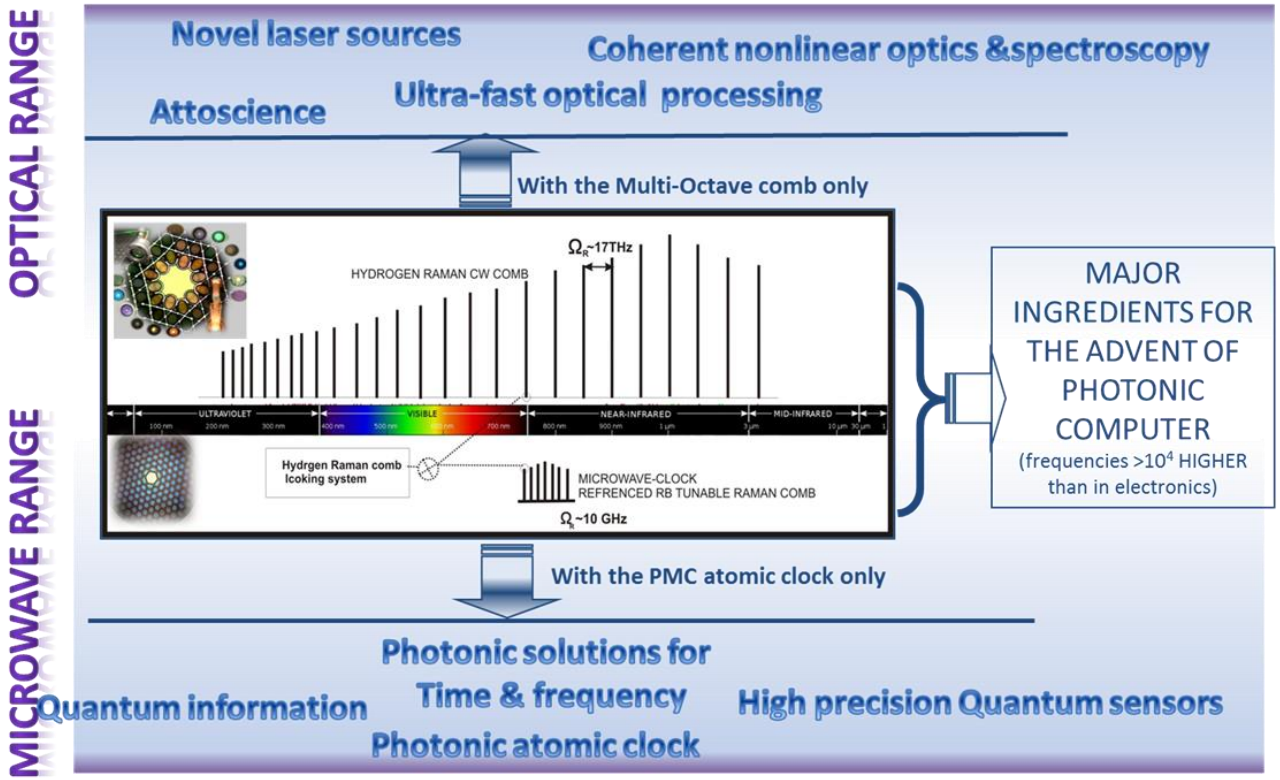


In-fiber moving lattice
&
particle accelerator

H_2 self-trapped in ultra-deep nanostructured potential lattice to emit high power laser with sub-recoil linewidth.

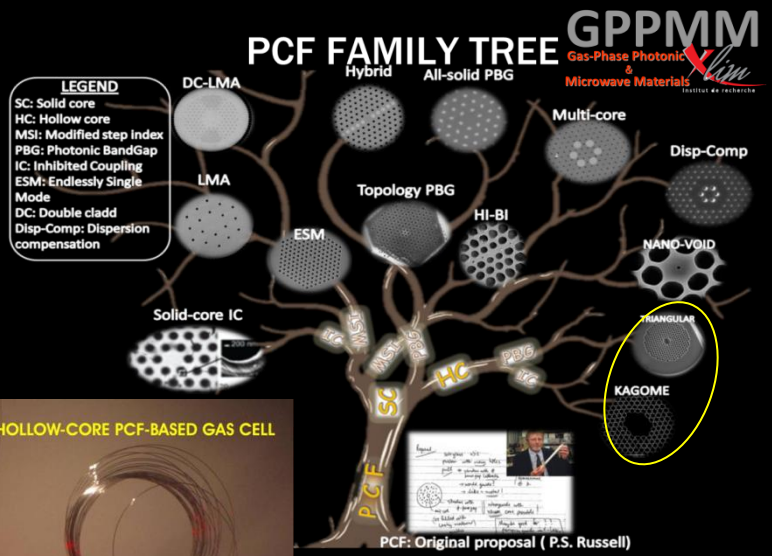
GPPMM RESEARCH PROJECT
LONG TERM GOAL

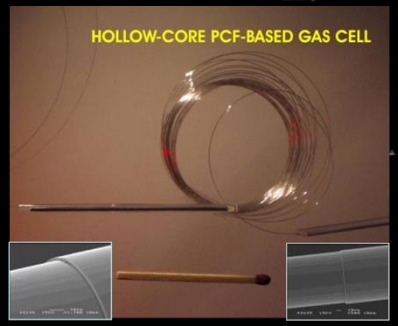
Building an atomic clock referenced photonic synthesiser based on gas-phase materials micro-confined in HC-PCF



Background and Talk outline

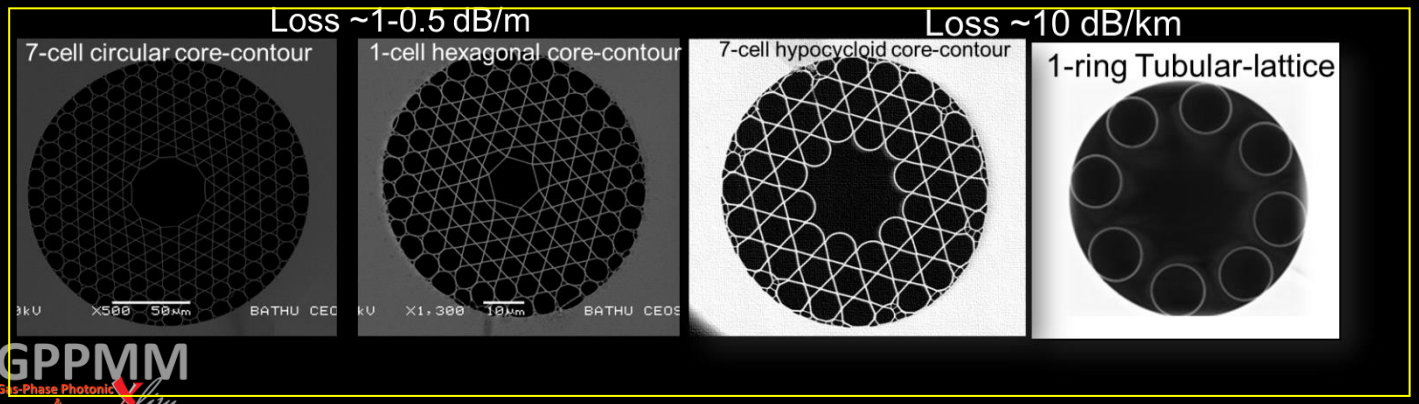
- *HC-PCF (Photonic Band Gap vs Inhibited Coupling)*
- *Core shaping induced Enhanced IC*
- *Milli-Joule fs pulse delivery and compression*
- *GLOphotonics IC HC-PCF based USP beam delivery*
- *Poor-man Self-compression*
- *Turning air in nonlinear medium*
- *High-field Sub-cycle self-compression*



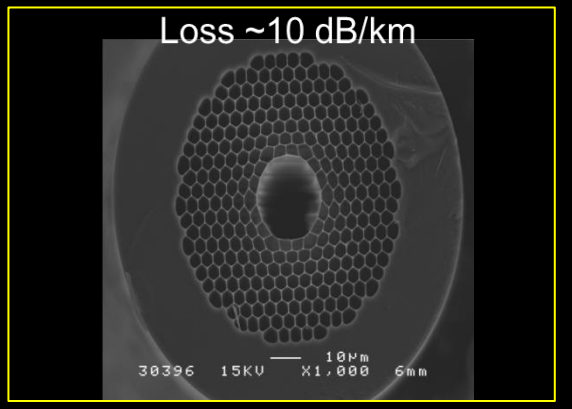


Photonic Microcell

IC guiding HC-PCF



19-cell PBG guiding HC-PCF

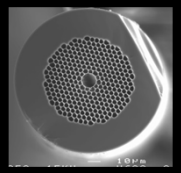


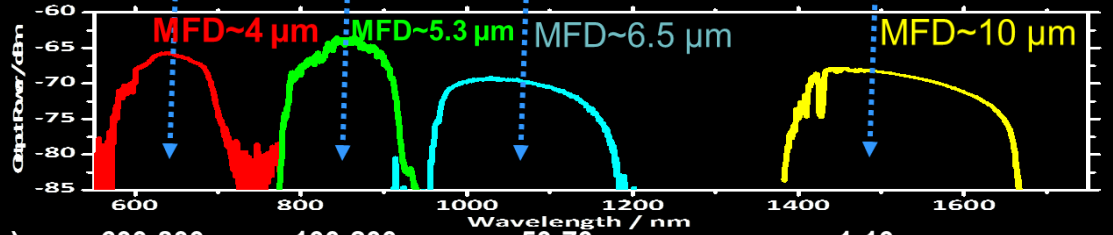
GPPMM
Gas-Phase Photonic & Microwave Materials

Current commercially available HC-PCF in a snap shot

HeNe 633nm | Ti:Saph 800nm | Nd:YAG 1064nm | Er-doped 1550nm

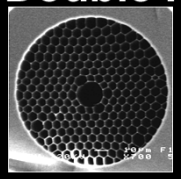
PBG

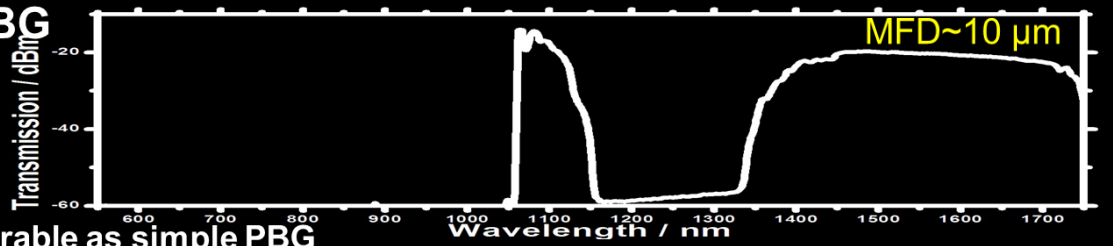




Loss (dB/km): 600-800 | 100-200 | 50-70 | 1-10

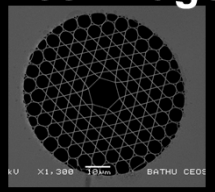
Double PBG

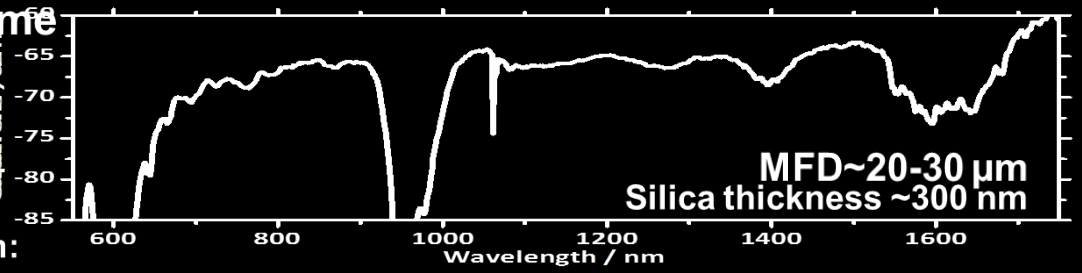




Loss comparable as simple PBG

1-cell Kagome



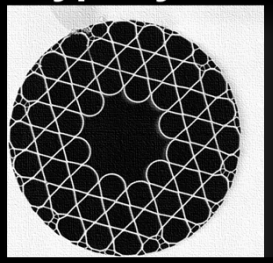


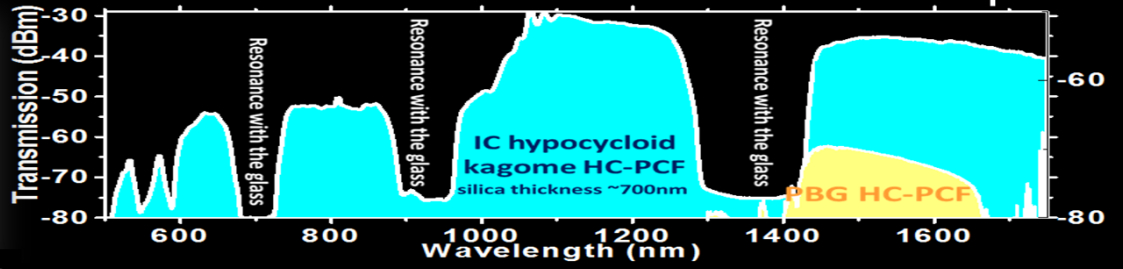
Loss 1-0.5 dB/m:

Hypocycloid Kagome

Silica thickness ~700 nm

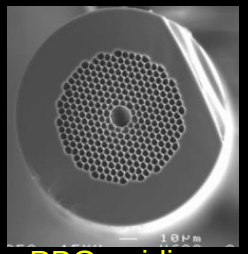
MFD~30-50 µm



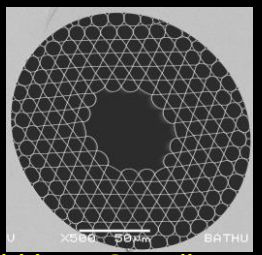


Loss 50-20 dB/km

HC-PCF TIME-LINE

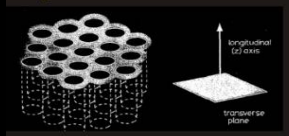


PBG guiding
Triangular HC-PCF:

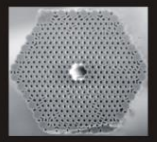


Inhibiting –Coupling guiding
Kagome HC-PCF:

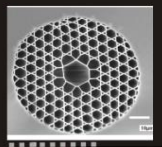
1995 — **1st Theoretical demonstration of Out-of Plane PBG**
Birks et al. Elect. Lett. 31,1941(1995)

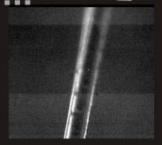


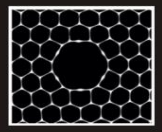
1999 — **First HC-PCF**
Cregan et al. **Science**, 285 (1999)



2002 — **First low-loss and applied HC-PCF**
Benabid et al. **Science**, 289 (2002)
Benabid et al. Opt. Express, 10 (2002)
Venkataraman et al. ECOC 2002

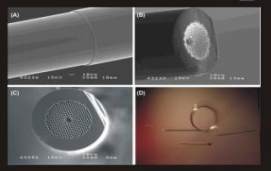






2003 — MW soliton delivery
Ultra-low threshold SRS

2004 — ~1dB/km loss HC-PCF

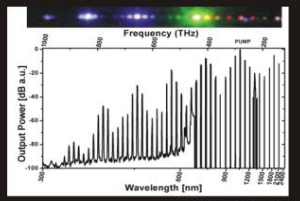


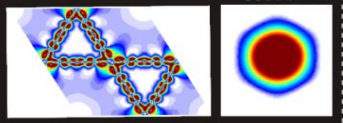
2005 — **First Photonic micro-cell**
Benabid et al. **Nature**, 434 (2005)

EIT in a molecular gas
Slow light

EIT in Rb

PHOTONIC BAND GAP

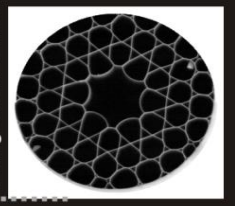




INHIBITED COUPLING
Couny et al. **Science**, 318 (2007)

IC GUIDING SOLID PCF
Grujic *et al.* Opt.Express 18 25556(2010)

HYPOCYCLOID-CORE HC-PCF (negative curvature core)
Wang et al., CLEO 2010, paper CPDB4 (2010).

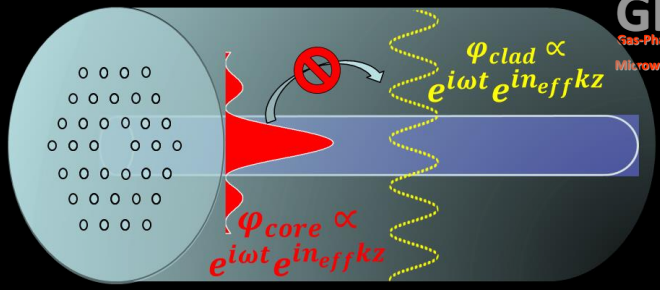


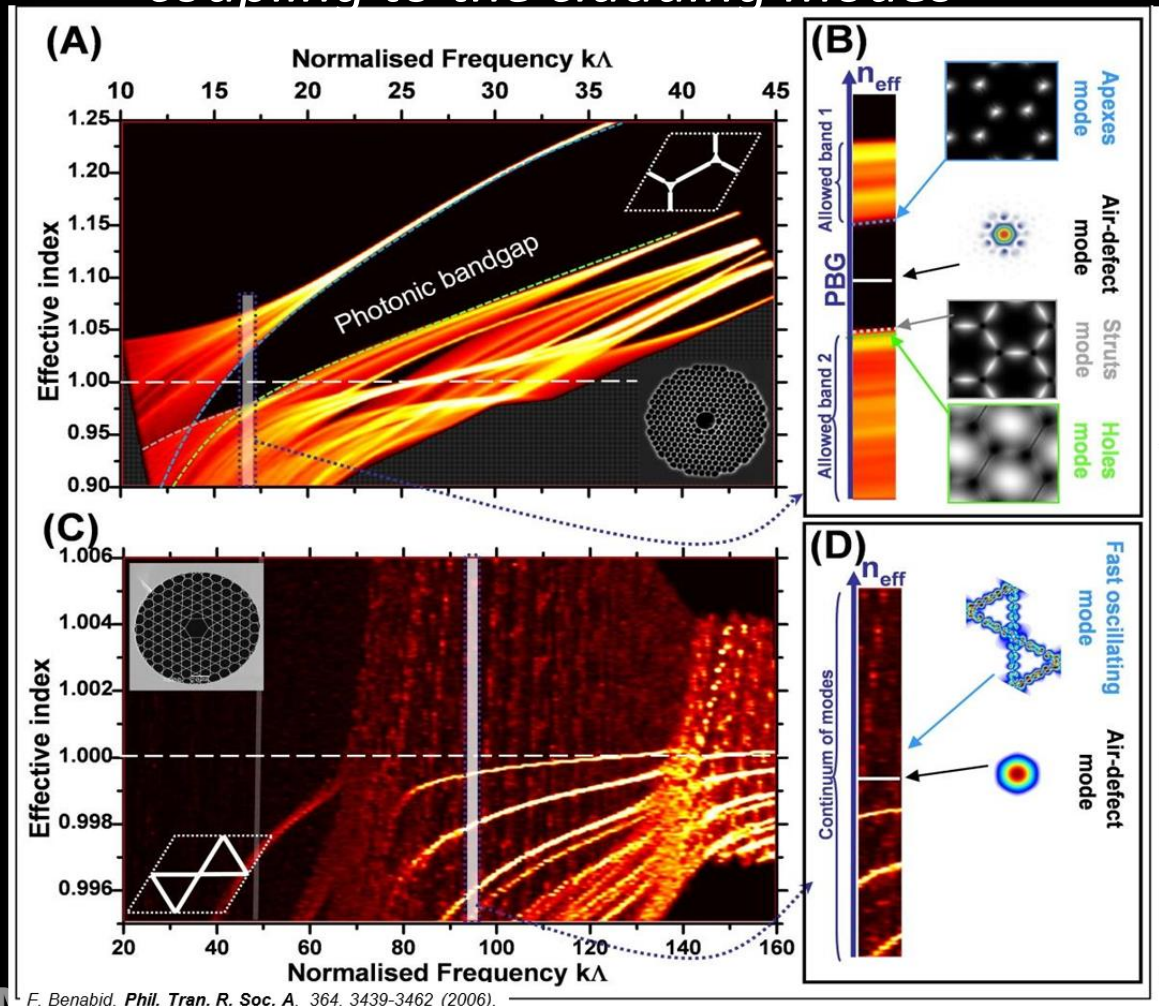
INHIBITED COUPLING

2002 — 2007 — 2010

PBG versus IC

Guiding light in a optical fiber is preventing the guided mode from coupling to the cladding modes



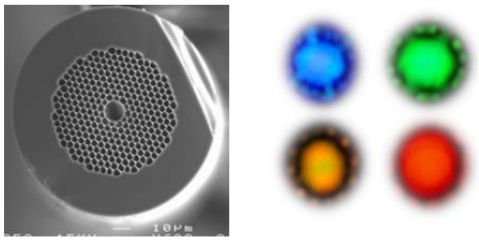


F. Benabid, **Phil. Tran. R. Soc. A**, 364, 3439-3462 (2006).
F. Benabid and J. P. Roberts, **JMO** 58, 87-124 (2011)

PBG guiding
Triangular HC-PCF:

Criterion for PBG guidance

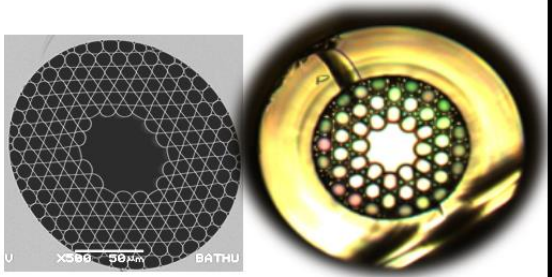
$$\{|\varphi_{clad}\rangle\} = \emptyset$$



Inhibiting –Coupling guiding
Kagome HC-PCF:

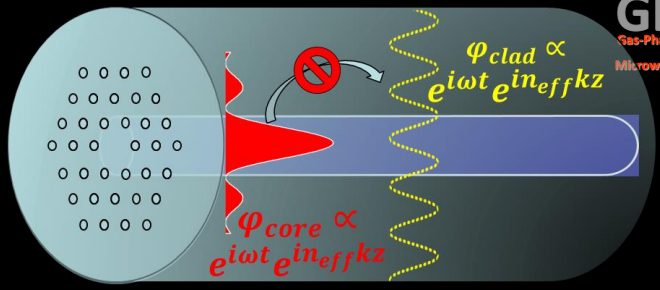
Criterion for IC guidance

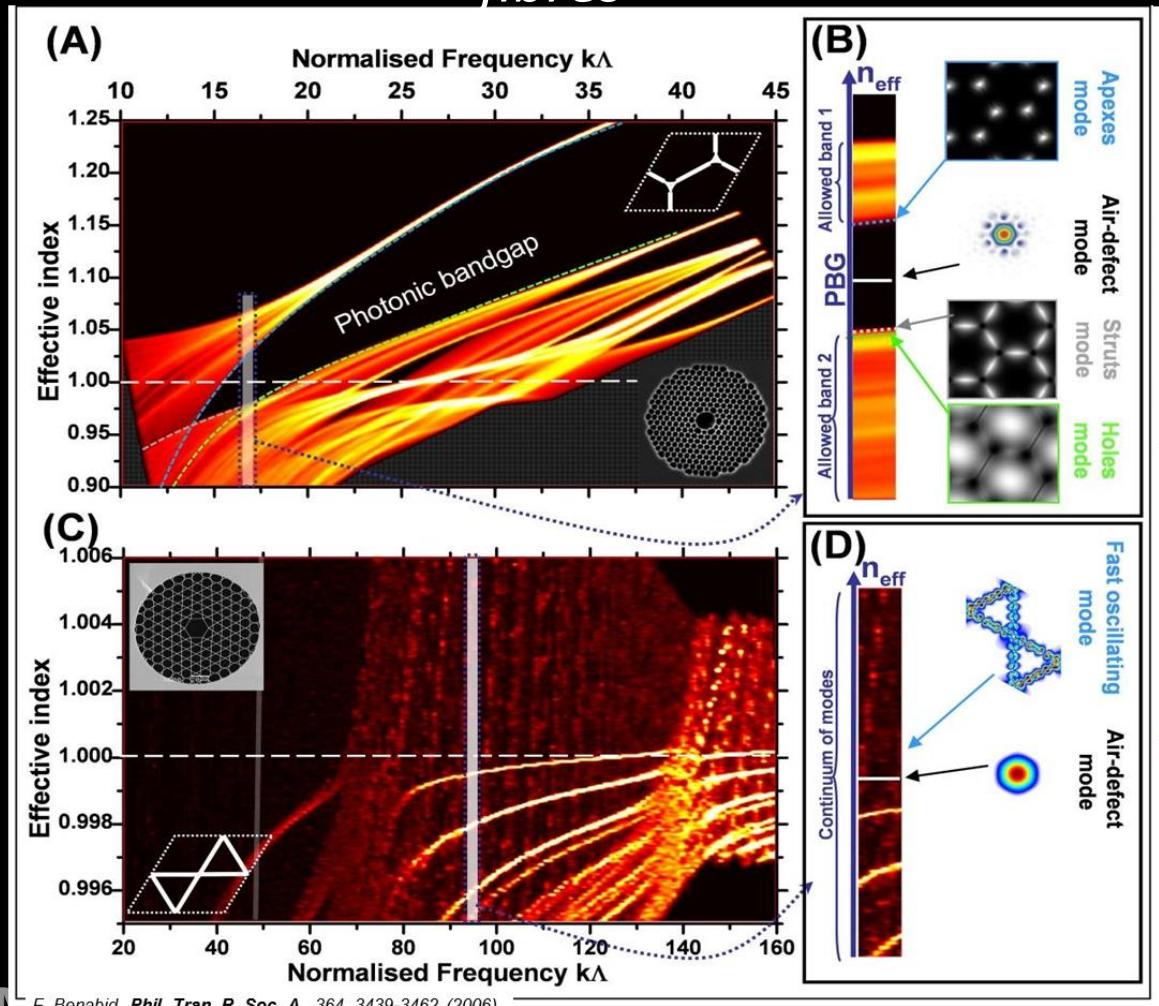
$$\langle\varphi_{clad}|\Delta n^2|\varphi_{core}\rangle \to 0$$



PBG versus IC

IC mechanism: Design toolbox that led to negative curvature hollow fibres

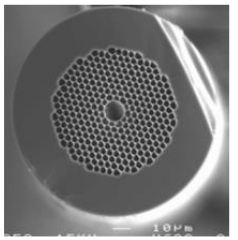


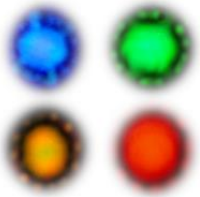


PBG guiding
Triangular HC-PCF:

Criterion for PBG guidance

$$\{|\varphi_{clad}\rangle\} = \emptyset$$



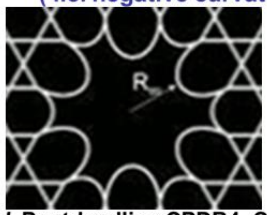


Inhibiting –Coupling guiding
Kagome HC-PCF:

Criterion for IC guidance

$$\langle\varphi_{clad}|\Delta n^2|\varphi_{core}\rangle \to 0$$

Introduction of hypocycloid core-contour
(i.e. negative curvature)

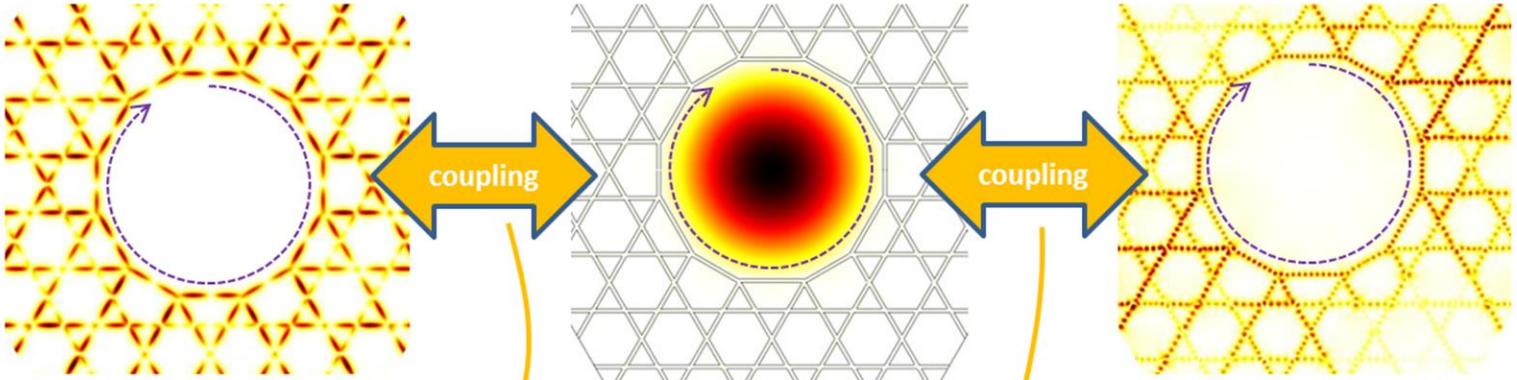


Wang *et al.* Postdeadline CPDB4, CLEO (2010)

F. Benabid, ***Phil. Tran. R. Soc. A***, 364, 3439-3462 (2006).
F. Benabid and J. P. Roberts, ***JMO*** 58, 87-124 (2011)

Driving design parameters in IC guiding HC-PCF

Transverse phase mismatch between the mode of the continuum with that of the hollow core defect



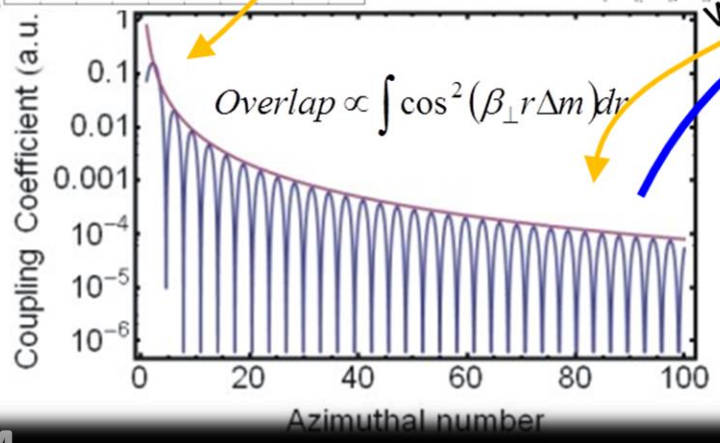
Low azimuthal number m

Core mode with m=0

High azimuthal number m

Strong coupling

weak coupling

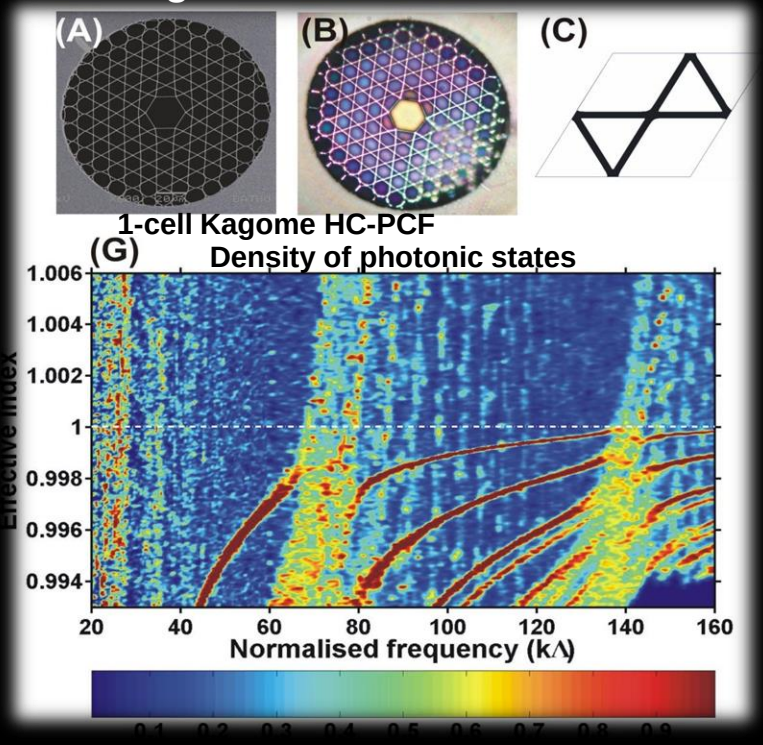


Power coupling between the slowly transverse phase-varying core modes and the fast-oscillating cladding modes decreases exponentially vs m

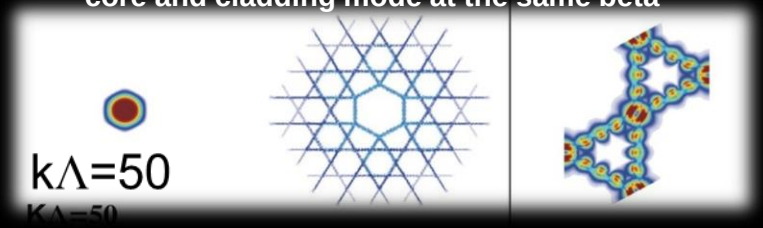
Routes for enhancing IC guidance

Benabid et *al.* Science, 298, 399 (2002)
Couny et *al*. Opt. Lett. **31**, 3574-3576 (2006)
Couny et *al.* Science, **318** (2007)
Wang et *al*. CLEO 2010, PD, CPDB4 (2010)
Wang et *al*. Opt. Lett. **36**, 669-671 (2011))

IC guidance relies on strong transverse mismatch between cladding modes and core modes



core and cladding mode at the same beta



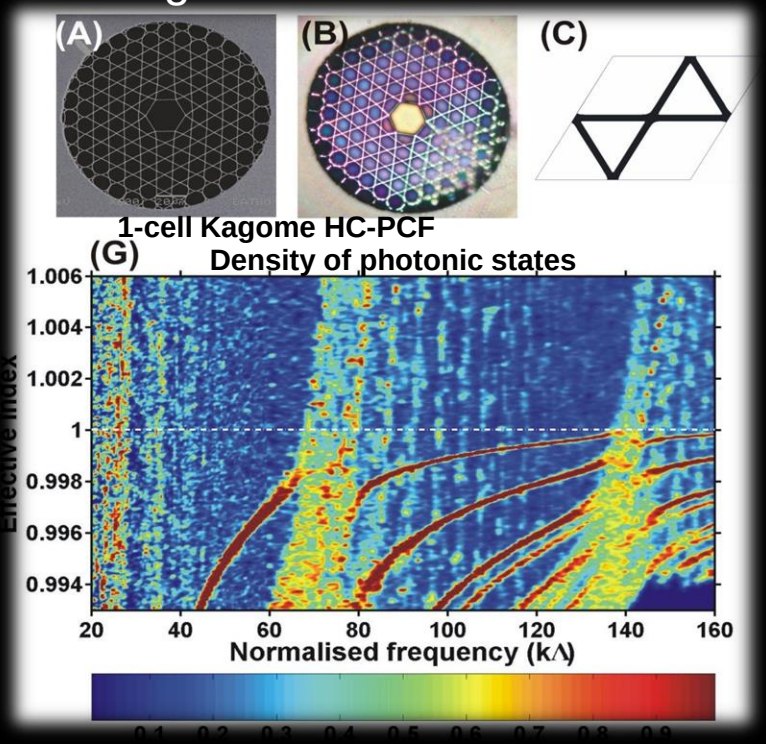
Cladding optimization route

Guiding rules for IC:
A cladding structure that favourably support high "azimuthal-number"-modes. E.G. a cladding with elongated thin strings with no bends or corners and made of an anti-resonant material.

Routes for enhancing IC guidance

Benabid et *al.* Science, 298, 399 (2002)
Couny et *al.* Opt. Lett. **31**, 3574-3576 (2006)
Couny et *al.* Science, **318** (2007)
Wang et *al*. CLEO 2010, PD, CPDB4 (2010)
Wang et *al*. Opt. Lett. **36**, 669-671 (2011)
Debord et *al*. Opt. Express **21**, 28597 (2013)
Alharbi et *al*. Opt. Express **21,** 28609 (2013)

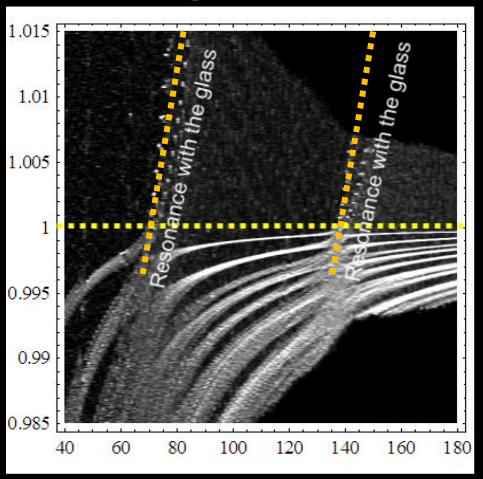
IC guidance relies on strong transverse mismatch between cladding modes and core modes

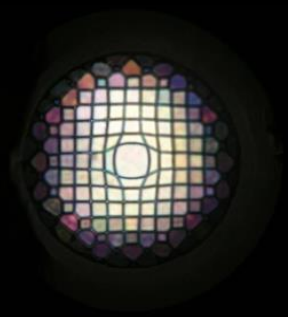


core and cladding mode at the same beta

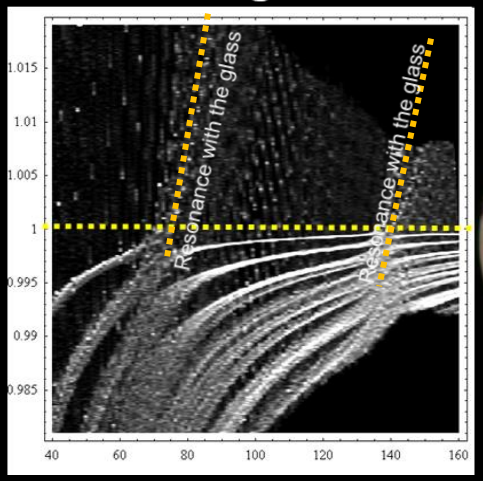
Cladding optimization route

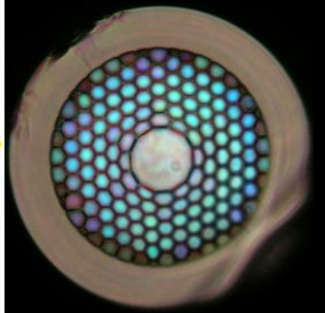
Square





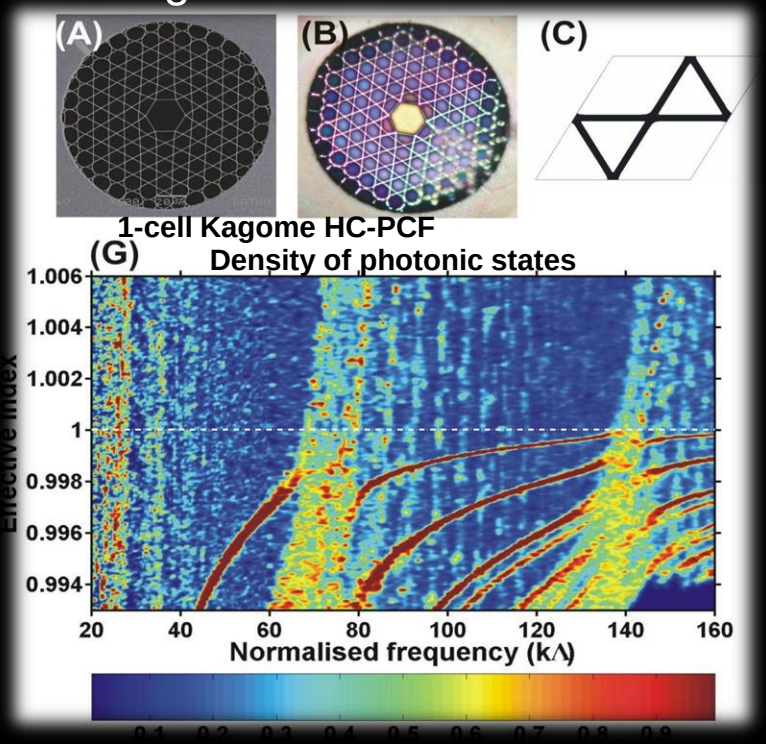
Triangular





Routes for enhancing IC guidance

IC guidance relies on strong transverse mismatch between cladding modes and core modes

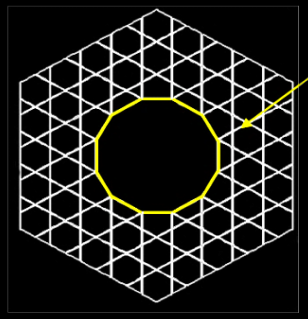


core and cladding mode at the same beta

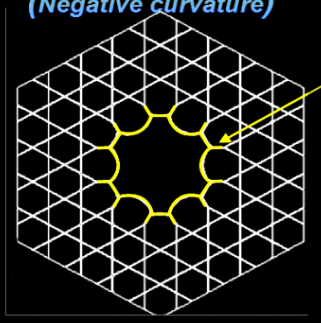
Benabid et *al.* Science, 298, 399 (2002)
Couny et *al.* Opt. Lett. **31**, 3574-3576 (2006)
Couny et *al.* Science, **318** (2007
Wang et *al*. CLEO 2010, PD, CPDB4 (2010)
Wang et *al*. Opt. Lett. **36**, 669-671 (2011))
Bradley et al. IEEE JLT, (2013)

Core optimization route

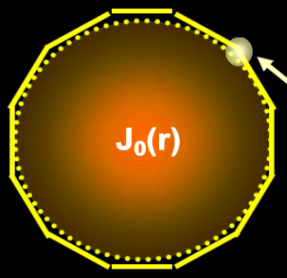
Standard core shape



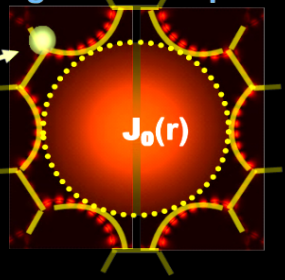
Hypocycloid core shape
(Negative curvature)



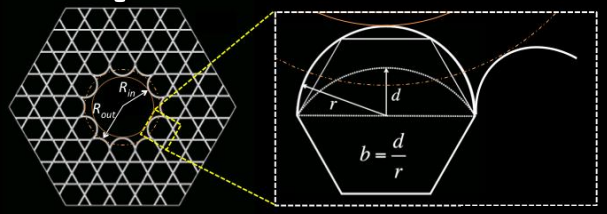
Enhancing the azimuthal number *m*
Reducing the overlap intergral



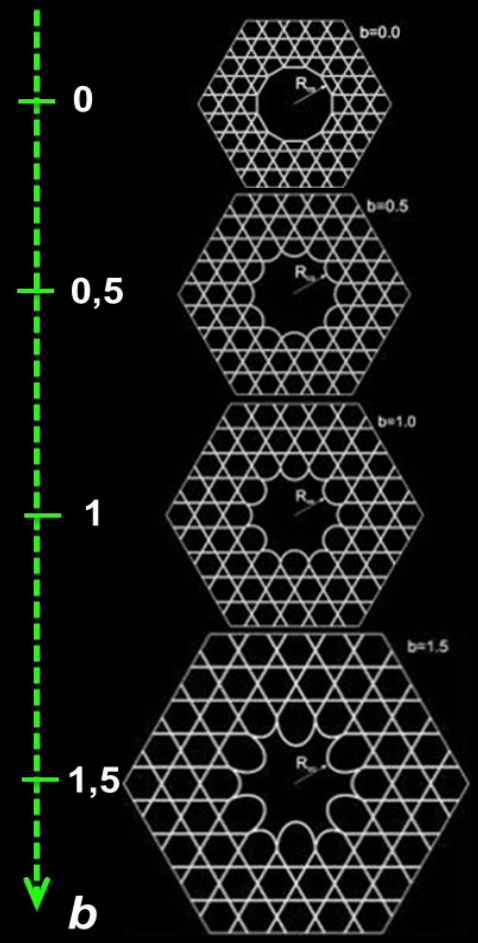
Defect or corner induced
Low *m (e.g. m=1) are "pushed away" in the hypocycloid shape*

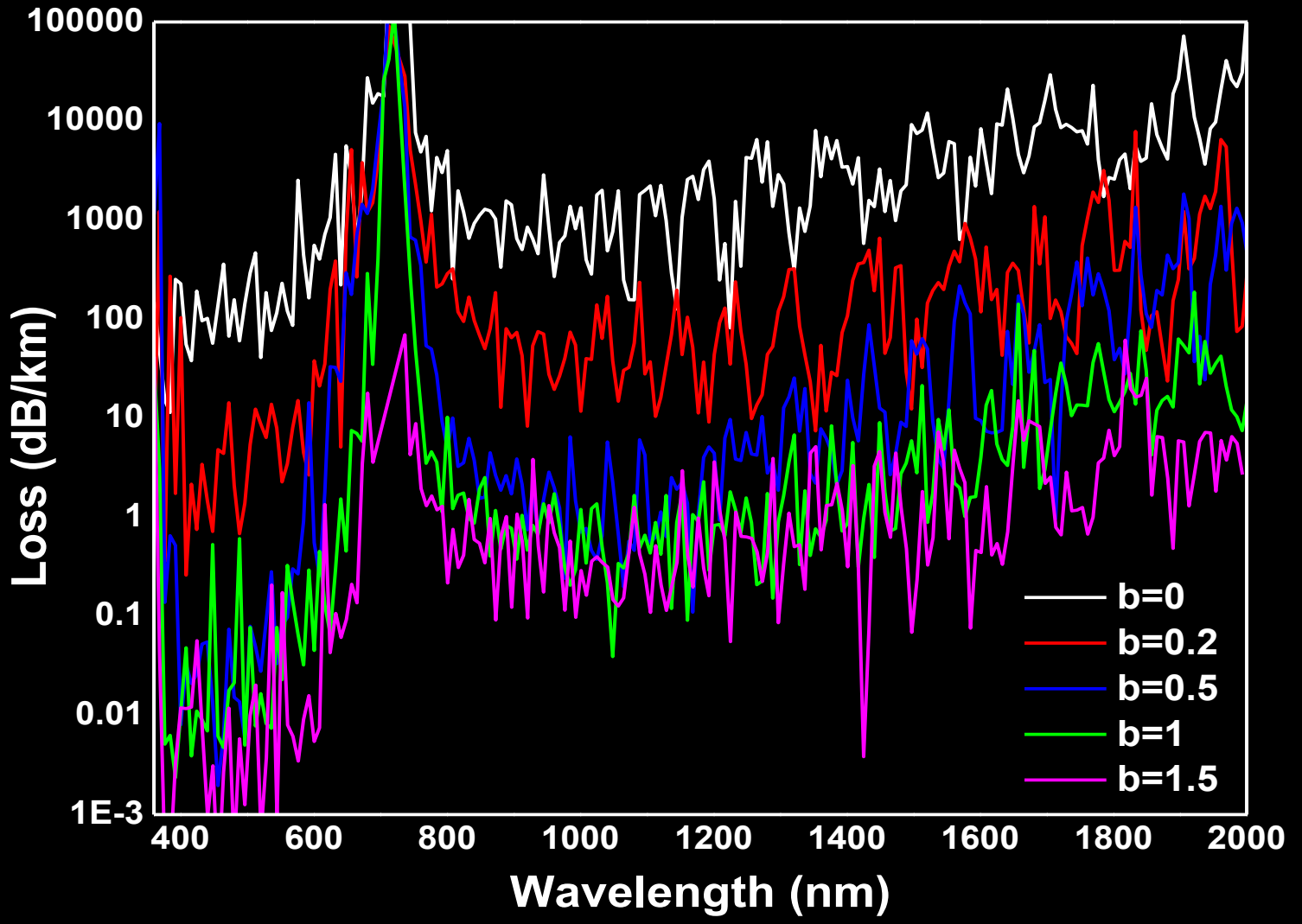


Cups curvature on enhancing IC

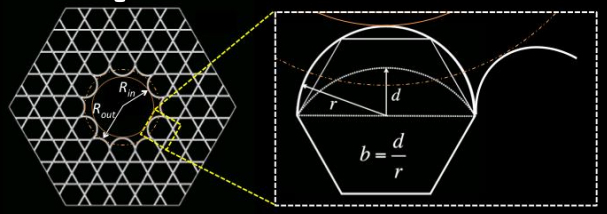


B. Debord et *al*. Opt. Express **21**, 28597 (2013)
M. Alharbi et *al*. Opt. Express **21,** 28609 (2013)

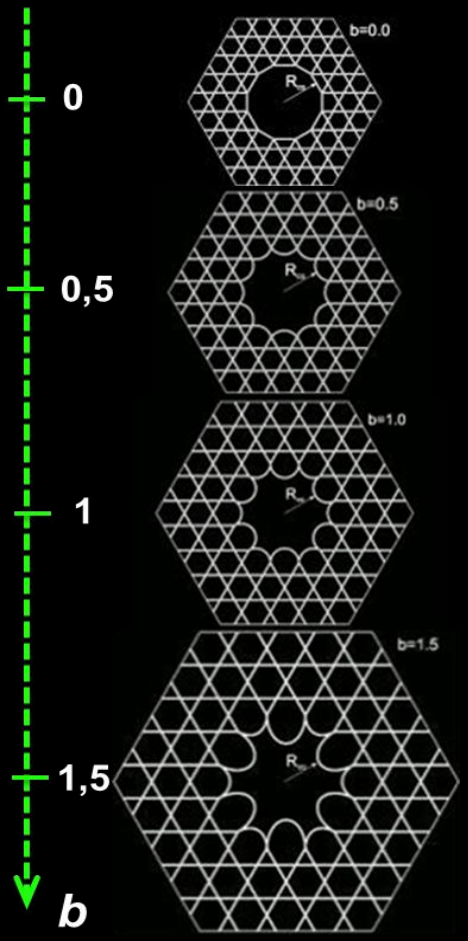


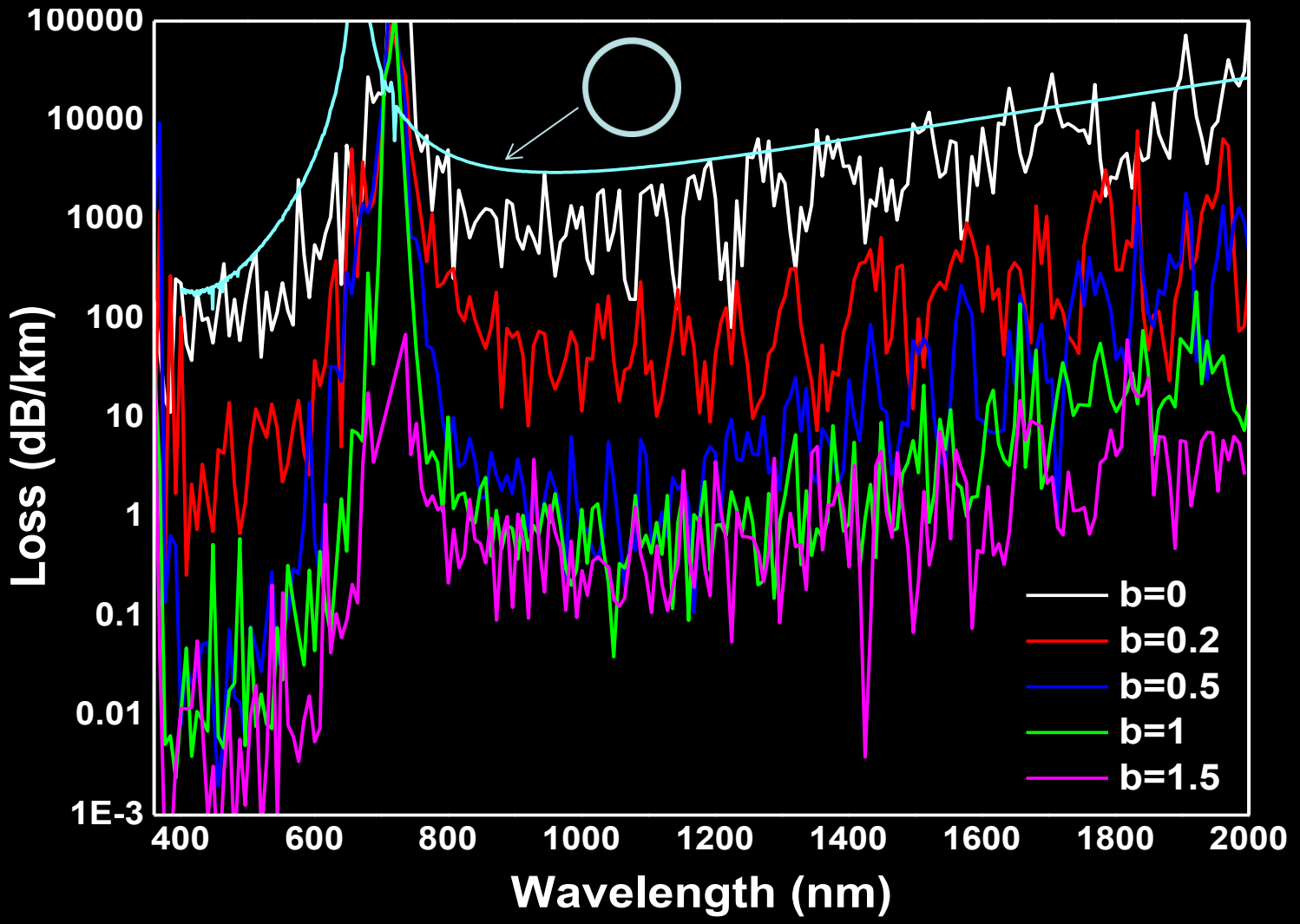


Cups curvature on enhancing IC



B. Debord et *al*. Opt. Express **21**, 28597 (2013)
M. Alharbi et *al*. Opt. Express **21,** 28609 (2013)

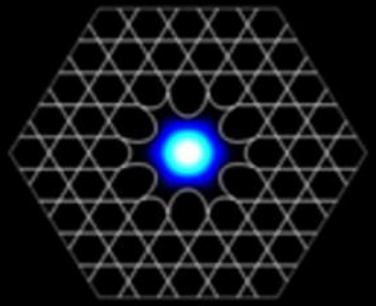




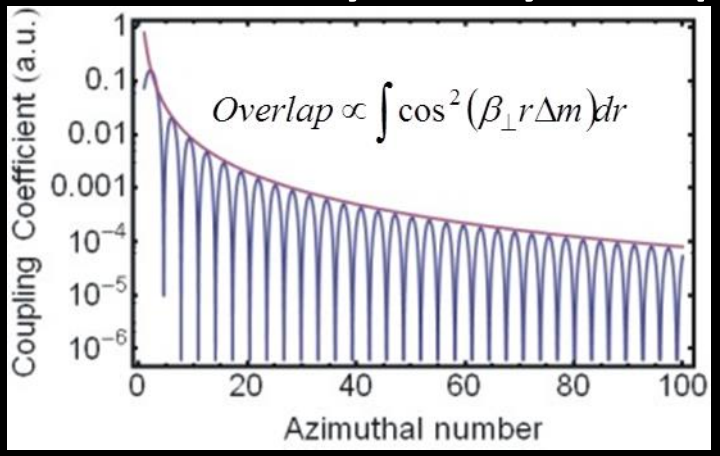
Cups curvature on enhancing IC

Debord et *al.* CLEO, CTu2K.4 (2013)
Alharbi et *al.* CLEO,**CTu2K.7** (2013)

Reduction on spatial overlap

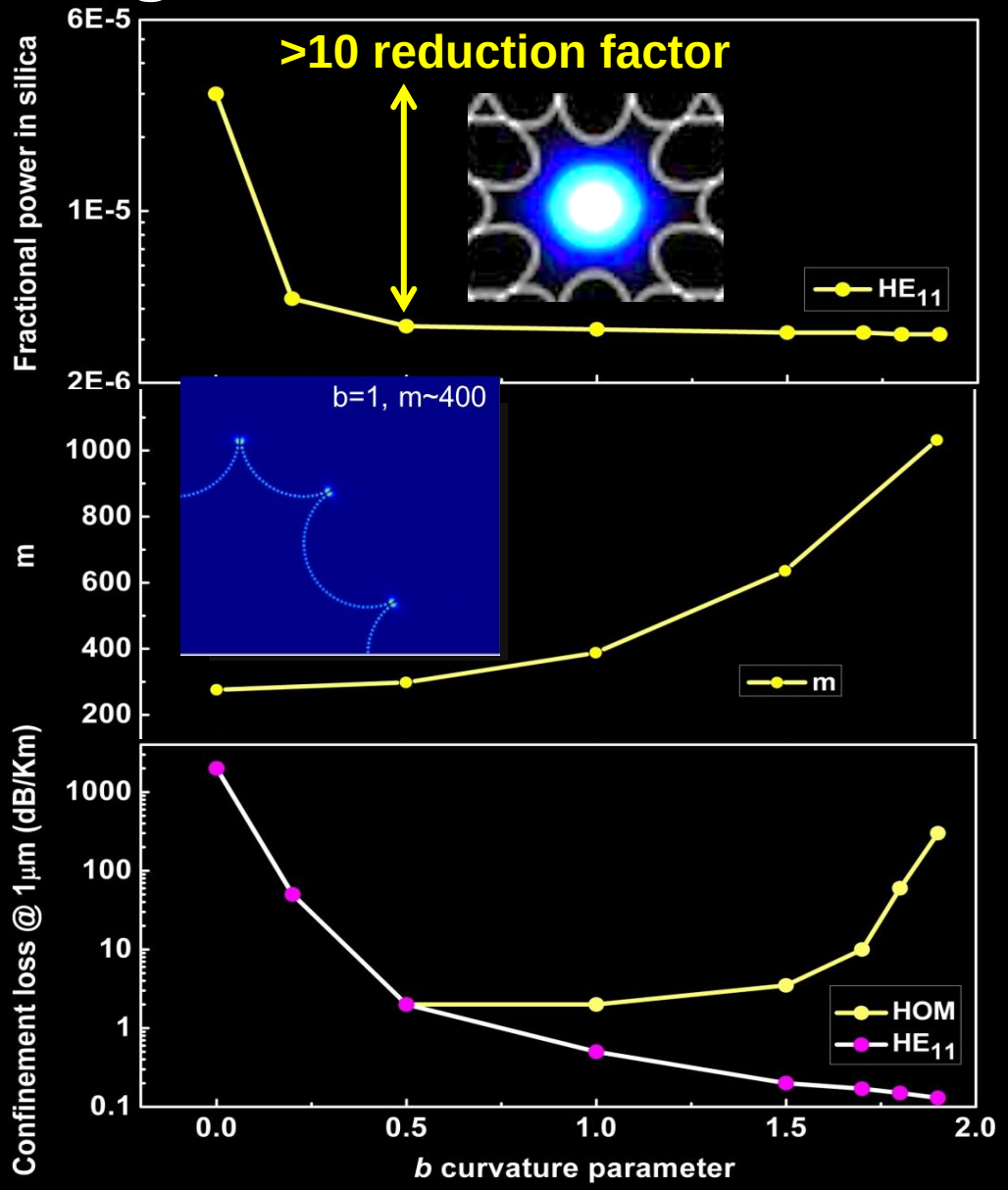


Reduction on symmetry overlap

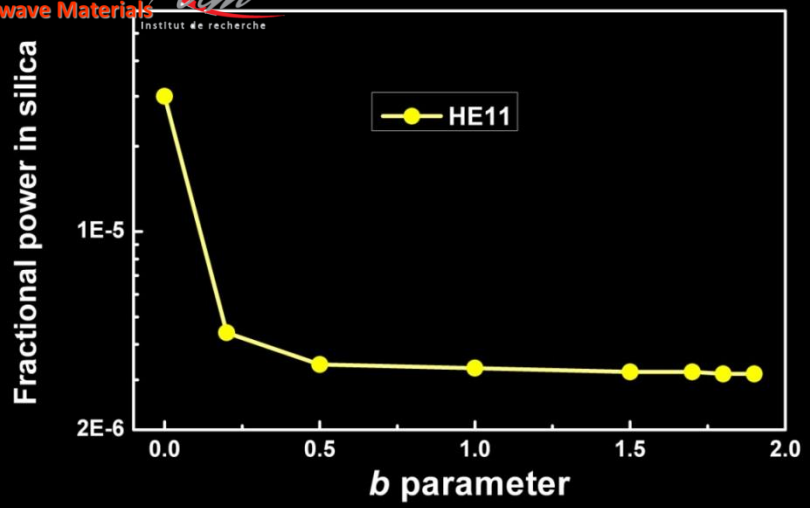


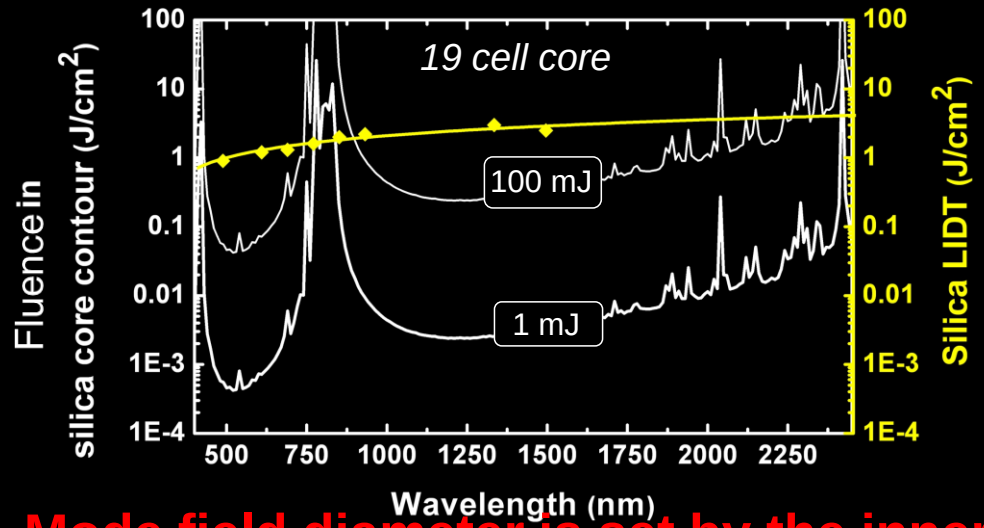
Cleansing of modal content

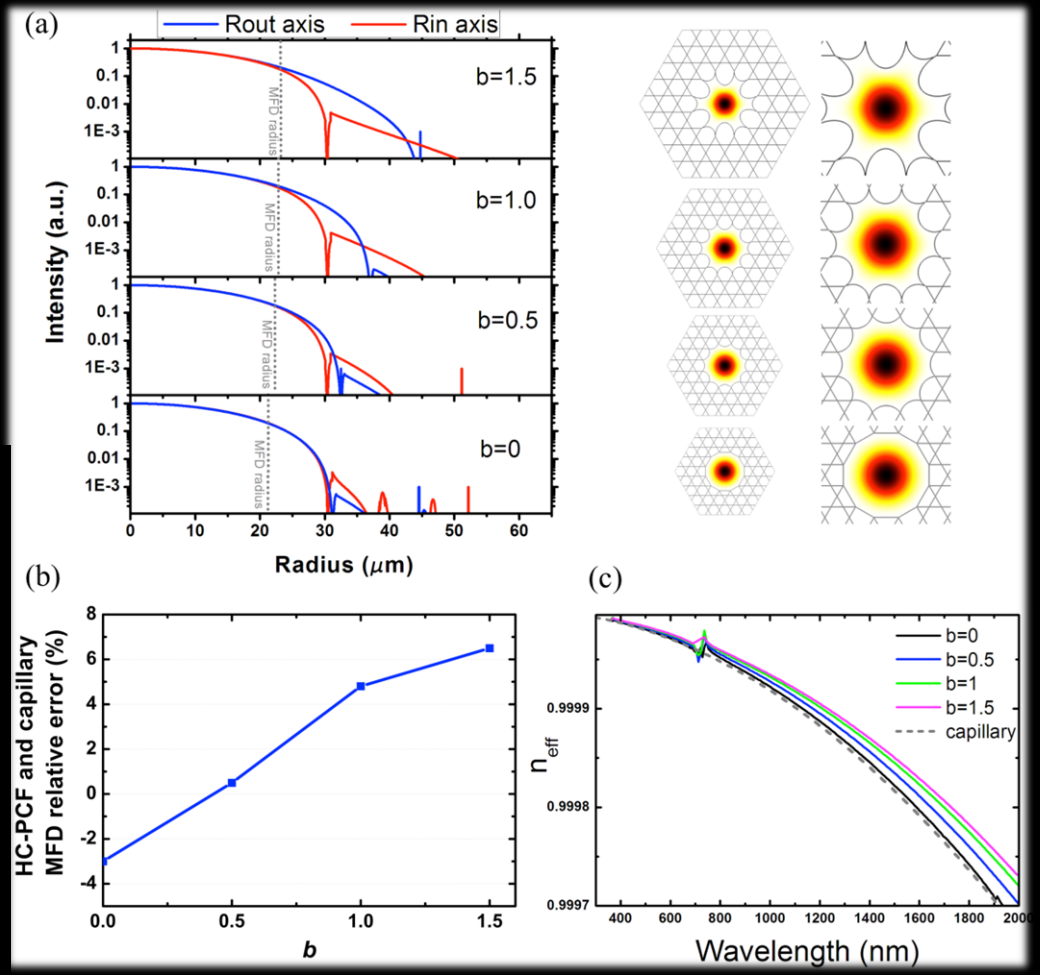
From a few mode operation to truly a single mode



Impact of curvature increase on energy handling



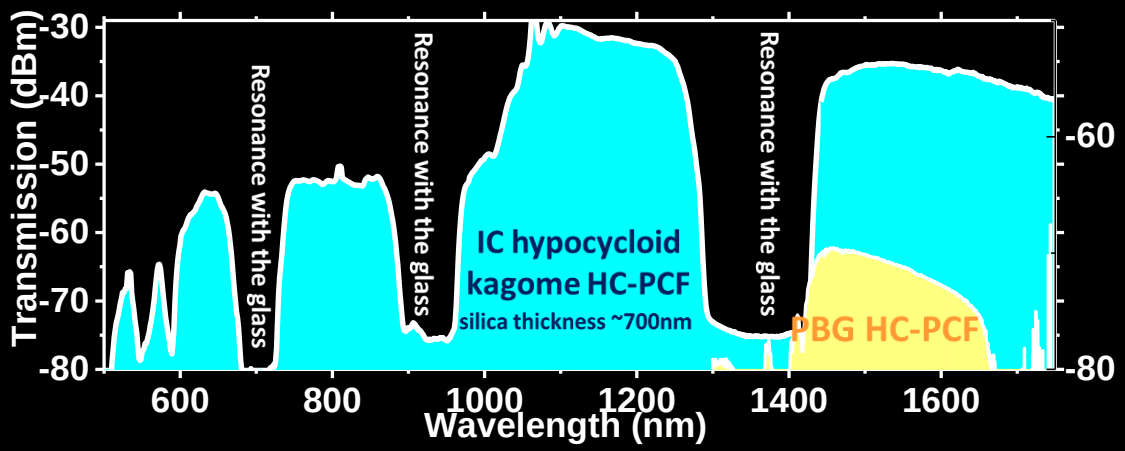


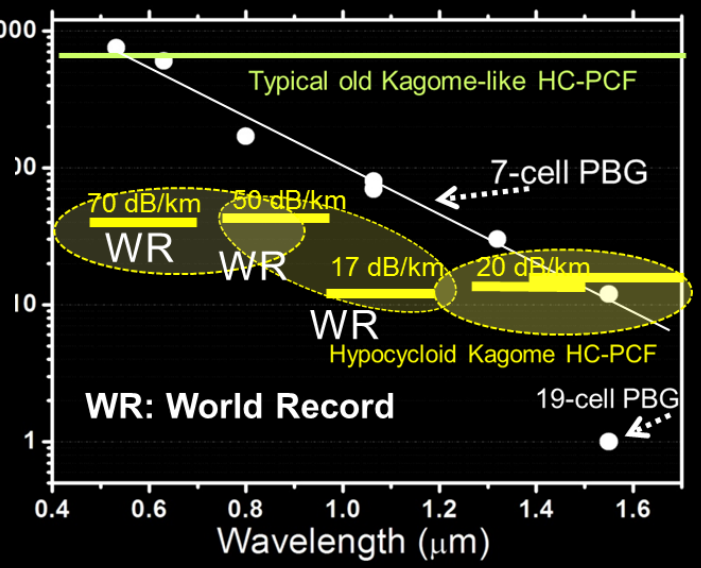


- **Mode field diameter is set by the inner radius of the hypocycloid core-contour**
- **Decrease of power overlap with silica surround to a ppm level**

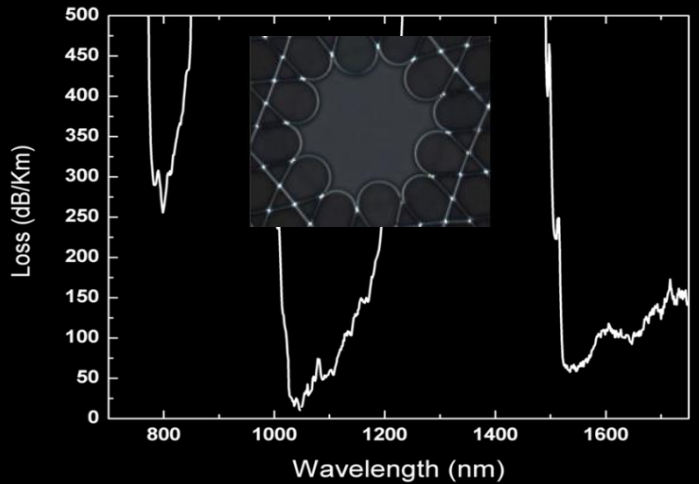
IC guidance current state-of-the-art

Superior alternative to PBG

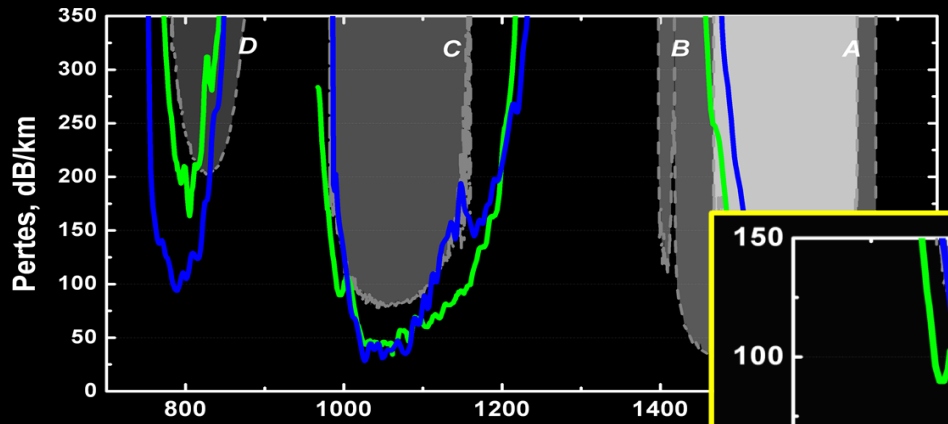


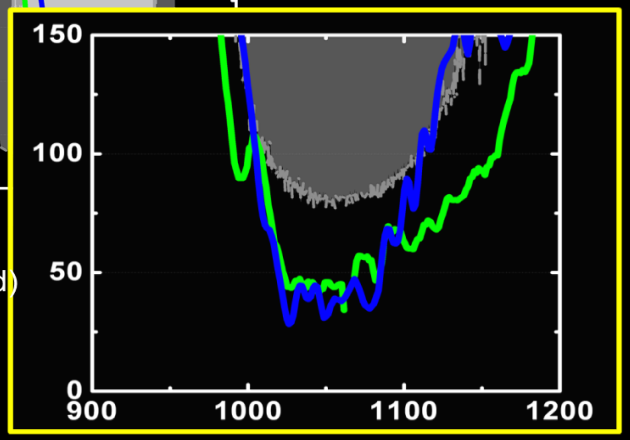


Hypocycloidal (b~1) kagome HC-PCF (world record @ 1μm)



Record loss figure of 17 dB/km @ ~1μm



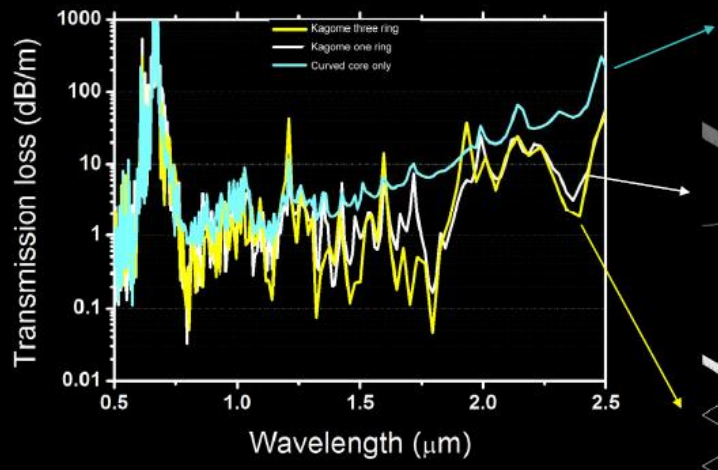


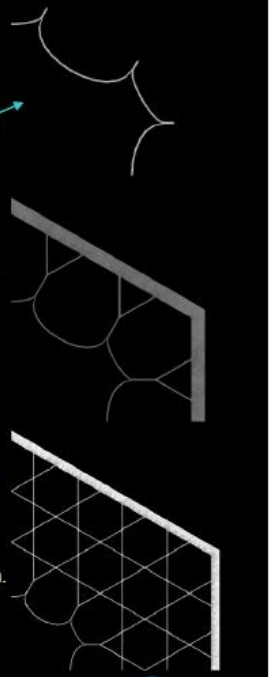
A: 19-cell PBG 1500nm HC-PCF (world record)
B: 7-cell PBG 1500 nm HC-PCF
A: 7-cell PBG 1000 nm HC-PCF
A: 7-cell PBG 800 nm HC-PCF

Kagome PCF with a single ring= negative curvature hollow fiber

Simulations

Our simulations using a finite element method (JCMwave)





- Cladding structure does contribute to the confinement at least for shorter wavelength.
- Adding more rings has suppressed some loss resonances.
- Three rings is the optimum. No need for more rings.
- The current structure is not appropriate for good guidance at the visible.

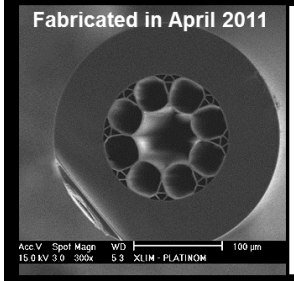
UNIVERSITY OF BATH

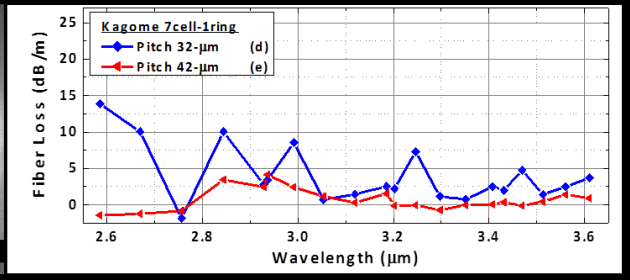
CLEO 2010 –Postdeadline Session II
Thursday, May 20, 2010, 8:30 PM, San Jose, California , USA

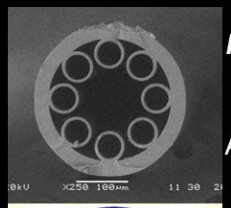
Centre for Photonics & Photonic Materials

LOSS RECORD extended to the Mid-IR

A.V.V. Nampoothiri *et al.*, Opt. Mat. Express, 2, 948(2012)

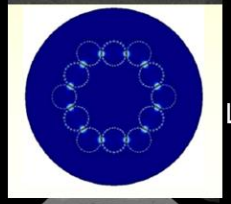




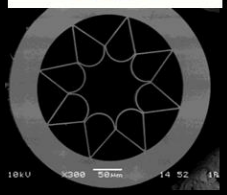


First follow-up literature on the subject

A.D. Pryamikov et al. Opt. Exp. 19 1441-1448(2011)



L. Vincetti et al. J. Lightw. Tech,30, 10(2012)



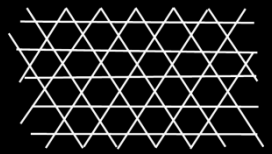
F. Yu, Opt. Exp., 20(10)10, 11153-11158 (2012)

IC PCF with a single ring of tubular lattice

presented in a postdeadline CLEO 2016

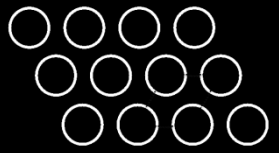
GPPMM Gas-Phase Photonic & Microwave Materials — Xlim institut de recherche

Kagome lattice



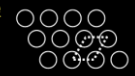
- ✔ Long silica struts
- ✔ Typical azimuthal number $m \approx 200$

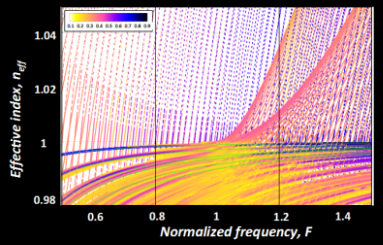
Tubular lattice



- ✔ No connecting nodes

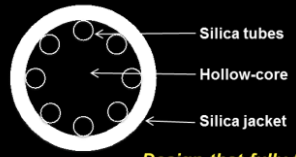
Tubular lattice





Large pitch regime[3]

Hollow-core tubular lattice fiber

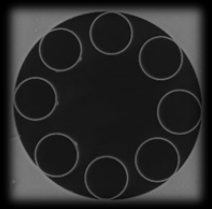


Design that fully filled the guiding rules of the IC

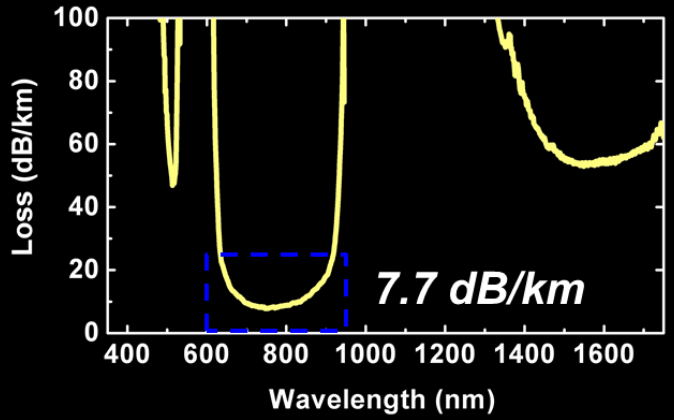
- ✔ No struts silica nodes
- ✔ Long core silica contour perimeter (x2 compared to Kagomé HC-PCF)

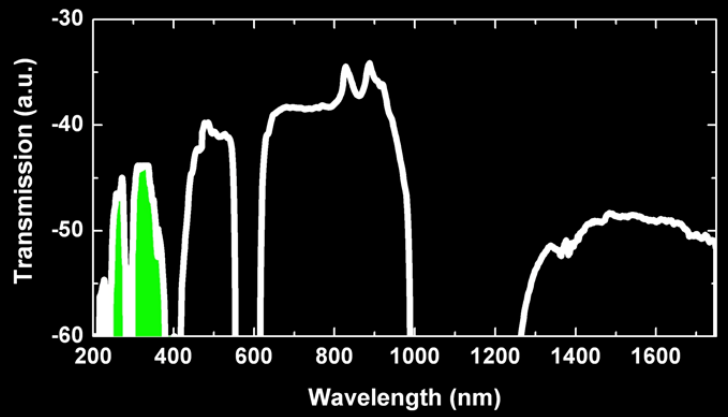
2 record IC HC-PCFS – UV transmission

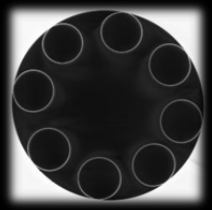
Vincetti *et al.*,"", Optics Express, vol. 18, n° 22 (2010)
Vincetti *et al.*,"Waveguiding mechanism in tube lattice fibers", Optics Express, vol. 18, n° 22 (2010)
[3]Couny *et al.*, Opt. Exp, vol. 15, pp. 325 (2007)



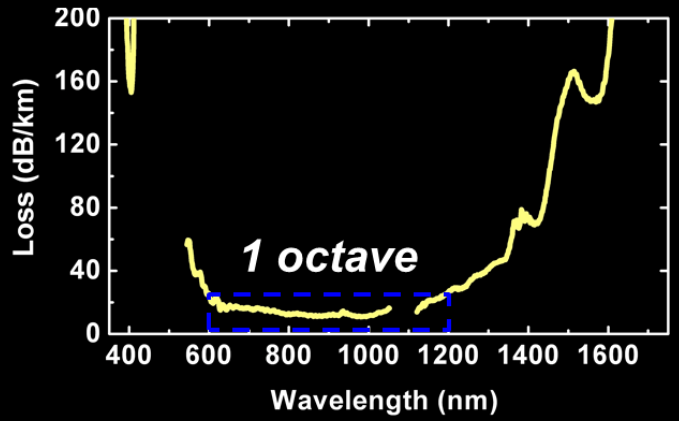
R_{core}= 38 µm
t = 550 nm

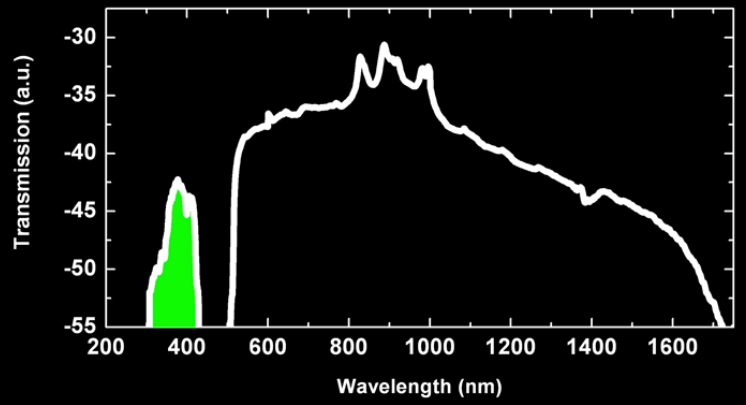






R_{core}= 41 µm
t = 250 nm





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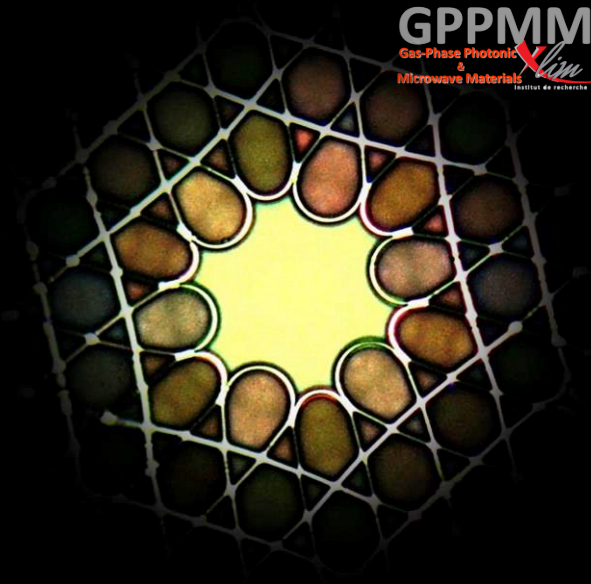


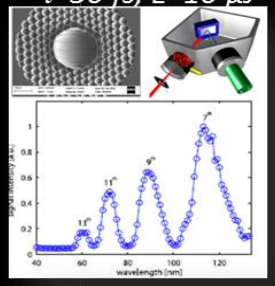
…the extremely energetic, intense & short

- *Platform for Milli-Joule femtosecond laser-pulse delivery and compression in hypocycloid core Kagome HC-PCF*
- *Near PettaWatt/cm^2*
- *Industrial fibre beam delivery*
- *“Poor man” Pulse compressor*
- *“Rich man” Sub-cycle pulse compression*
- *Super optical-nonlinearity with air*

Kagome HC-PCF a platform for high optical field and ultra-fast optics

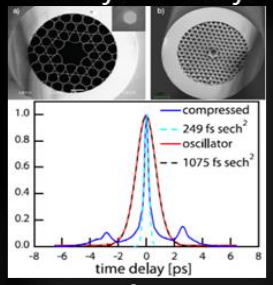
1. Heckl et *al*. Appl Phys B 97, 369–373 (2009)
2. Heckl et *al*. Opt. Express 19, 19142(2011)
3. Wang et *al*. Opt. Lett. 37, I3111-3113 (2012)
4. Emaury et *al*. Opt. Express 21, 4986-4994 (2013)
5. Fourcade-Dutin et al. Postdeadline CLEO 2013, Debord et *al*. Opt. Express, 22, 10735 (2014)
6. Mak et *al*. Opt. Lett. 38, 3592(2013)
7. Balcuinas, postdeadline ASSL, JTh5A.5. (2013)

1ST HHG IN HC-PCF
τ=30 fs, E=10 μJ



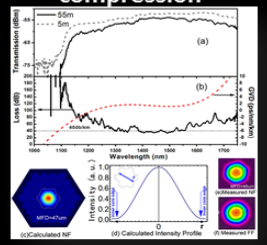
GPPM/MPI/ETH/ICL [1]

1ST COMPRESSION IN IC HC-PCF
τ=470 fs → <50 fs



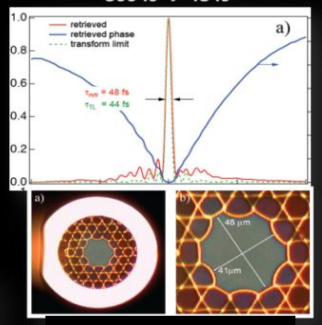
GPPM/ETH [2]

RECORD LOSS IC HC-PCF (40 dB/km)
100 μJ USP delivery & compression



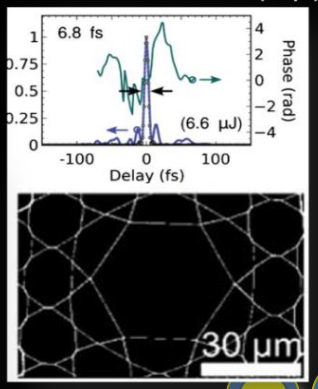
GPPM/RAYDIANCE [3]

High avg power USP compression
860 fs → 48 fs



GPPM/ETH [4]

COMPRESSION 24 → 6.8 fs (~7 μJ)

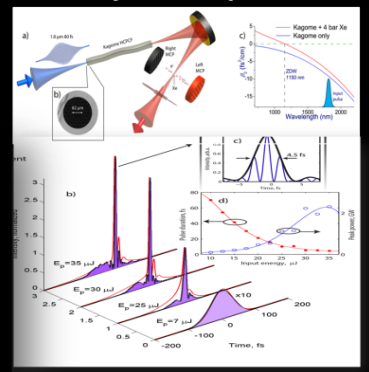


MPI, Erlengen[6]

RECORD 1mJ USP delivery & compression

GPPM/GLO/AS [5]

Sub-Cycle compression



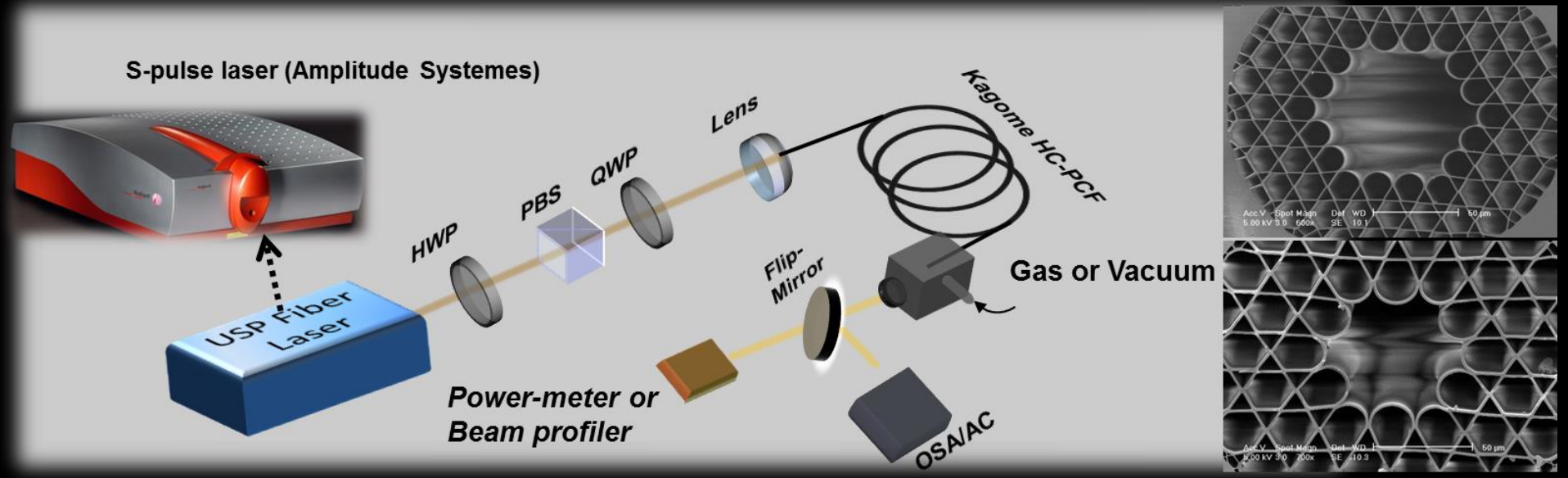
GPPMM/VIENNA [7]

2008 2009 2010 2011 2012 2013 2014

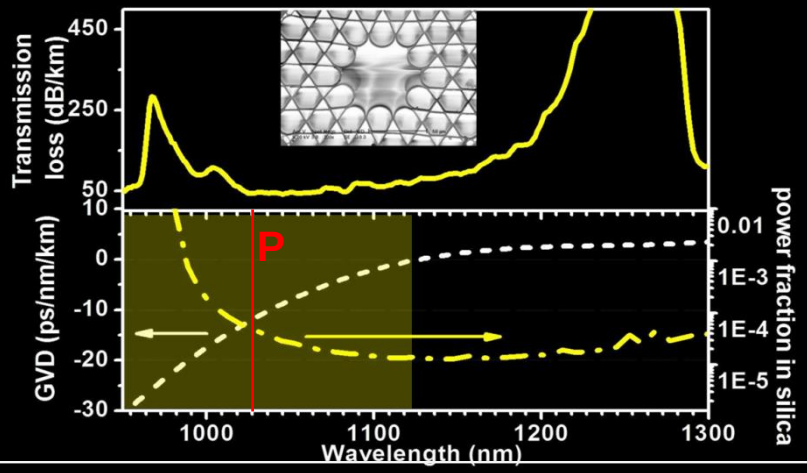
Kagome HC-PCF a platform for high optical field and ultra-fast optics

Milli-Joule USP laser transport and compression

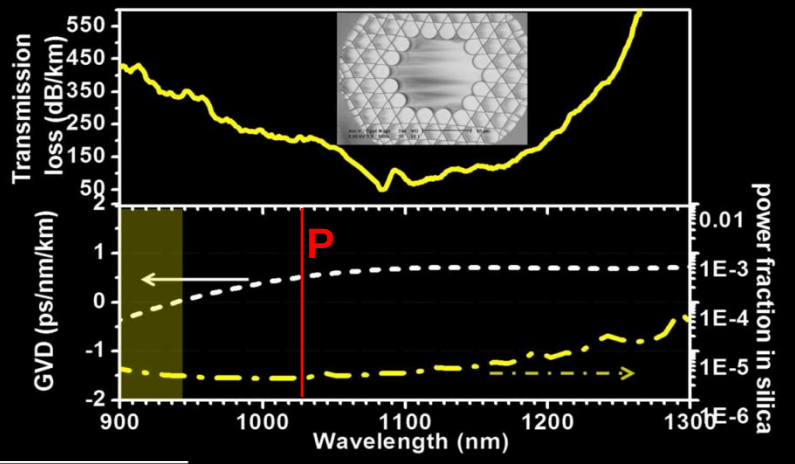
C. Fourcade-Dutin, in CLEO: 2013, Postdeadline paper CTh5C.7.



Core-size = 52 µm, b-curvature parameter ~ 1
@ 1030: GVD ~-11ps/nm/km. Loss~45dB/km



Core-size = 80 µm, b-curvature parameter ~ 1
@ 1030: GVD ~ 0.5 ps/nm/km. Loss~200 dB/km

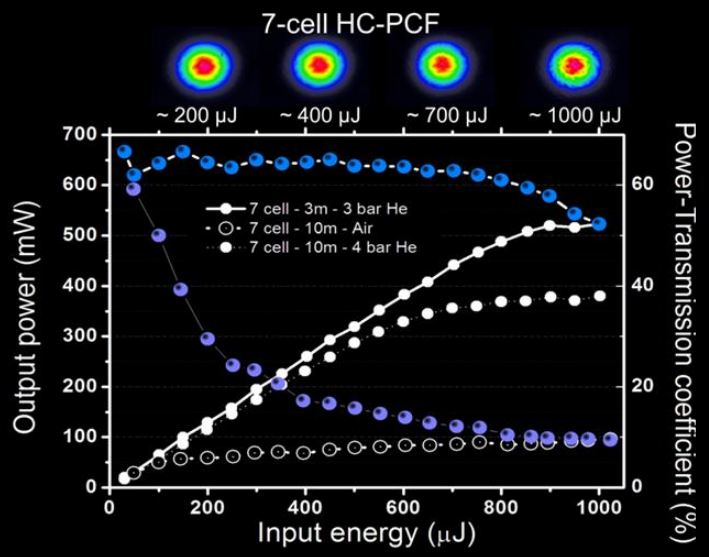


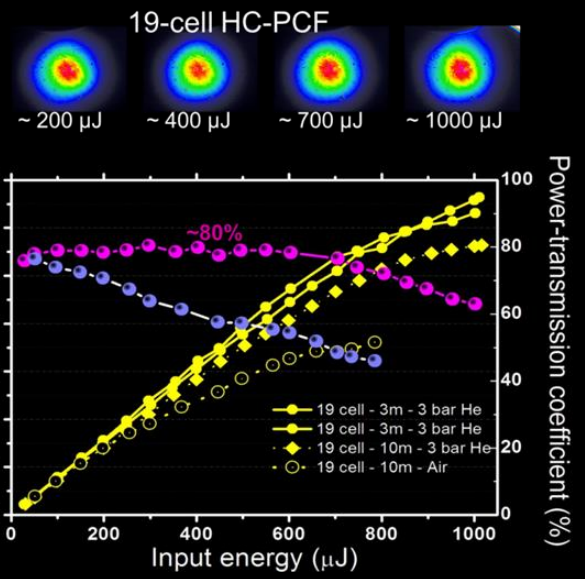
Laser: 1030nm center-wavelength, 500 fs pulse-duration, 1 KHz rep.rate, Max Energy=1mJ
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells and 19 cells , lengths: 3 m and 10 m
Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber), and 20 cm (19 cell fiber)
Coupling: HC-PCF input end exposed to air. Output end: in gas/vacuum chamber or exposed to ambient air

Kagome HC-PCF a platform for high optical field and ultra-fast optics

Milli-Joule USP laser transport and compression

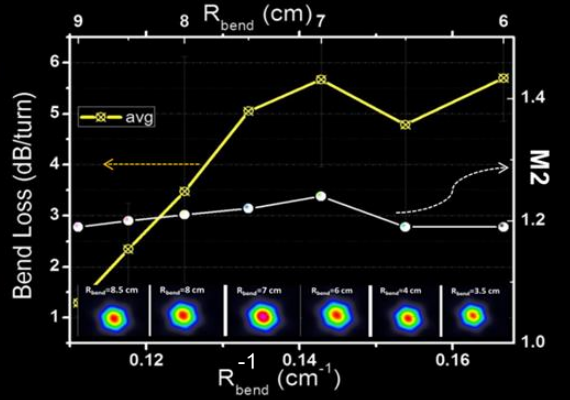
“Linear” transmission





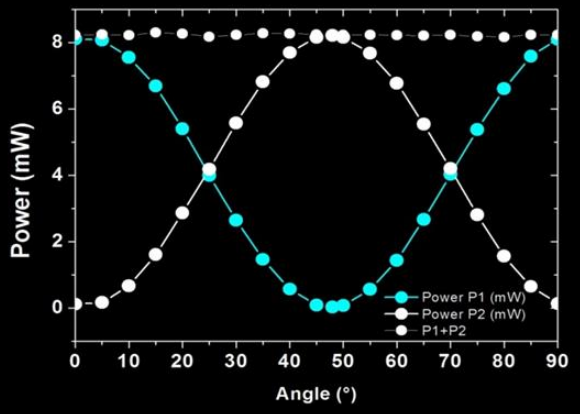
Bend loss

3-dB/turn radius ~8 cm
Single mode operation intact upon bend
Measured M2 ~1.2



PER

A staggering figure of 25dB PER was measured



Kagome HC-PCF a platform for high optical field and ultra-fast optics

Milli-Joule USP laser transport and compression

GPPMM Gas-Phase Photonic & Microwave Materials — Xlim institut de recherche

Tuning to your desired optical nonlinearities

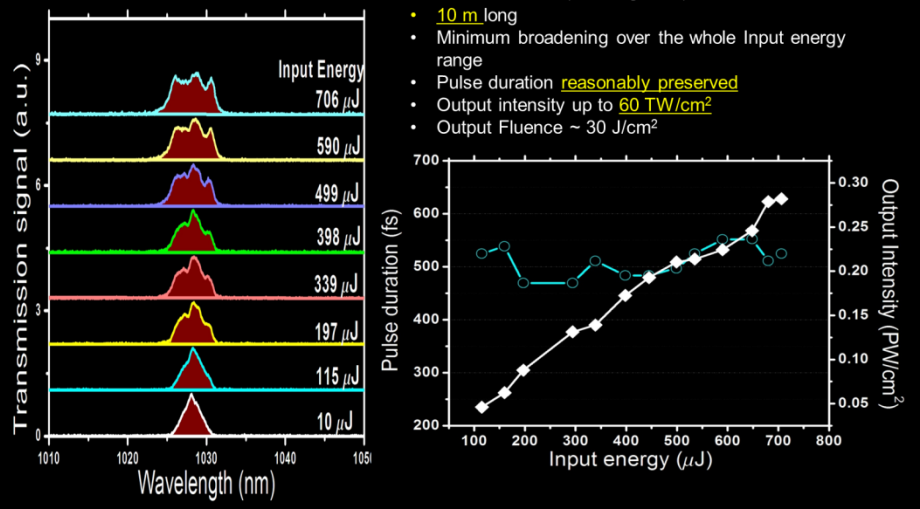
1. Control parameters: fiber dispersion, effective area, gas choice
2. Nonlinear regimes: (i) Ultra-low nonlinearity for « HiFi » USP transportation. (ii) Solitonic self-compression, (iii) SPM broadening

	He-filled 19 cell fiber	Air-filled 19 cell fiber	He-filled 7 cell fiber	Air-filled 7 cell fiber
Dispersion length, $L_D\ (m)$	555	577	28	28
Nonlinear length, $L_{NL}\ (m)$	1.9	0.09	0.9	0.04
Self-focusing critical power, $P_{cr}(\mathrm{GW})$	2026	9.5	2026	9.5
Ionization threshold intensity, $I_{it}(\mathrm{TW}.cm^{-2})$	200	40	200	40

Nonlinear transmission #1

19-cell hypocycloid kagome HC-PCF
(He flowing in core)

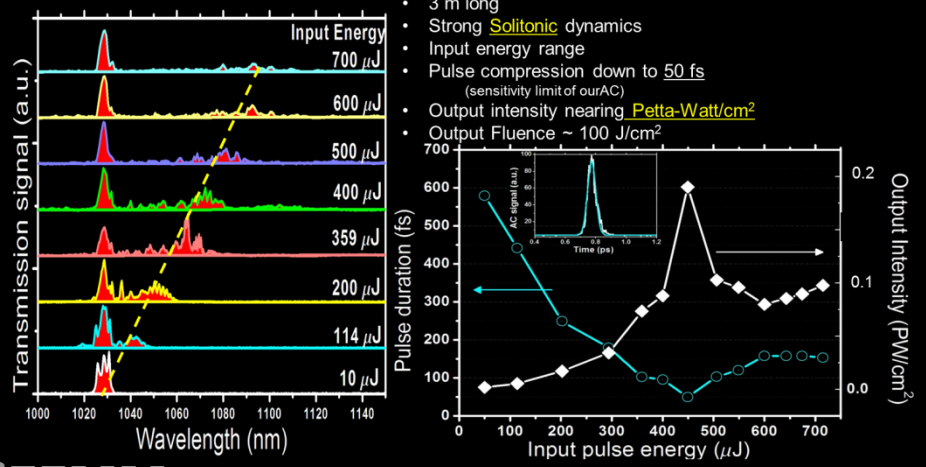
- 10 m long
- Minimum broadening over the whole Input energy range
- Pulse duration reasonably preserved
- Output intensity up to 60 TW/cm²
- Output Fluence ~ 30 J/cm²



Nonlinear transmission #2

19-cell hypocycloid kagome HC-PCF
(Air in core)

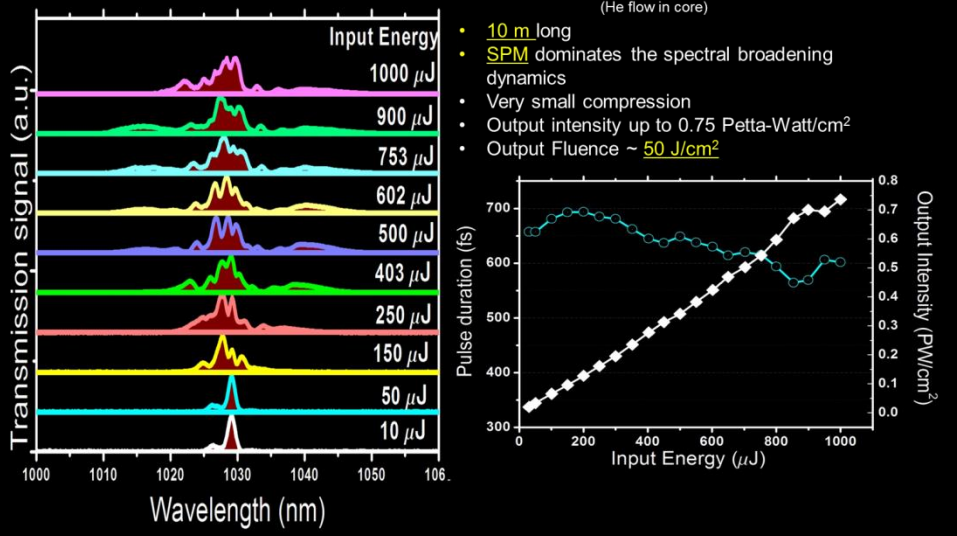
- 3 m long
- Strong Solitonic dynamics
- Input energy range
- Pulse compression down to 50 fs (sensitivity limit of ourAC)
- Output intensity nearing Petta-Watt/cm²
- Output Fluence ~ 100 J/cm²



Nonlinear transmission #3

7-cell hypocycloid kagome HC-PCF
(He flow in core)

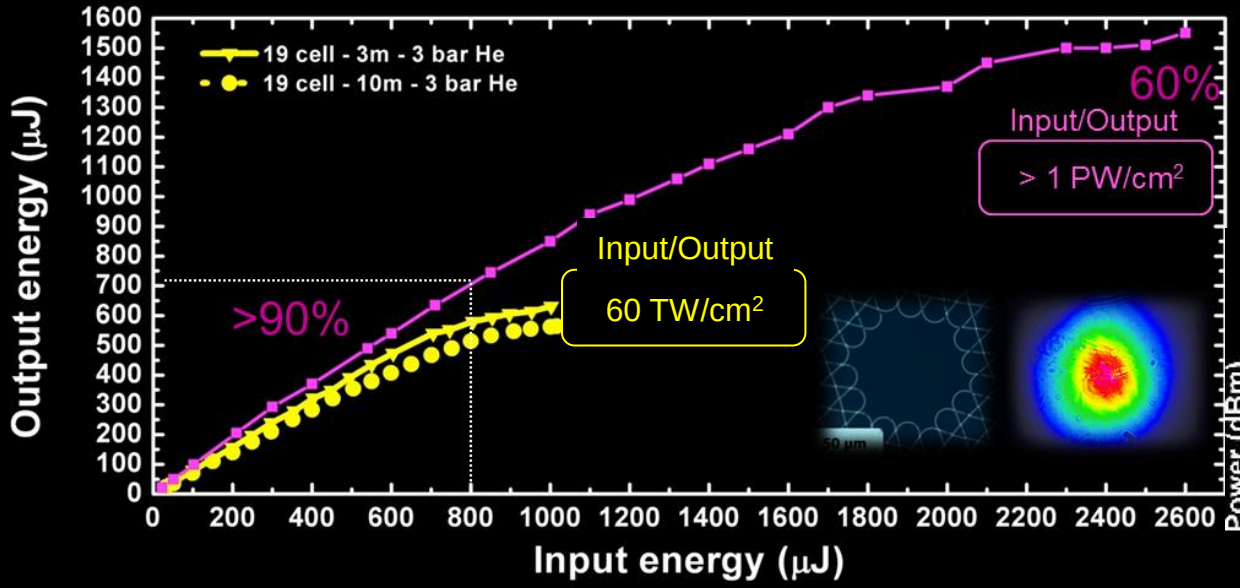
- 10 m long
- SPM dominates the spectral broadening dynamics
- Very small compression
- Output intensity up to 0.75 Petta-Watt/cm²
- Output Fluence ~ 50 J/cm²



GPPMM Gas-Phase Photonic & Microwave Materials — Xlim institut de recherche

Tailored *spectral broadening for High energy Ti:Sapph laser*

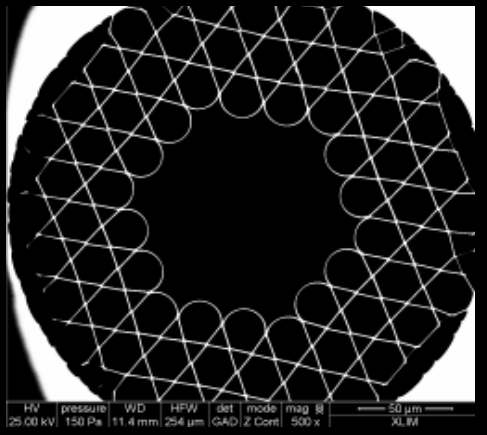
- 2.6 mJ energy handling – 30 fs input pulses
- 81 GW input peak power (*54/ previous work)
- Few mode guidance
- 60% transmission coefficient
- 35 cm-long He-filled hollow-core
- Output intensity up to 1.1 PW/cm^2



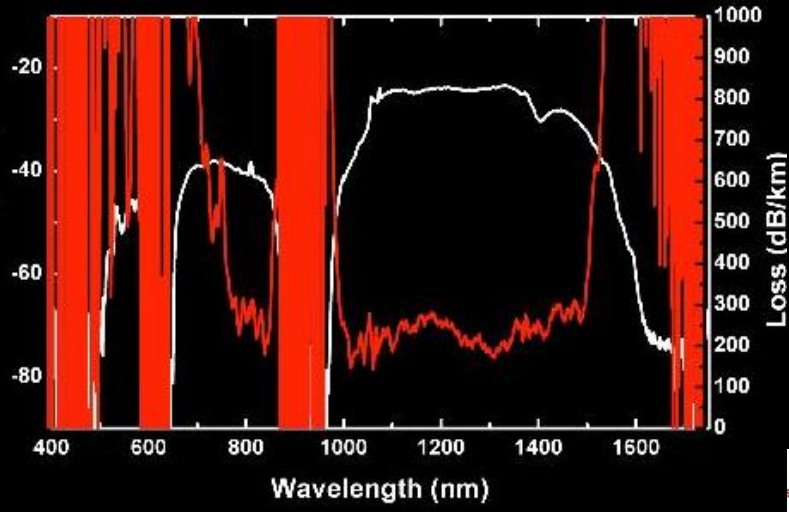
B. Debord et *al*. CLEO US, STh4L.7. (2015)

Ultra-large core Kagome hollow-core photonic crystal fiber

19 Cell HC-PCF, MFD 70-100 µm

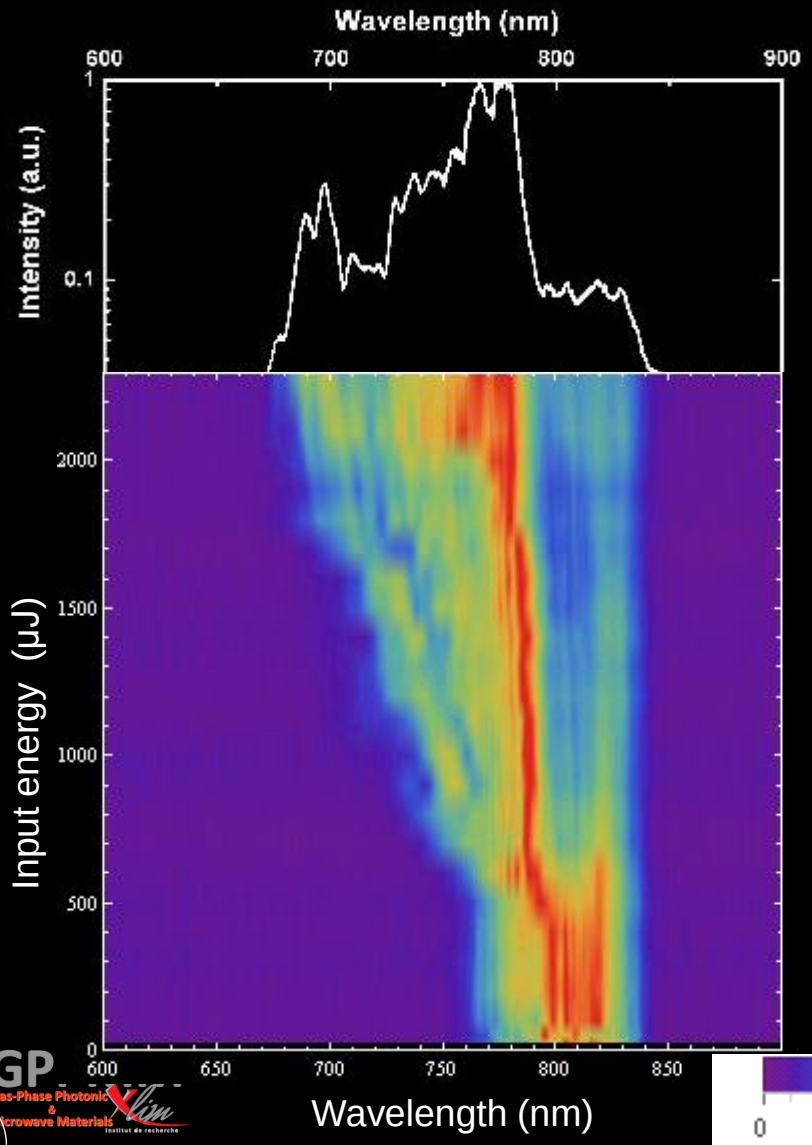


Optimization for 800 nm guidance

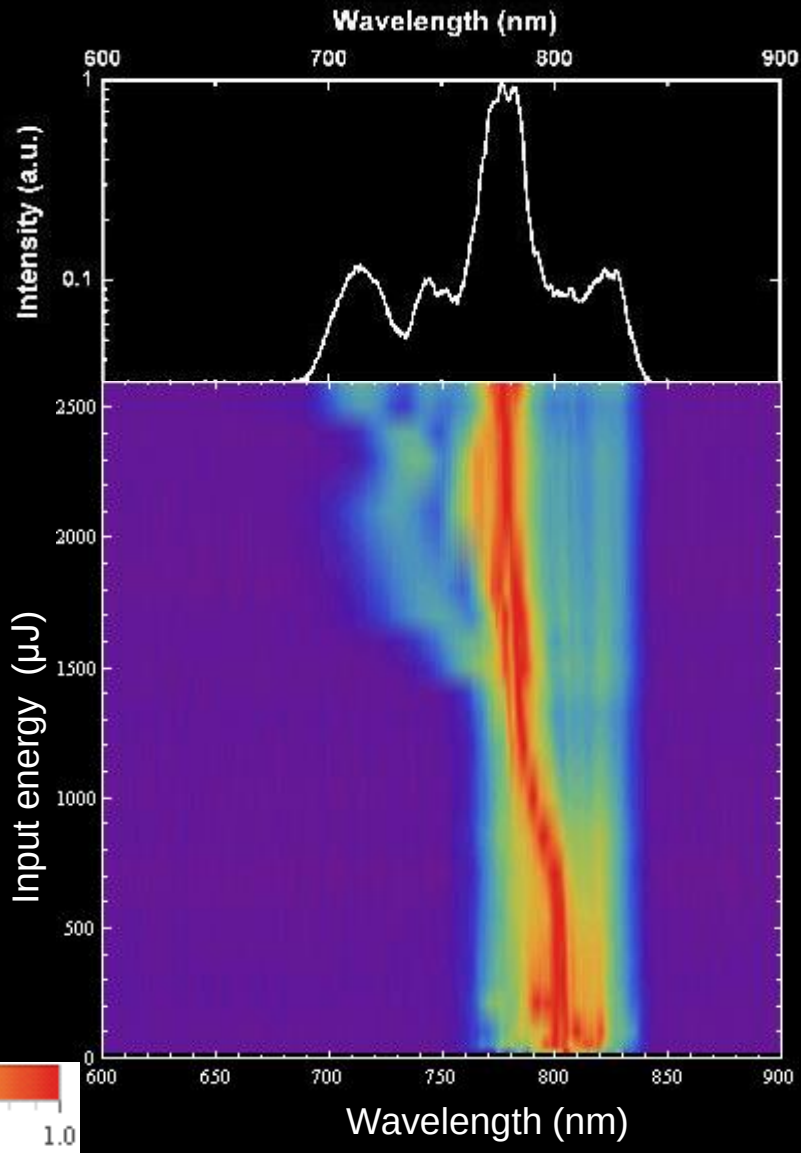


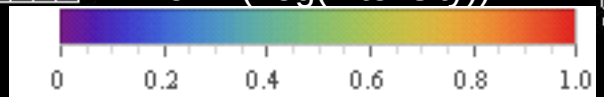
Tailored *spectral broadening for High energy Ti:Sapph laser*

Fiber length : 55 cm
Fiber filled with: Hélium 3bar



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

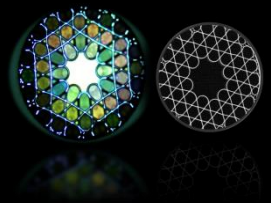


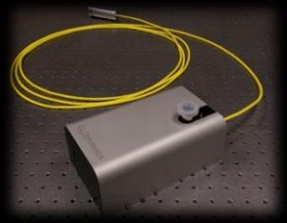


Kagome fiber goes industrial

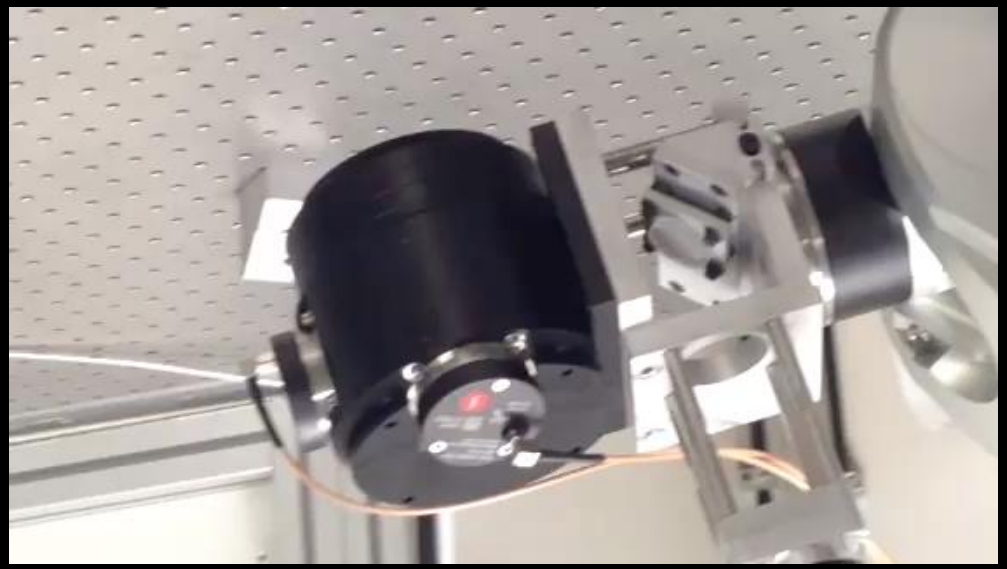
GLOphotonics

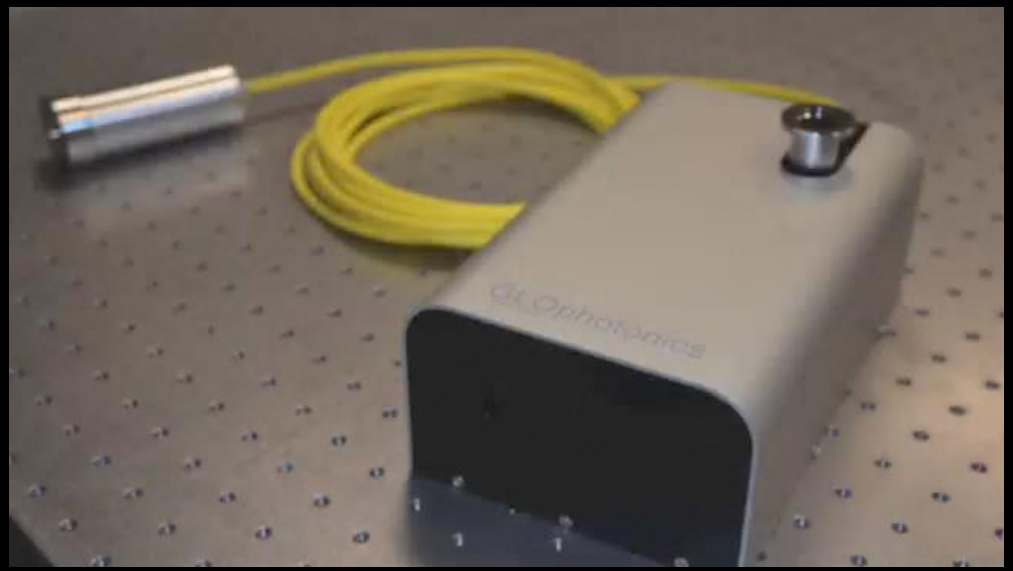
The Hollow-Core PCF and Photonic MicroCell™ Company



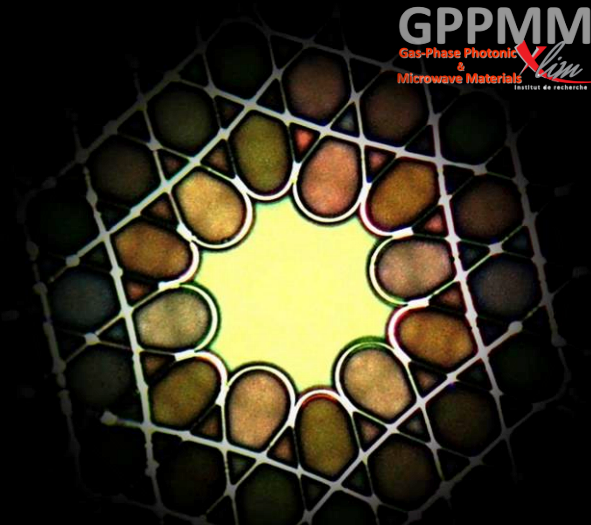


PRISM AWARDS FINALIST





GPPMM
Gas-Phase Photonic & Microwave Materials
Xlim institut de recherche



Poor man's pulse compressor

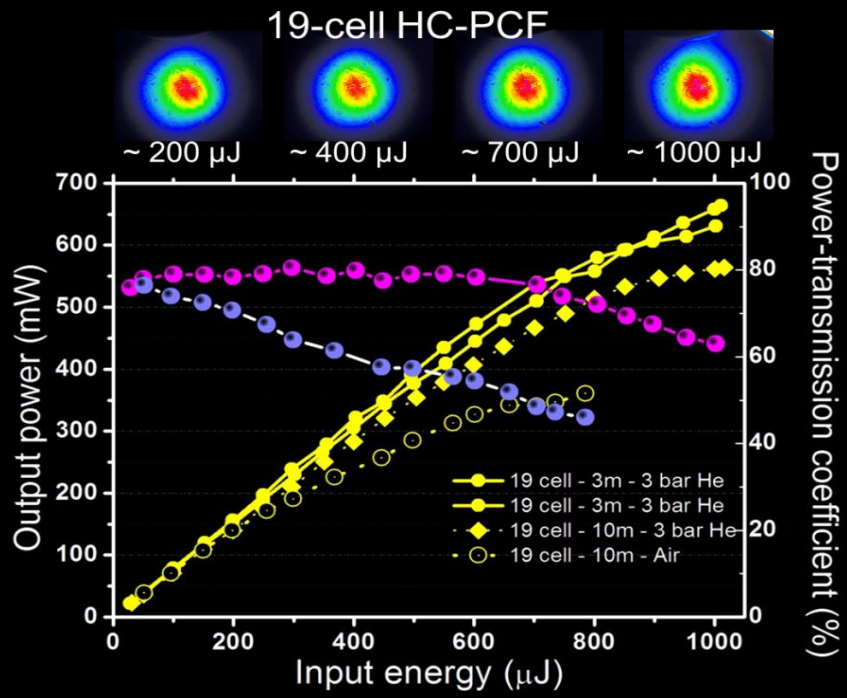
Addressing the following question:

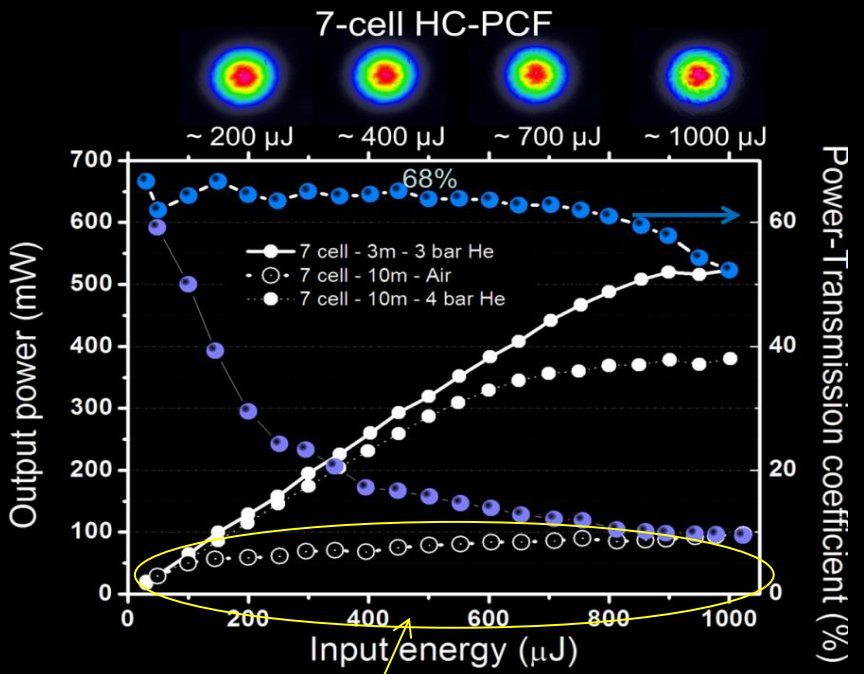
What is our room of manouvre in optimising self-compressing typical high energy USP (duration >500 fs and E>100 µJ) duration with the simplest set-up possible?

Meaning using only a « bare » 7-cell kagome HC-PCF », and with no gas filling/management or special excitation .

Kagome HC-PCF:

An emerging Platform for Nonlinear optics and material microprocessing





	He-filled 19 cell fiber	Air-filled 19 cell fiber	He-filled 7 cell fiber	Air-filled 7 cell fiber
Dispersion length, $L_D\ (m)$	555	577	28	28
Nonlinear length, $L_{NL}\ (m)$	1.9	0.09	0.9	0.04
Self-focusing critical power, $P_{cr}(\mathrm{GW})$	2026	9.5	2026	9.5
Ionization threshold intensity, $I_{it}(\mathrm{TW}.cm^{-2})$	200	40	200	40

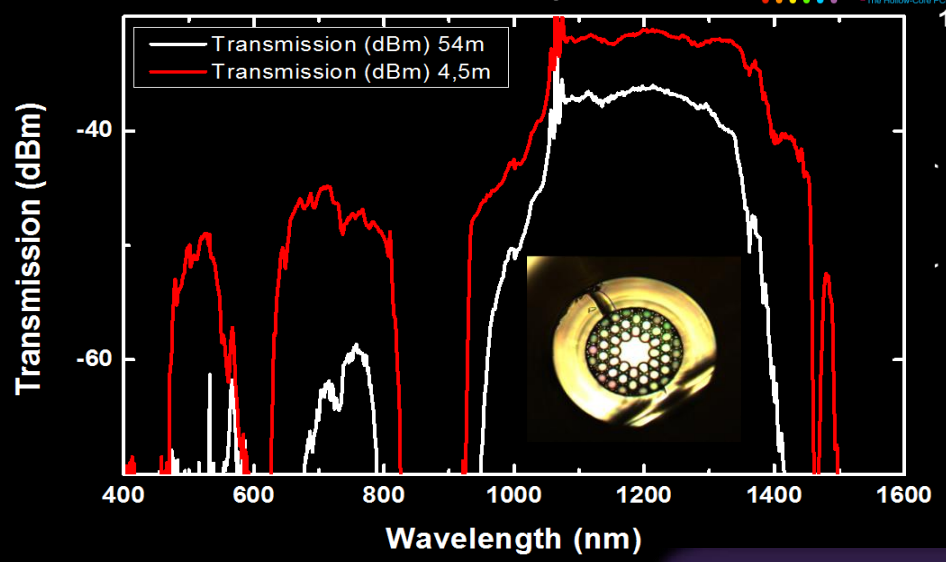
The less flattering picture

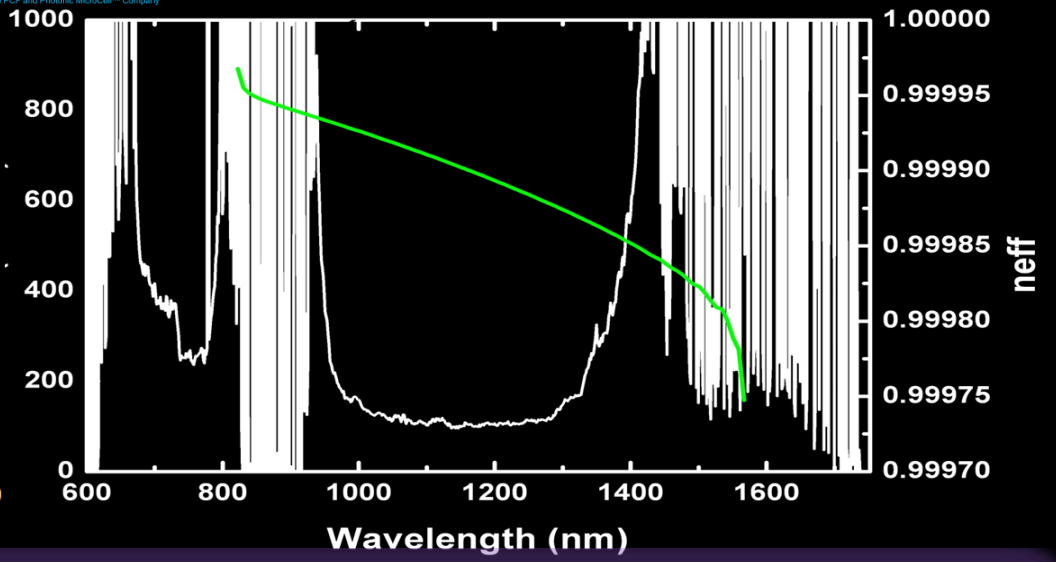
1. **High nonlinear loss**
2. **Plasma over-powering dynamics**

1 GW PEAK POWER IS TAKEN IN THE CALCULATIONS

SPECIFICATIONS OF THE CHOSEN FIBER/ SET-UP

Fiber available from GLOphotonics





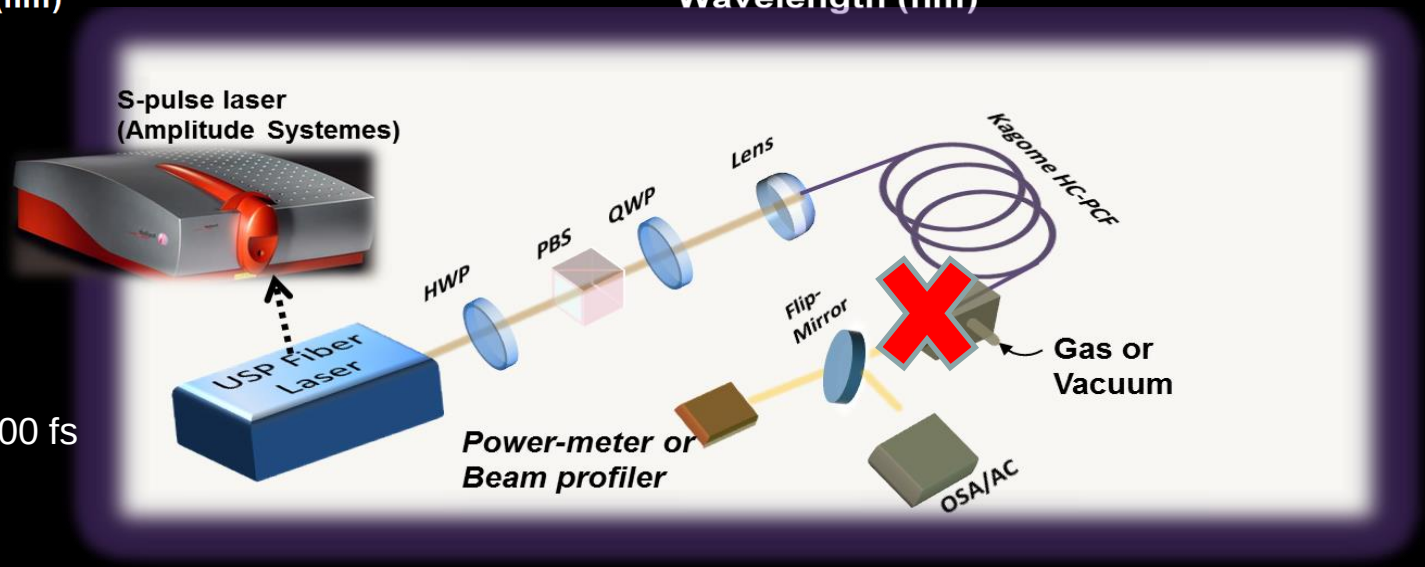
Fibre:
Inner diameter: 56 µm
b-parameter: ~1
Loss @ 1030 nm: 130 dB/km
GVD @1030 nm
1.5 ps/nm/km

Laser: 1030nm center-wavelength, 600 fs pulse-duration, 1 KHz rep.rate, Max Energy=1mJ

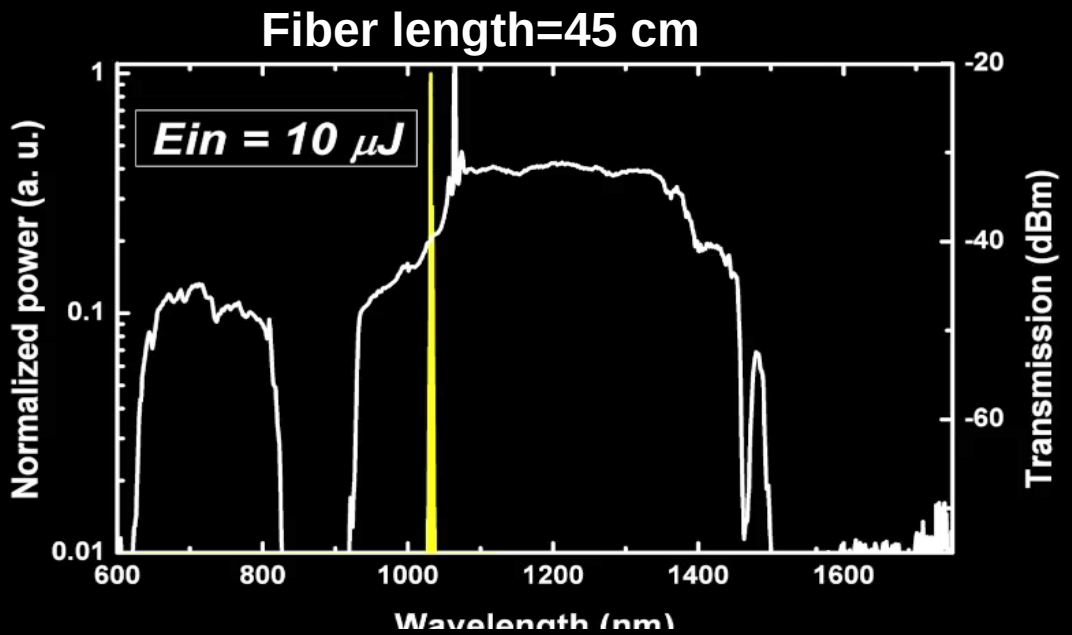
Detection

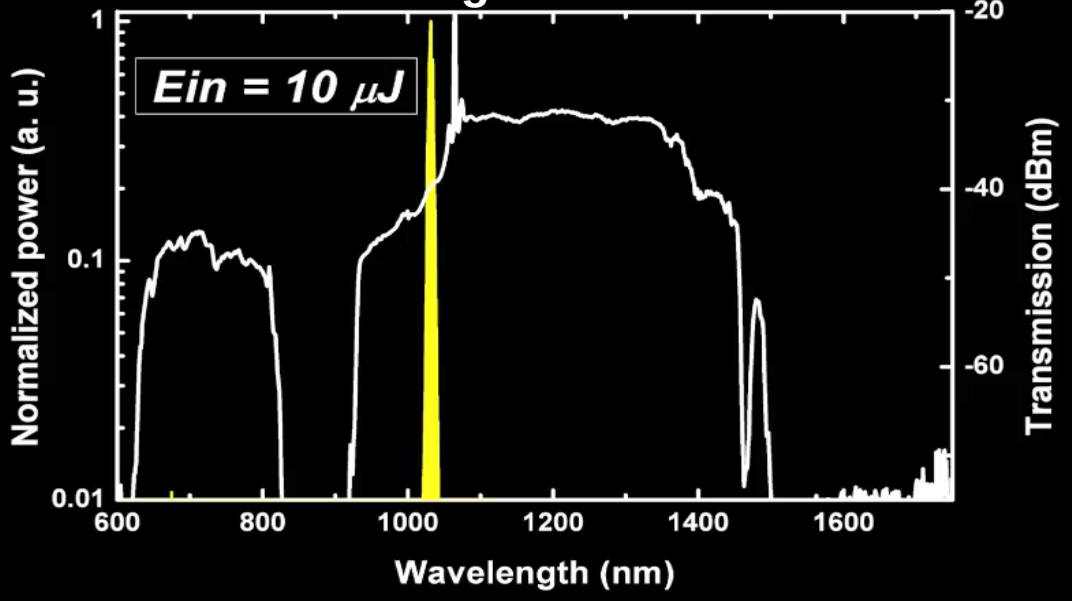
OceanOptics photospectrometer

AC traces with APE PulseCheck

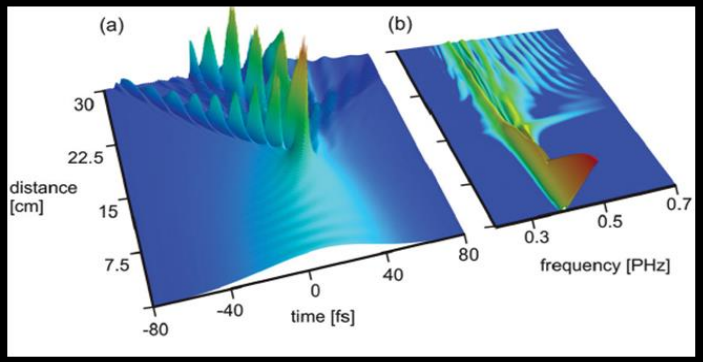


SPECTRAL DYNAMICS

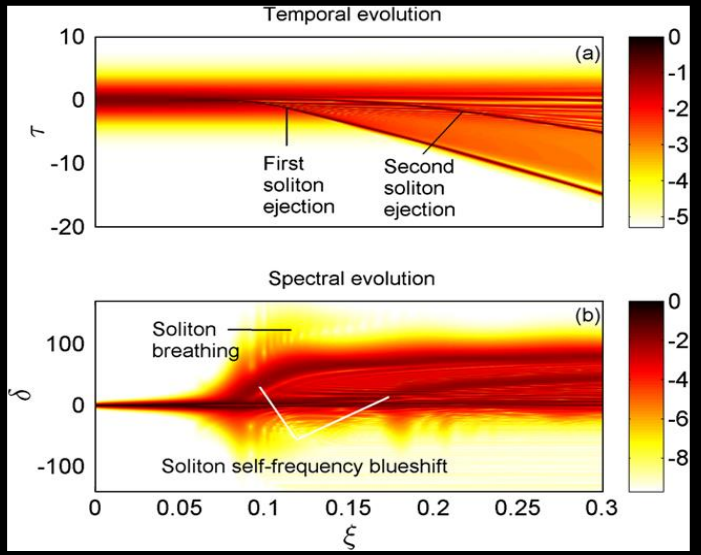




P. Hölzer et *al*. Phys. Rev. Lett. 107, 203901 (2011)



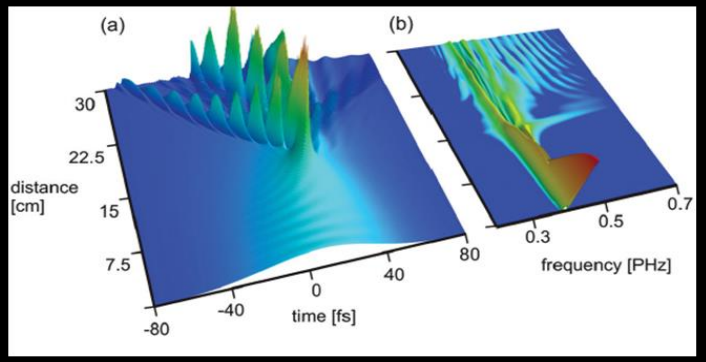
M.F.Saleh et *al*. Phys. Rev. Lett. 107, 203902 (2012)



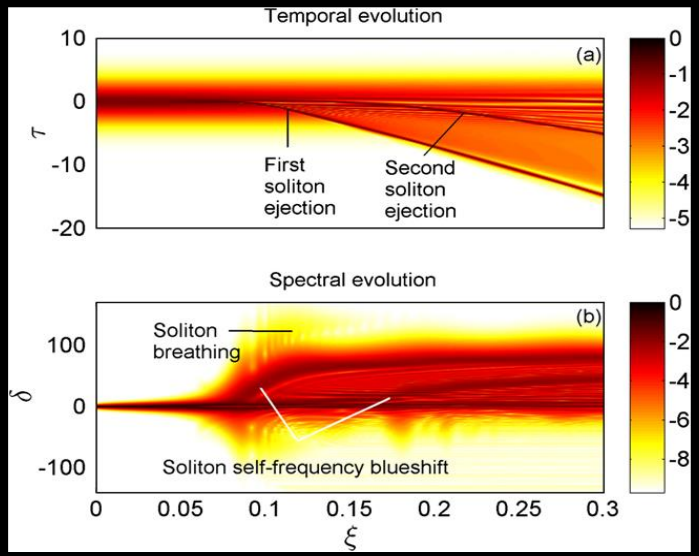
ENERGY/ LENGTH FOR OPTIMUM COMPRESSION

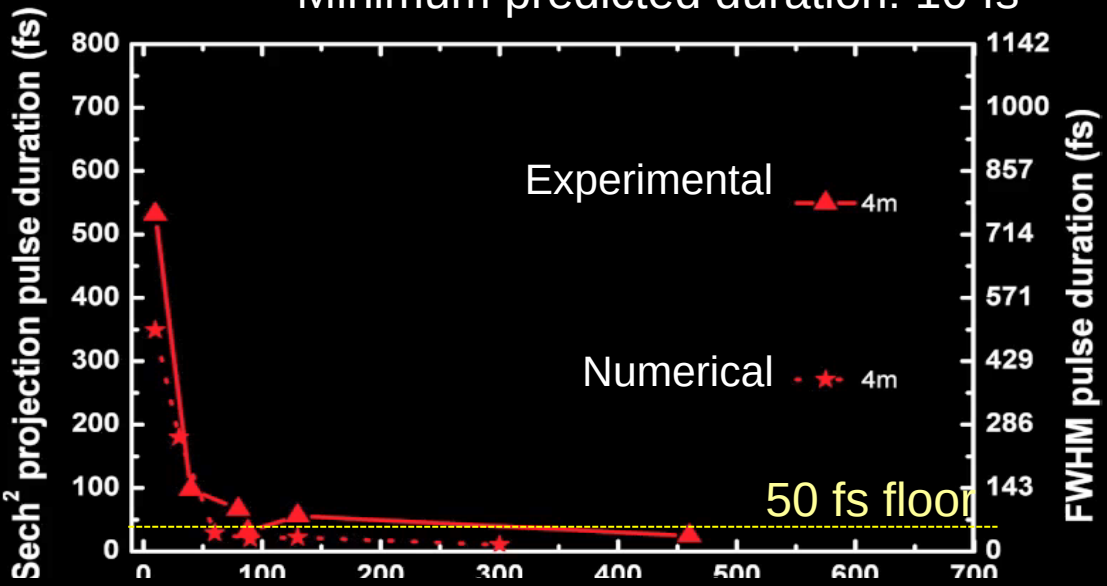
Minimum measured duration: 25 fs
Minimum predicted duration: 10 fs

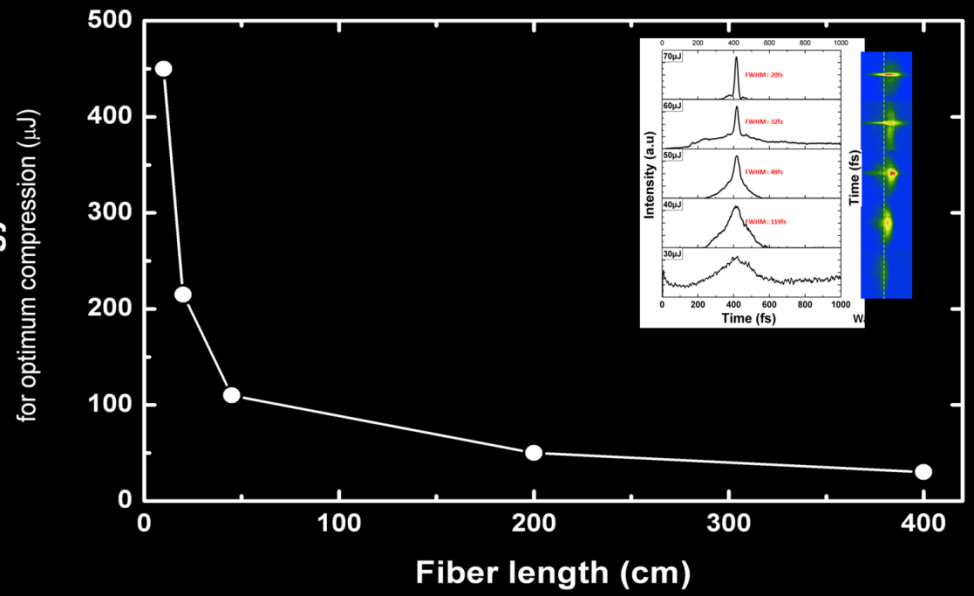
P. Hölzer et *al*. Phys. Rev. Lett. 107, 203901 (2011)

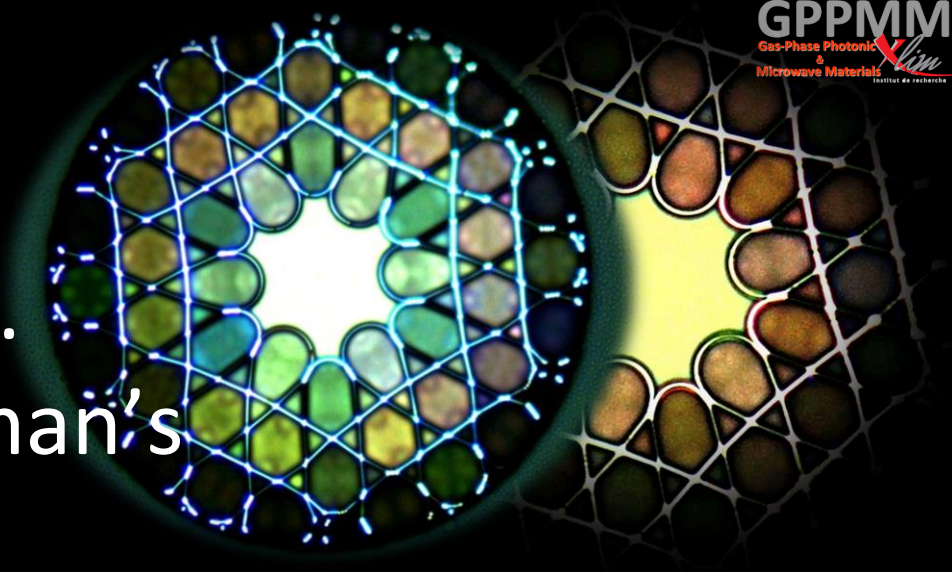


M.F.Saleh et *al*. Phys. Rev. Lett. 107, 203902 (2012)









Single, single, single pulse…
must be funny in the rich man's world

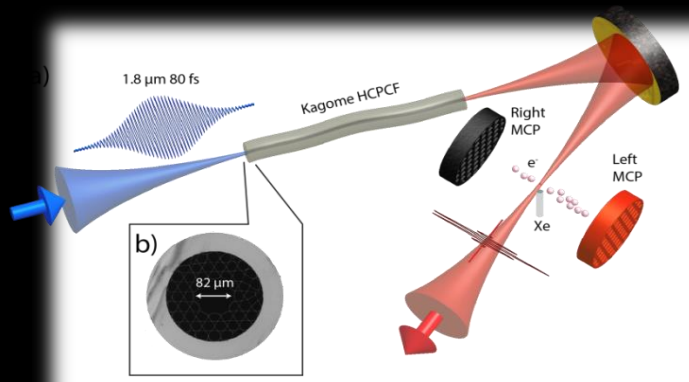
Addressing the following question:

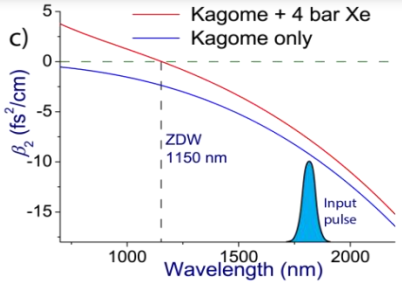
To what level of compression can we achieve with a nicely optimized laser

Sub-Cycle with single-step self-compression

Collaboration with groups of Baltuska (Vienna University of Technology) and A. Zheltikov (Moscou State University)

Balciunas *et al*. ASSL, Post-deadline paper JTh5A.5 (2013)

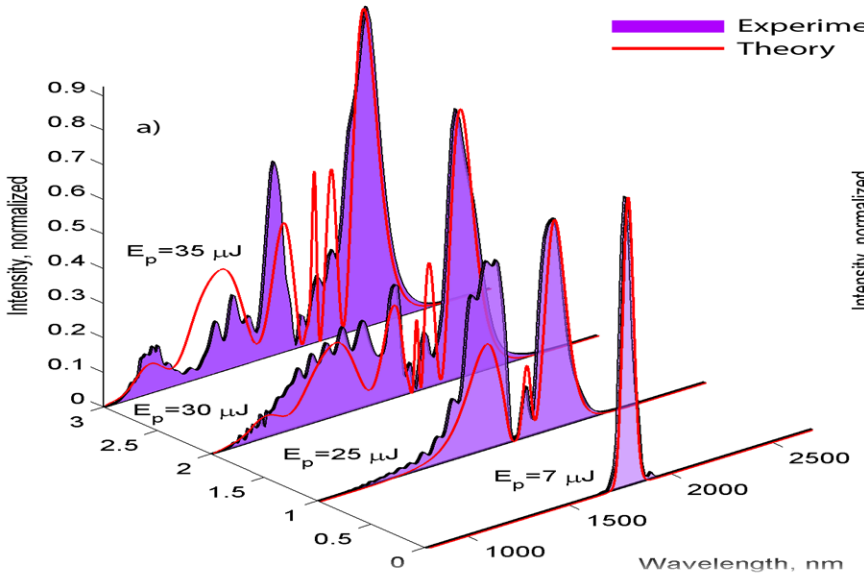


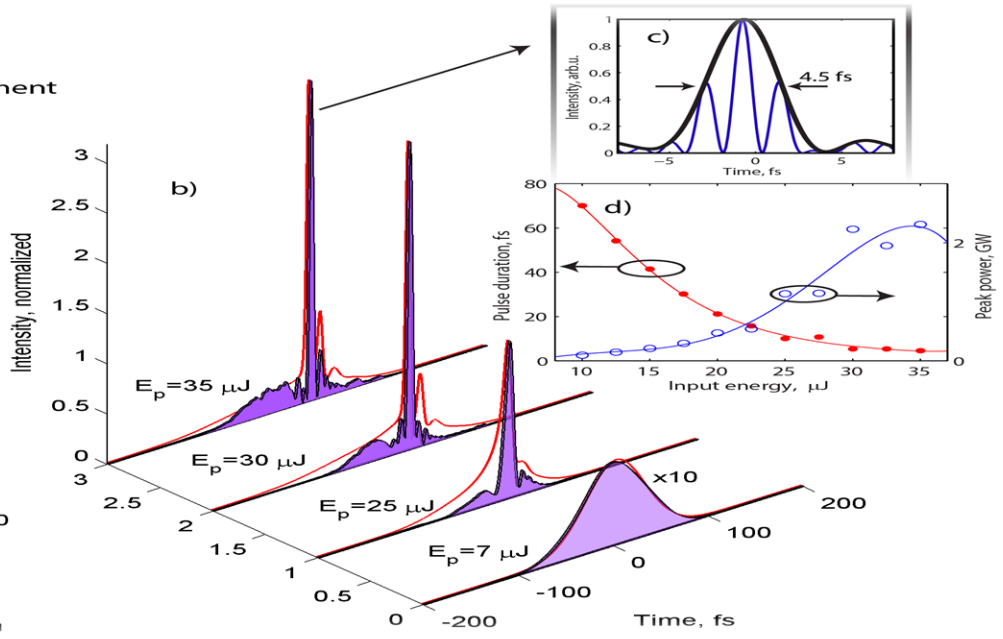


7-cell hypocycloid kagome HC-PCF

(Xenon in core)

- 0.2 m long HC-PCF
- GW peak power levels
- Compression from 80fs to ~4fs
- First sub-cycle MIR pulse



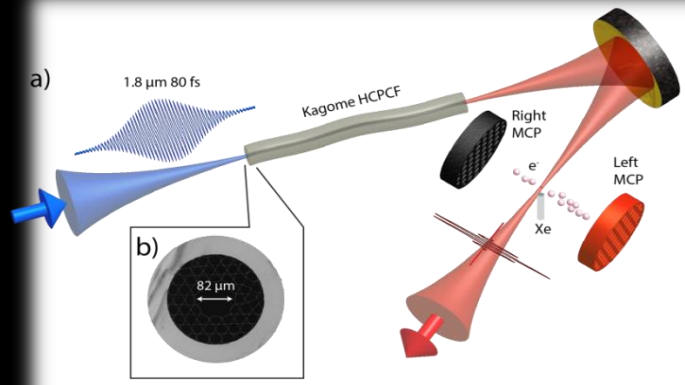


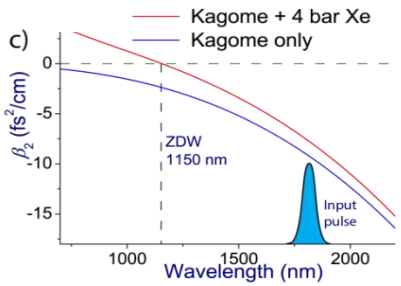
Laser: 1800nm center-wavelength, 80 fs pulse-duration, 1 KHz rep.rate, Max Energy=40µJ
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells , lengths: 0.2m
Xenon pressure 4bar

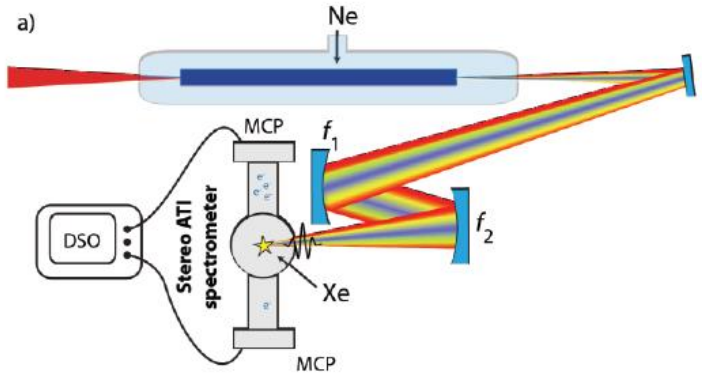
Sub-Cycle with single-step self-compression

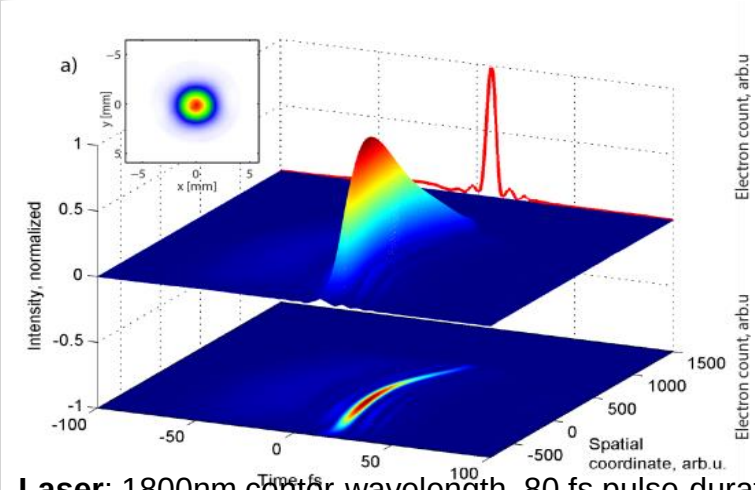
Collaboration with groups of Baltuska (Vienna University of Technology) and A. Zheltikov (Moscou State University)

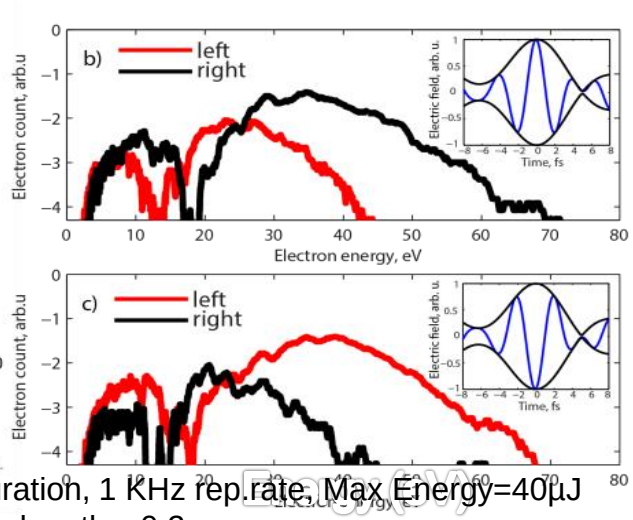
Balciunas *et al*. Nature Comm. 6, 6117 (2015)

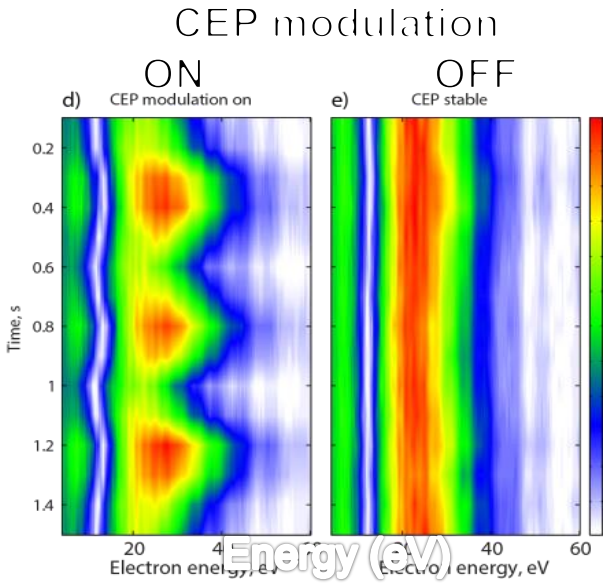












Laser: 1800nm center-wavelength, 80 fs pulse-duration, 1 KHz rep.rate, Max Energy=40µJ

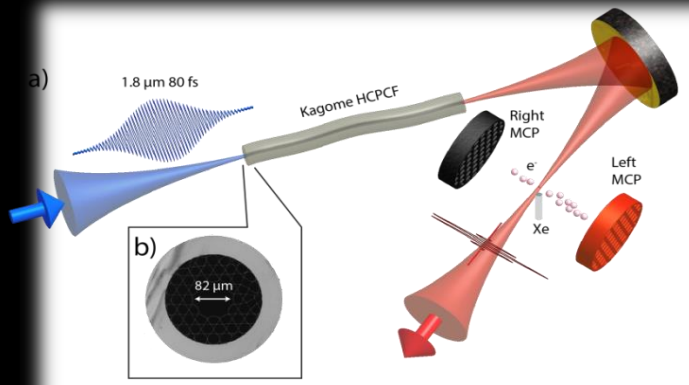
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells , lengths: 0.2m

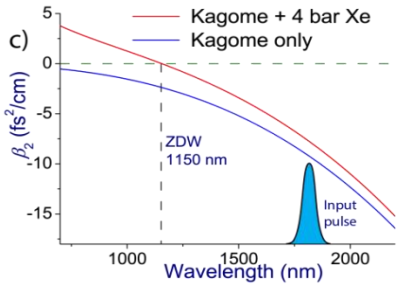
Xenon pressure 4bar

Sub-Cycle with single-step self-compression

Collaboration with groups of Baltuska (Vienna University of Technology) and A. Zheltikov (Moscou State University)

Balciunas *et al*. Nature Comm. 6, 6117 (2015)

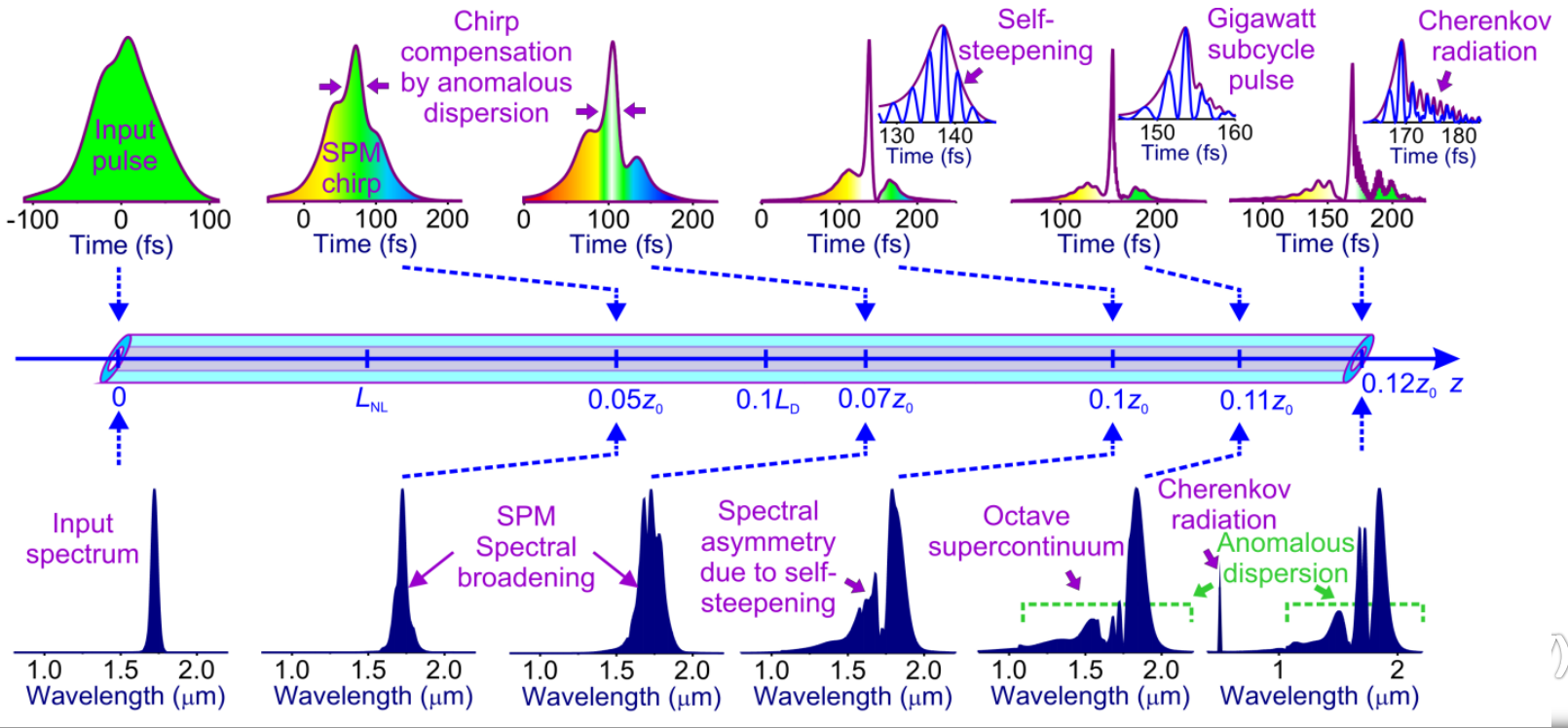


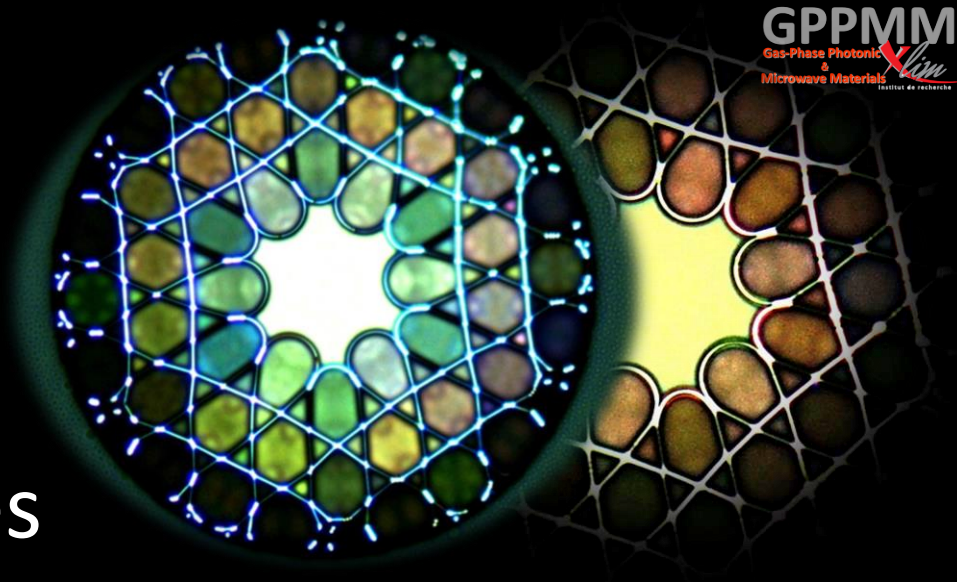


7-cell hypocycloid kagome HC-PCF

(Xenon in core)

- 0.2 m long HC-PCF
- GW peak power levels
- Compression from 80fs to ~4fs
- First sub-cycle MIR pulse





Super optical nonlinearities with air

Addressing the following question:

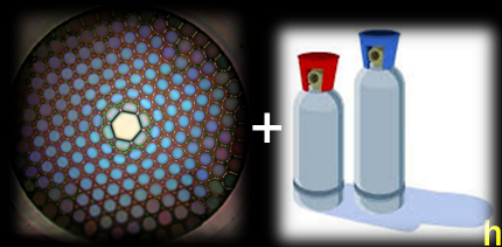
To what extent we can turn a « notoriously inert nonlinear medium » into a medium of choice in nonlinear optics?

Turning atmospheric air in strong nonlinear medium

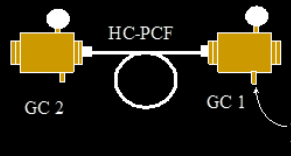
Addressing the following question:

Combining the low loss of hypocycloid Kagome HC-PCF and high laser intensities to generate optical nonlinearities in gases with intrinsic nonlinear strength response

B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)



Previous IC Kagome design



high pressure molecular gases

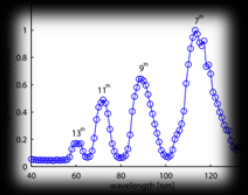
Transform the AMBIENT AIR to a nonlinear platform

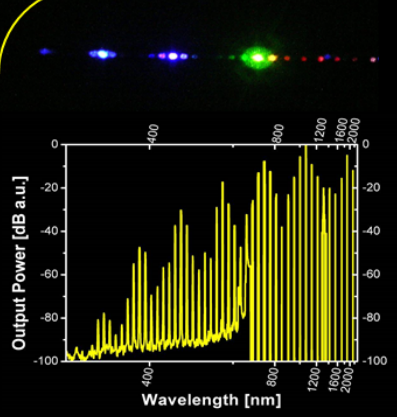
- 1000 µJ energy -
> 1 PW/cm² peak int.
> 10 GW peak power
(2013-2015)

× 1000 energy-level
And
X 100 lower transmission loss

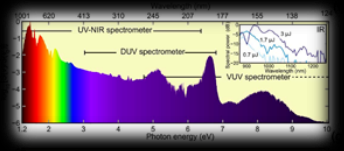
- 1 µJ energy -
10 TW/cm² peak intensity
0.07 GW peak power
(2007-2015)

High harmonic generation
Heckl *et al.* Applied Phy. B (2009)





Raman comb generation
Couny *et al.* Science 318 (2007)

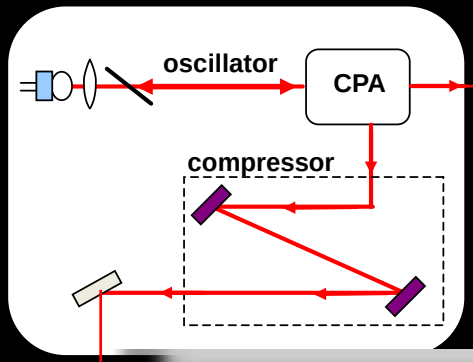


Supercontinuum generation
Belli *et al.* Optica 2 (2015)

Experimental set-up

B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)

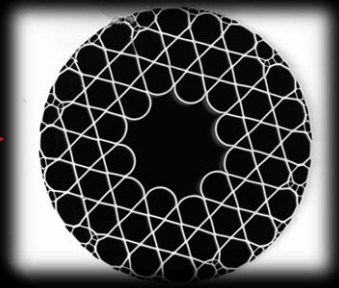
Yb-laser source 1.36mJ
(Amplitude Systemes)



Output 1
300 ps

λ/2 PBS λ/2 λ/4 Lens

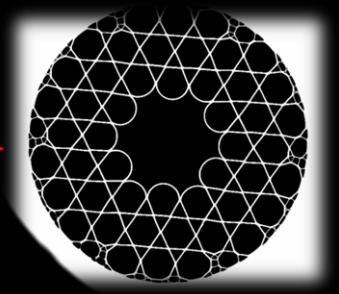
IC Fiber #1



Output 2
600 fs

λ/2 PBS λ/2 λ/4 Lens

IC Fiber #2

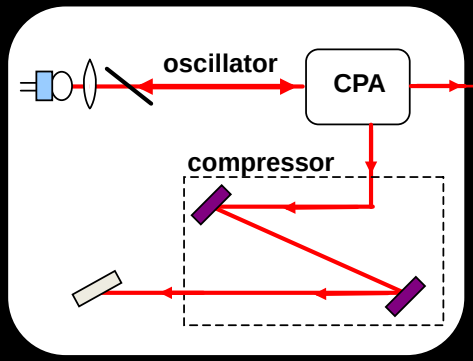


Laser: 1030nm center-wavelength, 1 KHz rep.rate, Max Energy=1.36mJ
Two output regimes made from the system: 300 ps and 600 fs pulses
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m
Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)
Coupling: HC-PCF input and output end exposed to ambient air

Experimental set-up

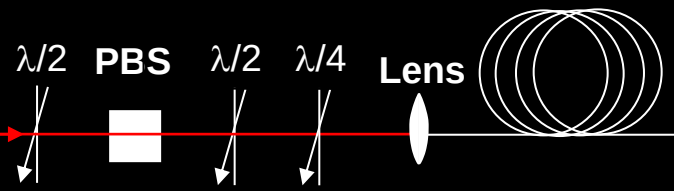
B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)

Input energy : 1.36 mJ
Input peak power : 0.004 GW
Input peak intensity : 0.3 TW/cm²



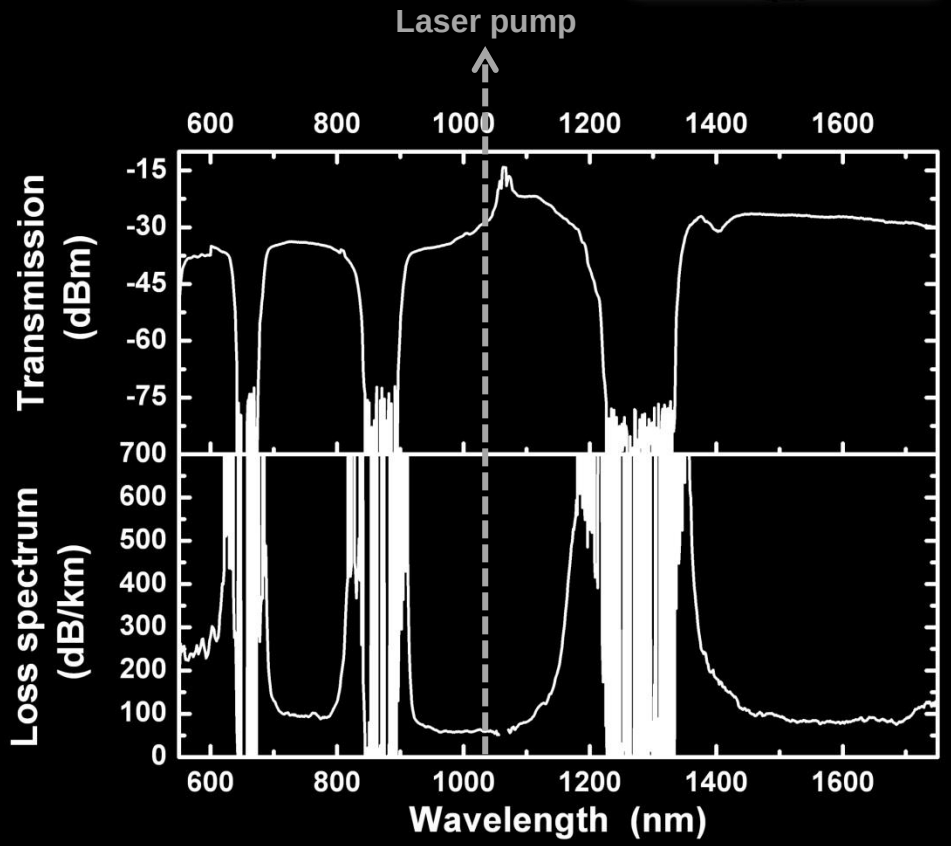
Output 1

300 ps



IC Fiber #1

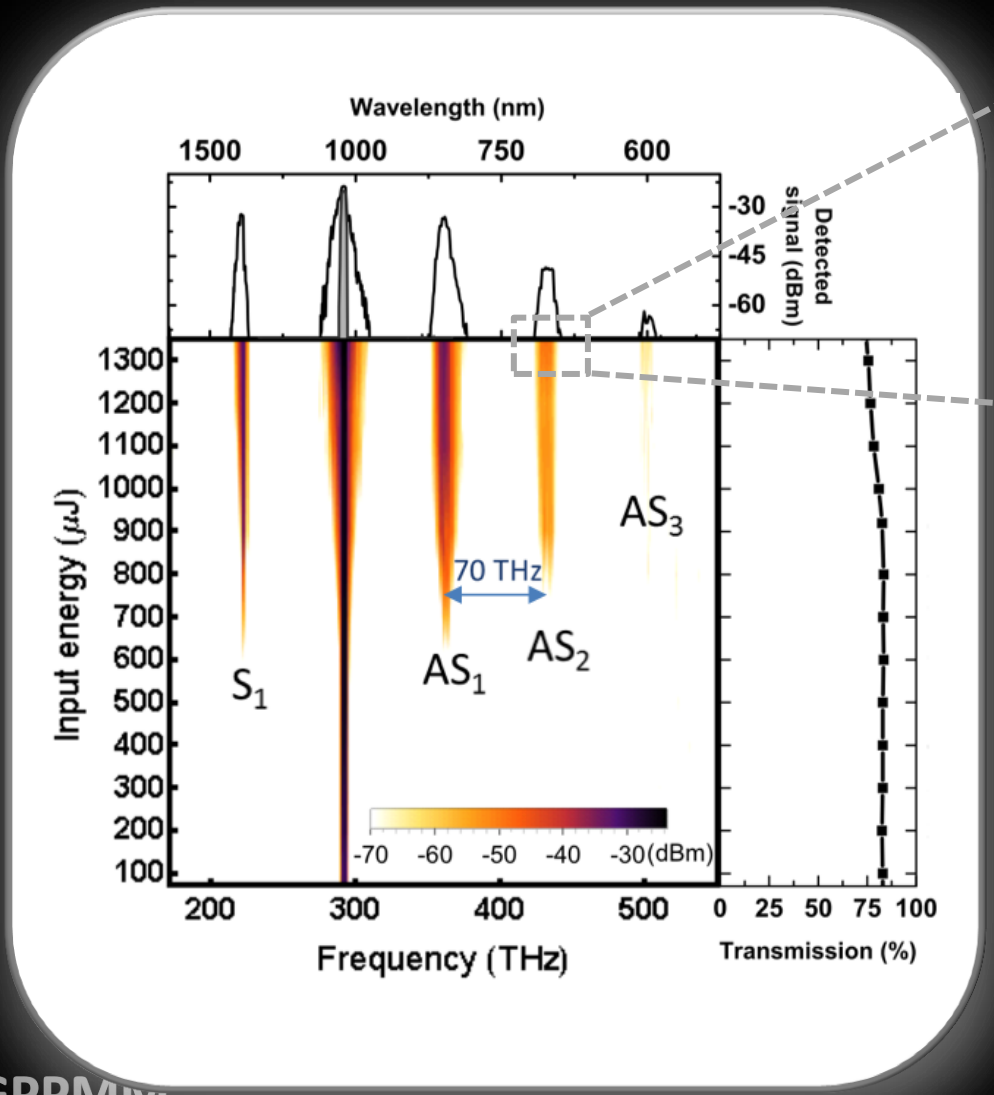
- **UV/Mid-IR guidance**
- **50 dB/km at the laser pump**
- **b~1**
- **Single mode - 42 µm MFD**
- **Filled at atmospheric air**



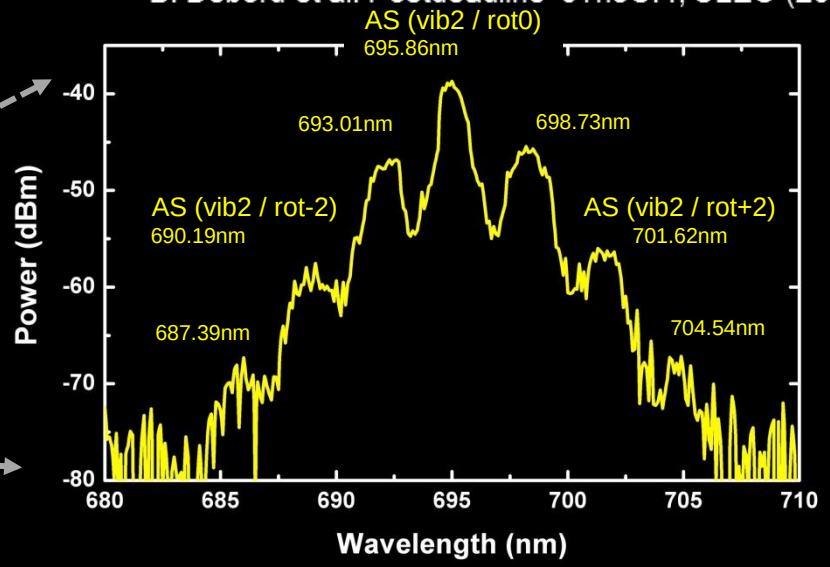
Laser: 1030nm center-wavelength, 1 KHz rep.rate, Max Energy=1.36mJ
Two output regimes made from the system: 300 ps and 600 fs pulses
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m
Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)
Coupling: HC-PCF input and output end exposed to ambient air

Raman comb generation

Measured output spectrum vs input energy



B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)



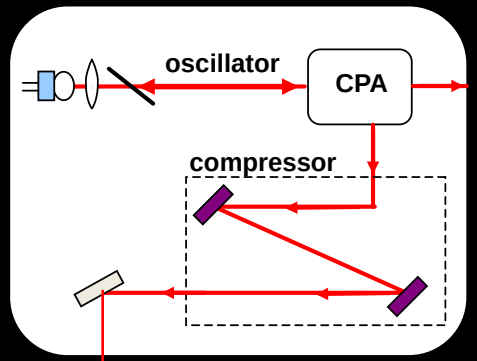
- **1.03 mJ energy transmitted**
- **75% transmission coefficient**
- **300 THz wide Raman comb**
- **~ 70 THz tooth-spacing (vibrational Raman response of N_2 molecules)**
- **Spectral broadening at high energy (rot sideband S6)**

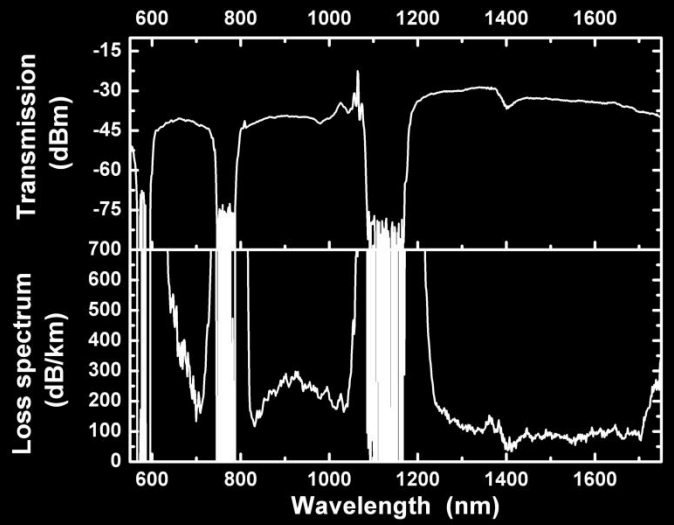
Experimental set-up

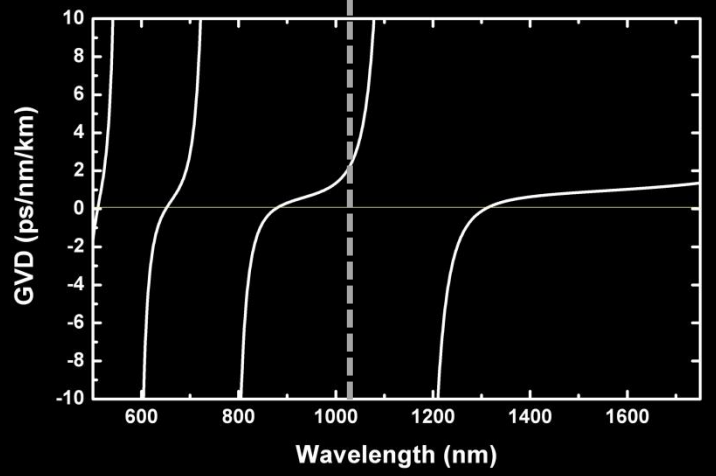
Laser pump
(transmission blue-shifted by 10%)

B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)

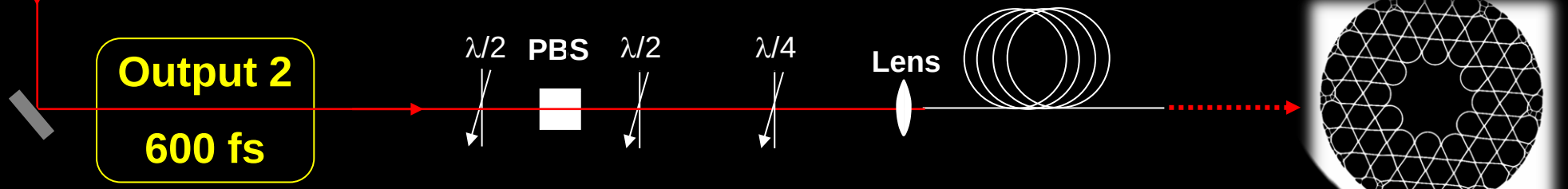
Input energy : 1.36 mJ
Input peak power : 2.13 GW
Input peak intensity : 154 TW/cm²







IC Fiber #2

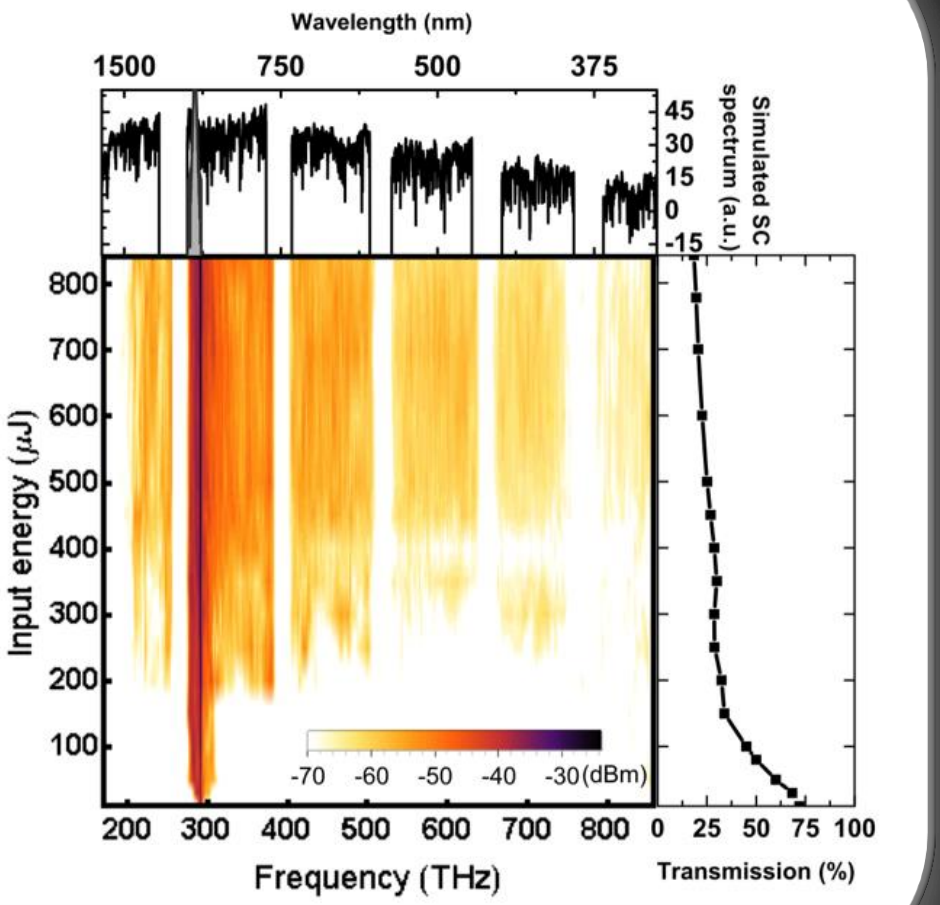


- **UV/Mid-IR guidance**
- **50 dB/km at the laser pump**
- **Single mode - 42 µm MFD (b ~1)**
- **Filled at atmospheric air**
- **Anomalous dispersion**

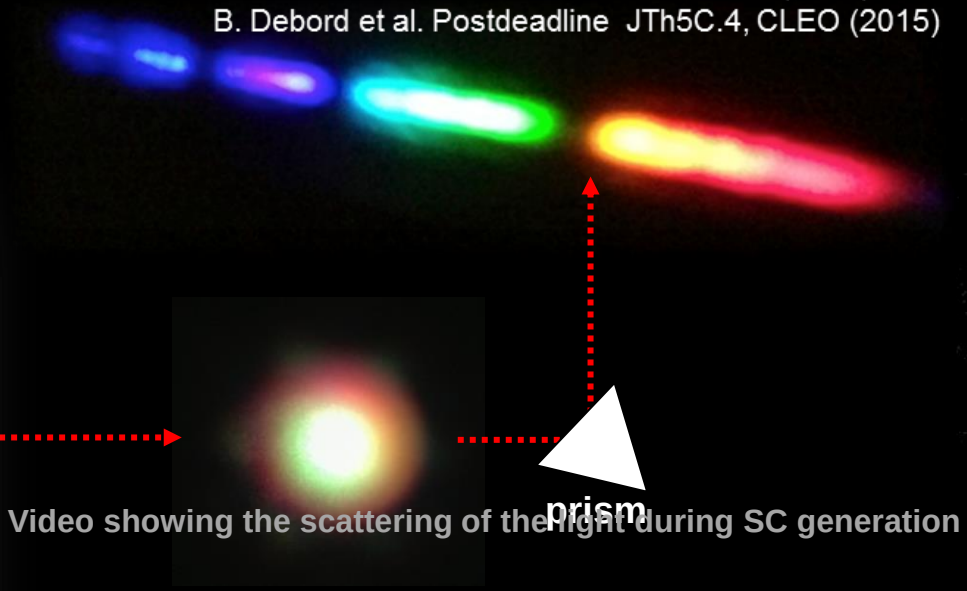
Laser: 1030nm center-wavelength, 1 KHz rep.rate, Max Energy=1.36mJ
Two output regimes made from the system: 300 ps and 600 fs pulses
Fiber: Hypocycloid-core kagome HC-PCF, 7 cells, lengths: 3 m and 3.8 m
Fiber positioning: coiled with ~10 cm coil-radius (7 cell fiber)
Coupling: HC-PCF input and output end exposed to ambient air

Supercontinuum generation

Response completely differs from the first case



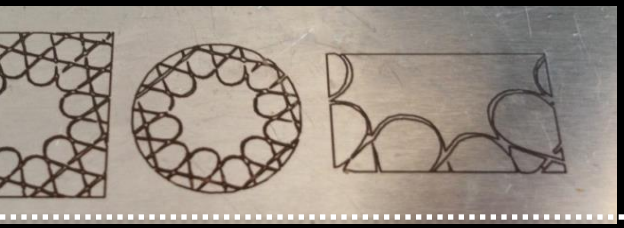
B. Debord et al. Postdeadline JTh5C.4, CLEO (2015)



Video showing the scattering of the light during SC 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 -



CONCLUSION

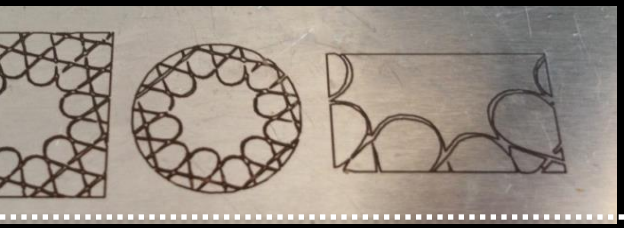
❖ **Hypocycloid-core Kagome HC-PCF**

- Record loss @1µm, 700 nm, 500 nm range
- Truly single-mode operation
- High PER
- Ultra-low optical overlap with the silica surround

❖ **Record USP Energy-level handling and pulse control**

- Pulse compression from 600 fs to 50 fs
- Beam delivery of USP lasers with PettaWatt/cm^2 output intensity levels
- Demonstration of micro-engraving in ceramic, glass, metals and semiconduct
- Demonstration of micro-machining directly from fibre
- Poor-man solution for USP compression
- Generation of Raman comb, SC and 3rd harmonic in atmospheric air
- Sub-cycle single-step self-compression of MIR pulses

Taming the extreme



THANK YOU

❖ The team behind the work

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Amplitude group,
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Vienna University of Technology (A. Baltuska) & Moscou state University (A. Zheltikov)
Max Born, Berlin (Anton Huzakou)

❖ Our Sponsors

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