The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1932-14

Winter College on Micro and Nano Photonics for Life Sciences

11 - 22 February 2008

ICO-ICTP Galieno Denardo Prize Awardee's Presentation

Mourad Zghal

École Supérieure des Communications de Tunis

Tunisia

Abdu Salam International Centre of Theoretical Physics (ICTP)

Trieste, Italy

February 18, 2008

Photonic Crystal Fibers: Modeling, characterization and applications

Mourad ZGHAL

Engineering School of Communications of Tunis (Sup'Com)
University of the 7th of November at Carthage

Tunisia

www.supcom.mincom.tn

Gallieno Denardo

SHORT COURSE ON
FIBER-OPTIC COMMUNICATIONS
TECHNOLOGY

18-23 march 2007
Port Elizabeth
South Africa

الجمعية التونسية للبصريات

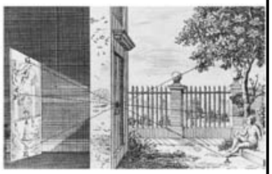
Société Tunisienne d'Optique

Creation of the
Optical Society of Tunisia
(2002)

Organization of conferences, workshops and schools

Popularization of optical phenomena in Tunisia

- Photographic workshops including conferences and trainings.
- Set up and use a *camera obscura* by means of only sheets of paper.



Medieval refraction – Al-Haytham (X-XIth century)

- Light is universal
  - Light coming from the sun, reflected by the moon, emitted by fire, reflected by a mirror or focussed by a lens, is light and it undergoes the same effects and phenomena.
- Image formed on the retina is inverted
  - implemented the *camera obscura* (dark cabin: qamara: قمرة) to experimentally prove that rays travel in straight lines and that the image is reverted like the retinal image.
- Names of the optical components of the eye
  - They are indeed Ibn-Haytham's appellations: *cornea* (القرنية), *retina* (الشبكية), *Vitreous Humor* (السائل الزجاجي), *Aqueous Humor* (السائل المائي), etc

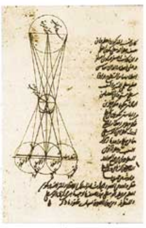


Diagram Illustrating Principles of the Camera Obscura, MS Illustration from a Résumé of Optics by Kamal al-Din al-Farisi, Istanbul, Fourteenth Century

Three centuries after Ibn al-Haytham's pioneering investigation of optics, the Persian al-Farisi extended Ibn al-Haytham's formulation of the principles underlying the phenomena of the camera obscura, familiar prototype of all photographic devices. Al-Farisi demonstrated that as apertures get smaller the images they focus get sharper; he also showed that inside the device the objects' image turns top to bottom and left to right. It was in probing the fundamental nature and workings of vision and of light that Islam's scientists made what are probably their most original and important findings.

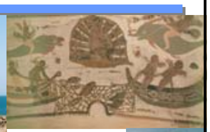
Zghal, Bouali, Ben Lakhdar, Hamam, ETOP'07
http://spie.org/etop/2007/etop07fundamentalsII.pdf

SUP'COM In brief

Engineering School ICT

University of 7th November at **Carthage**

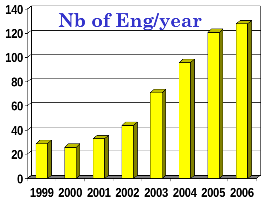
Ministry of Communications


5th year

4th year

3rd year



2 years

Preparatory institutes (national exam)

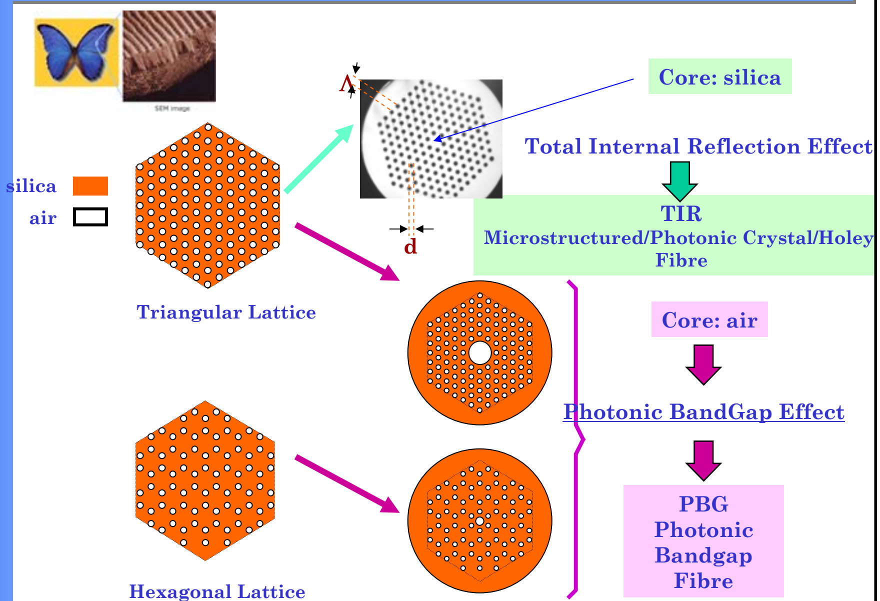
SUP'COM In brief

Gazala TechnoPark

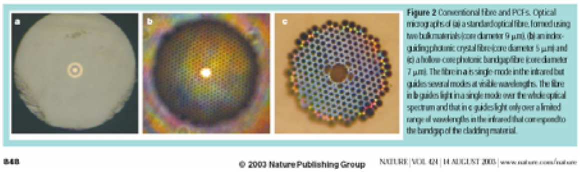
Outline

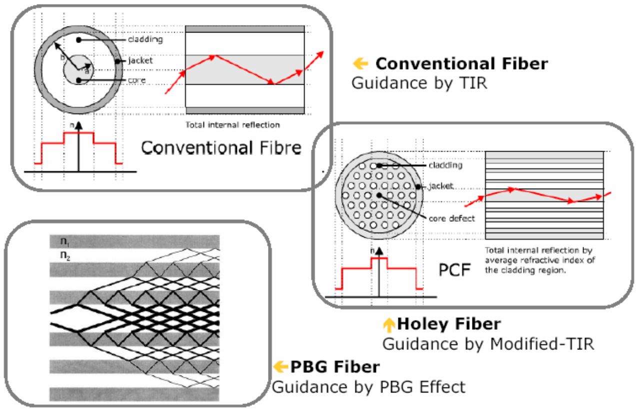
- Photonic Crystal Fibers
- Analysis of the fundamental mode
  - Birefringence
  - Chromatic dispersion
  - Cutoff wavelength
- Applications: Supercontinuum Generation
- Conclusions

PHOTONIC CRYSTAL FIBERS



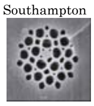
PRINCIPLE OF GUIDANCE IN PCFs





Conventional Fiber
Guidance by TIR

ORC
Southampton



Holes don't need to be periodic !!!

Holey Fiber
Guidance by Modified-TIR

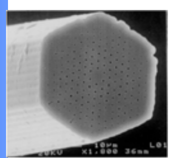
PBG Fiber
Guidance by PBG Effect

Reference: *Single-Mode Photonic Band Gap Guidance of Light in Air*, R. F. Cregan et al., 1999

EXPERIMENTAL REALISATIONS

Solid-core Holey Fibers

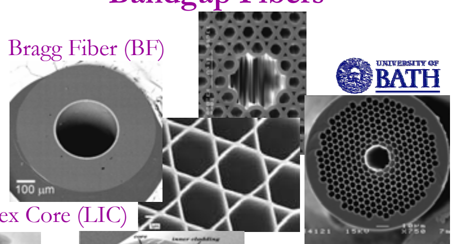
Photonic Bandgap Fibers



Endlessly single-mode

[T. A. Birks *et al.*, *Opt. Lett.* **22**, 961 (1997)]

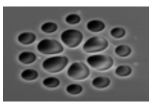
Bragg Fiber (BF)

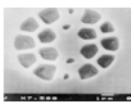


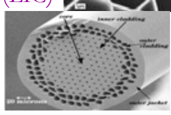
Low Index Core (LIC)

Hollow Core (HC)

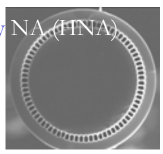
Exotic profiles



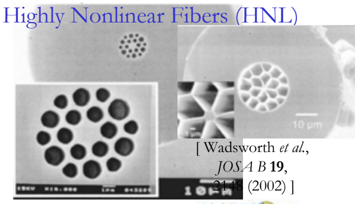




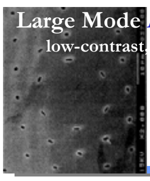
Highly NA (HNA)



Highly Nonlinear Fibers (HNL)



Large Mode Area (LMA)
low-contrast *linear* fiber



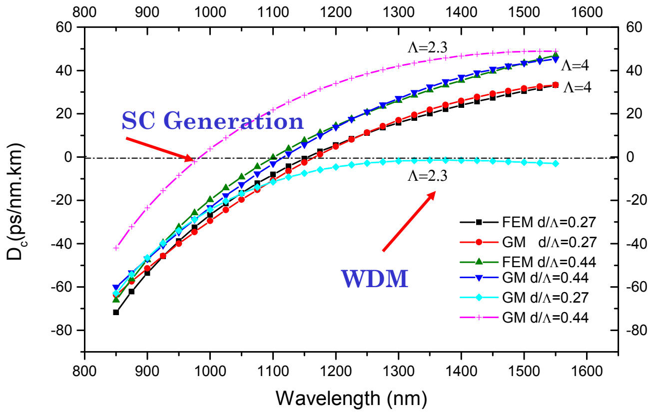
[J. C. Knight *et al.*, *Elec. Lett.* **34**, 1347 (1998)]

[Wadsworth *et al.*, *JOSA B* **19**, (2002)]

CHROMATIC DISPERSION

Dispersion properties of PCFs

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}$$



Adjust the ZDW by changing d, Λ — Dispersion compensation

Shift λ_0 → Short λ — Pulse compression

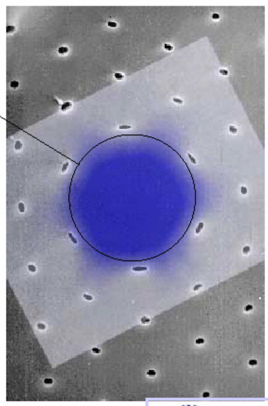
Zghal, Chatta, Bahloul, Attia, Pagnoux, Roy, Melin, Gasca, *SPIE Proc.* Vol. **5524**, 313-322, (2004)

WHY WE NEED THESE FIBERS ???

Very large mode area fibre in the blue

- core diameter 22 microns
  - blue (458 nm) mode
- core area ~20 times larger than possible in conventional fibre
  - control of index better than ~20 ppm would be required in MCVD
- high power applications:
  - advanced telecommunications
  - fibre lasers & amplifiers
  - laser machining
  - laser surgery

d= 1μm
Λ=11μm



Philip Russell, University of Bath, p.s.j.russell@bath.ac.uk

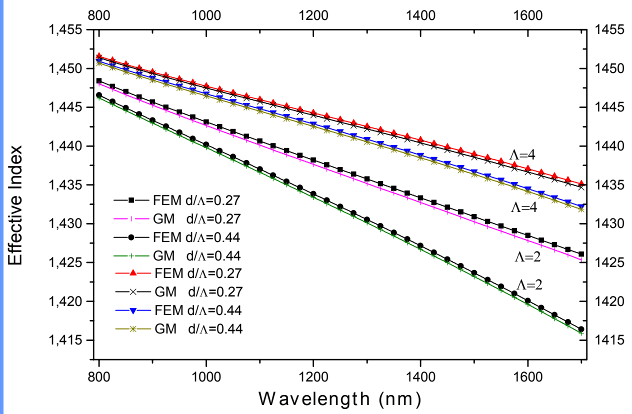
Knight et al, Electron. Lett. 34 (1347-1348) 1998

UNIVERSITY OF BATH

ANALYSIS SIMULATIONS

Effective Index computed by FEM, GM for different d/Λ at Different λ.

$$V=\frac{\pi D}{\lambda}(n_{core}^2-n_{clad}^2)^{1/2}$$



$n_{eff} \nearrow \quad \lambda \searrow$

So cladding dispersion helps fibre to remain single-mode, over an infinite frequency range

Endlessly Singlemode

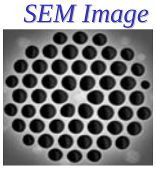
Strong variation of the effective index Vs wavelength for large d/Λ

Zghal, Chatta, Bahloul, Attia, Pagnoux, Roy, Melin, Gasca, *SPIE Proc.* Vol. **5524**, 313-322, (2004)

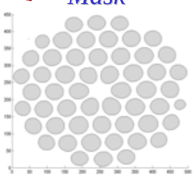
FINITE ELEMENT METHOD (FEM)

FINITE ELEMENT METHOD FEM

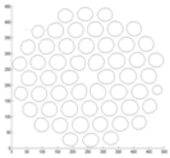
SEM Image



Mask



Parallax Problem

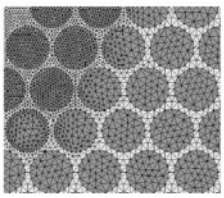


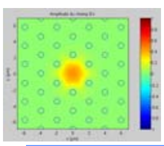
Determination of the border

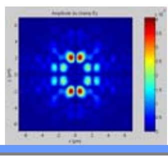
Uncertainties

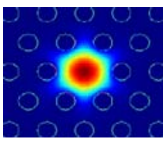
Influence of the mesh

Mesh





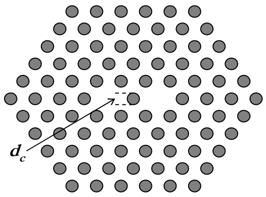


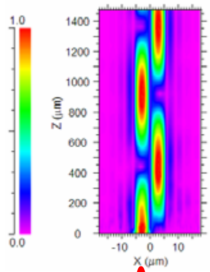


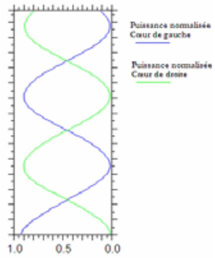
Determination (HE11x, HE11y)

PHOTONIC CRYSTAL FIBER COUPLER

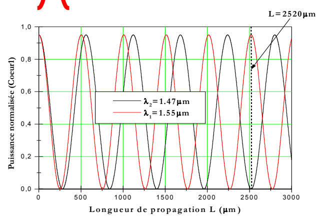
Wavelength /Polarisation splitter







Dual core PCF



d_c=0.5µm, Λ=2.5µm, d=1.2µm
λ_1=1.55µm=>L_c=252µm
λ_2=1.47µm=>L_c=280µm

Zghal, Cherif, Bahloul, *Optical Engineering*, **46**, (9), 2007

BIREFRINGENCE

BIREFRINGENCE

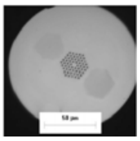
Measurements show that regular PCF can show High Birefringence

$\pi/3$ Symmetry

Phase Biref : $B_\varphi \quad \beta_x - \beta_y = 0$

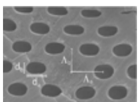
Groupe Biref (B_g) : $B_g = B_\varphi - \lambda \dfrac{dB_\varphi}{d\lambda}$

Stress



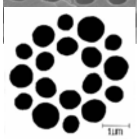
$\Rightarrow B_{\varphi_1}$=9,3e-5

Shape distorsion



$\Rightarrow B_{\varphi_2}$=4,4e-4

Regular geometry



$\Rightarrow B_{\varphi_3}$ *=1e-3*

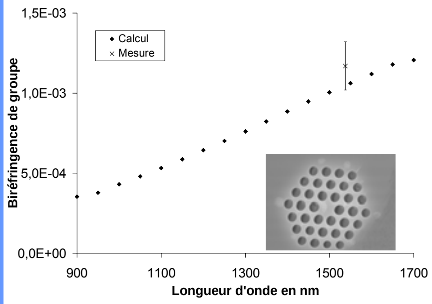
B_{φ_1} *et* $B_{\varphi_2} < B_{\varphi_3}$

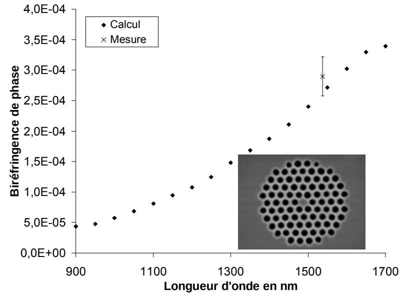
Origin of B_{φ_3}?

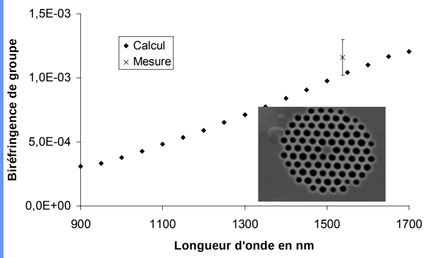
Shape ? *Stress ?*

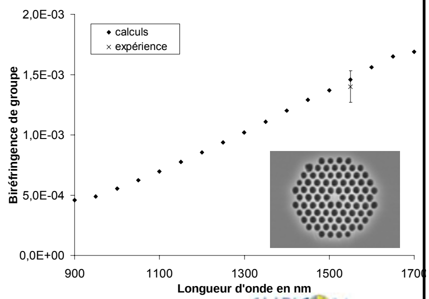
ANALYSIS SIMULATIONS

Measured and calculated group Biref.









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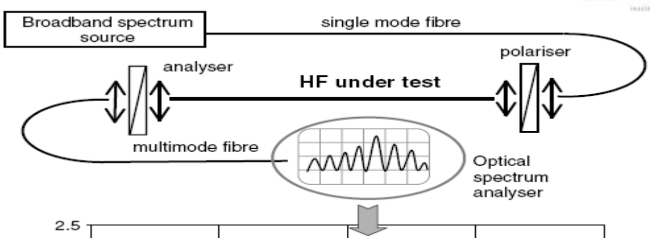
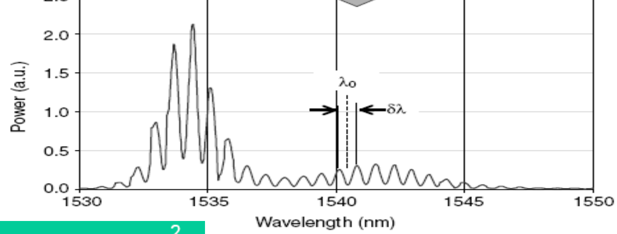
BIREFRINGENCE

Experimental Study of the birefringence

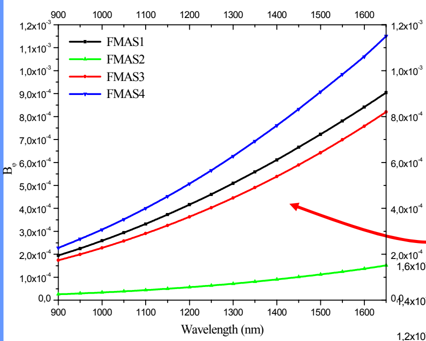




$$\Delta N_g = B_G = B - \lambda \frac{dB}{d\lambda} = \frac{\lambda_0^2}{L.\ \delta\lambda}$$

SUP'COM

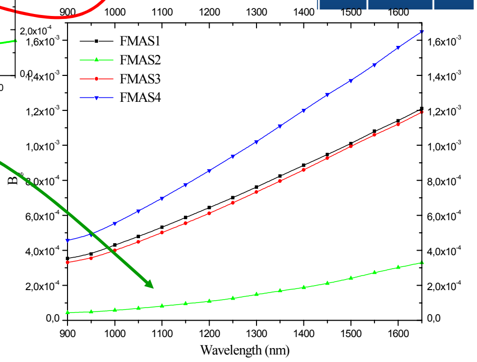
BIREFRINGENCE



Phase Biref

$$B_\varphi = \alpha\lambda^k$$

	α	k
FMAS1	$1.0584\ 10^{-11}$	2.4657
FMAS2	$2.3342\ 10^{-14}$	3.0488
FMAS3	4.792310^{-12}	2.5589
FMAS4	$5.3799\ 10^{-12}$	2.5892



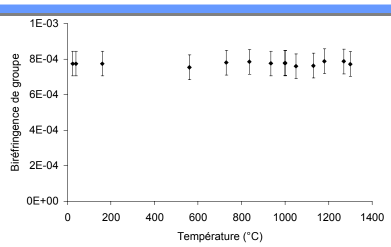
Similar to Elliptical core Hi-Bi PCF

Group Biref

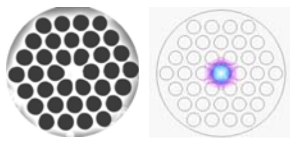
$$B_g = B_\varphi(1-k)$$

Labonté, Pagnoux, Roy, Bahloul, Zghal, *Optics Communications*, **262** (2) 180-187, 2006

BIREFRINGENCE



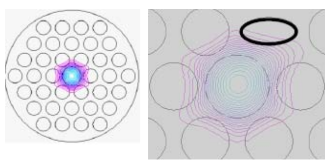
Effect of temperature (stress)



Real structure B= 1.37 10^{-5}

Slight geometrical imperfections

- Inner Stress influence: Negligible variation with T
- Strong influence of the geometry (shape)
- Careful control of the manufacturing process (1st corona)



Shape defect: Elliptical hole

1st corona: B= 7.95 10^{-4}

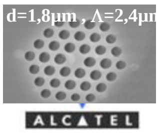
2nd corona: B= 1.4 10^{-5}

M. Zghal *et al. IEEE Canadian Review*, Vol 54, (2007).

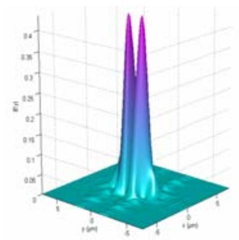
CUT-OFF WAVELENGTH

Determination of the cut-off wavelength of PCFs

d/Λ=0,75



- NL processes in PCF with a small core surrounded by rings of large holes
  - ZDW shifted toward short λ
  - The endlessly single-mode condition not fulfilled
  - A cutoff λ must be precisely determined

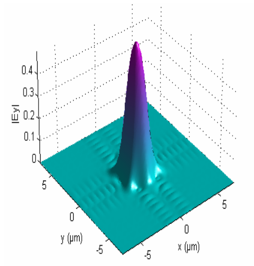


λ= 0,98 µm

~~ITU G650~~

❖Based on the measurement of higher-order modes' differential loss versus the fiber bending radius

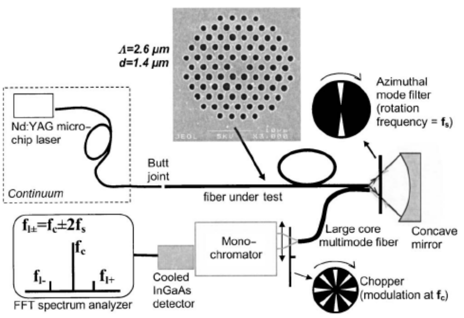
❖Higher-order modes in High NA PCF are much less sensitive to bending than in SMF



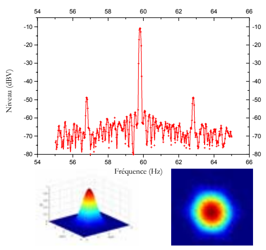
λ= 1.55µm

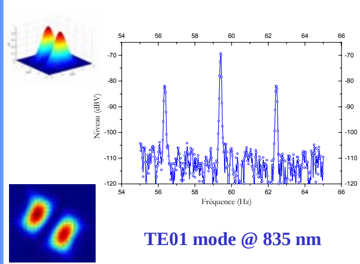
Labonté, Pagnoux, Roy, Bahloul, Zghal, Melin, Burov, Renversez, *Optics Letters*, **31**, (12), 1779, (2006)

CUT-OFF WAVELENGTH

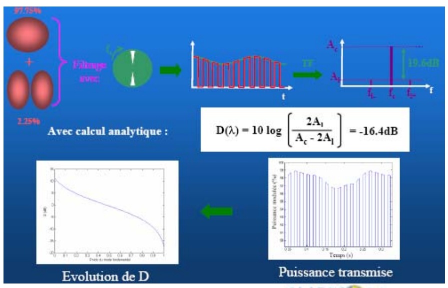


Fundamental mode @ 1550 nm

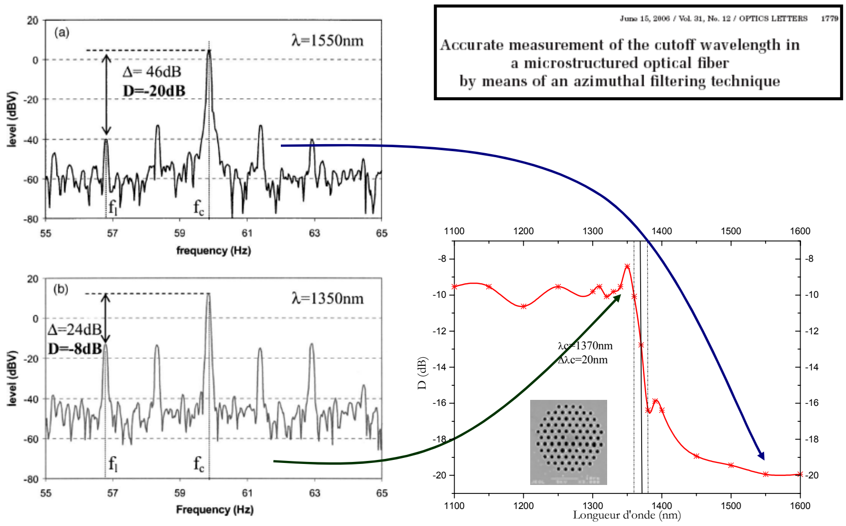




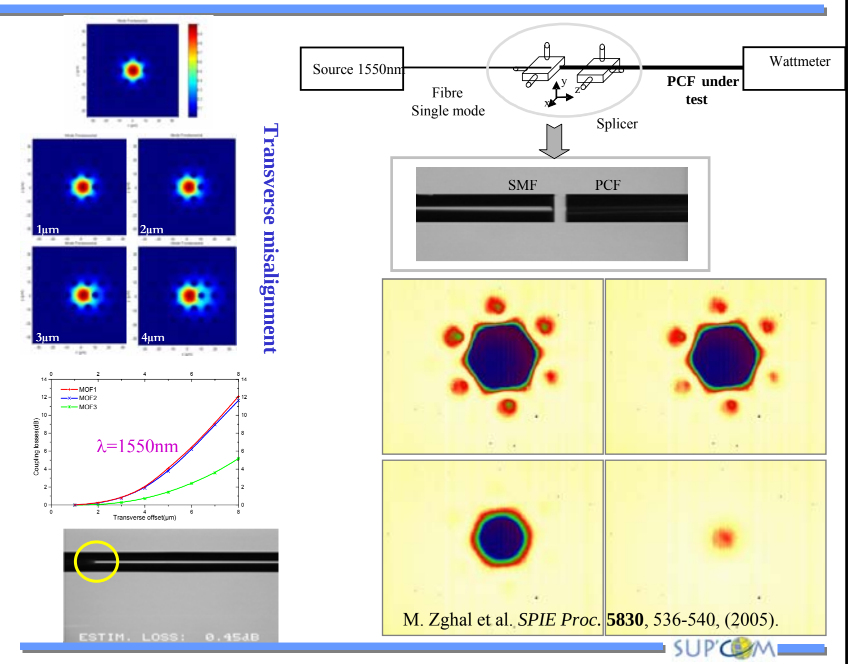
TE01 mode @ 835 nm



CUT-OFF WAVELENGTH

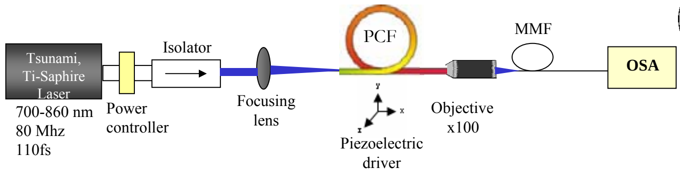


LOSS MEASUREMENTS

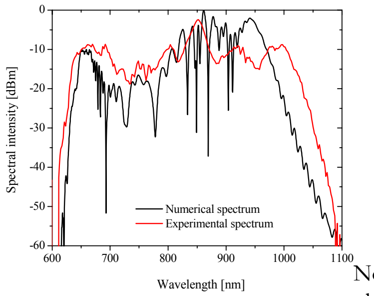


M. Zghal et al. *SPIE Proc.* **5830**, 536-540, (2005).

SUPERCONTINUUM GENERATION



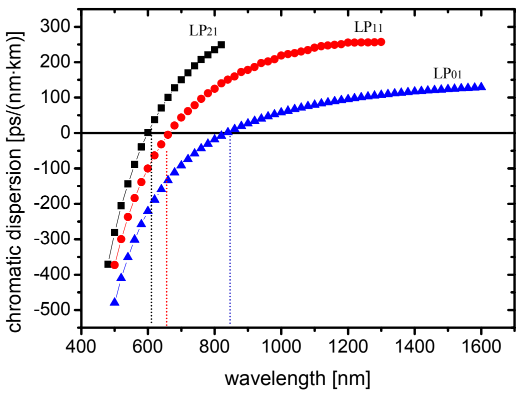
Pumping wavelength = 805nm

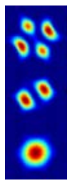


Continuum is quite beautiful!

Normal dispersion regime: SPM is leading to a ultra-wide symmetric spectral broadening.

DISPERSION PROPERTIES





A_{eff} = 3.82 μm²

A_{eff} = 3.26 μm²

A_{eff} = 3.46 μm²

$\lambda_{cut\text{-}off,11} \cong 1300$ nm

$\lambda_{cut\text{-}off,21} = 830$ nm

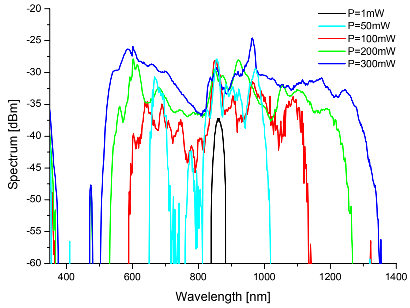
$\lambda_{ZD,01} = 840$ nm $\lambda_{ZD,11} = 660$ nm $\lambda_{ZD,21} = 600$ nm

The PCF presents a wide range of wavelengths in which the LP_{01} mode experiences normal dispersion, whereas LP_{11} and LP_{21} propagate in the anomalous dispersion regime.

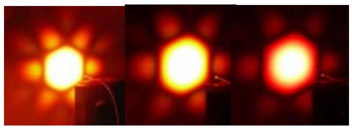
Cherif, Zghal, Tartara, Degiorgio, Opt. Express **16**, 2147-2152 (2008)

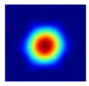
SCG BY FONDAMENTAL MODE

Pump wavelength **850 nm** → Anomalous dispersion regime of the fundamental mode



Far field with decrease of power from left to right





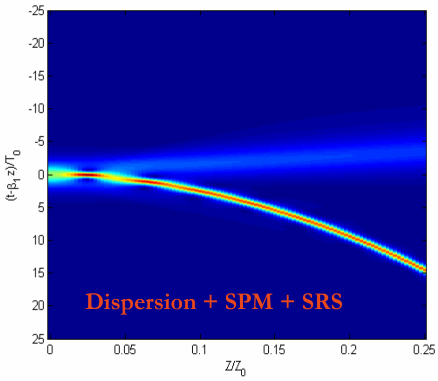
- At 50 mW: the peak around 920 nm is the first soliton formed and subsequently self-frequency shifted to longer wavelengths as the pumping power is increased.
- Dispersive wave generated in the blue side of the spectrum.

PROPAGATION MODELING

Generalized Nonlinear Schrödinger Equation (Standard NLSE)

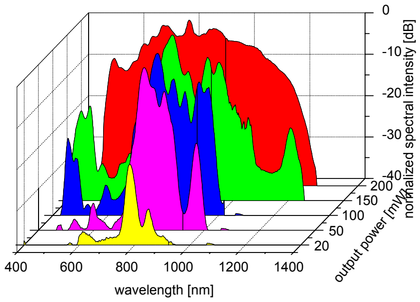
$$\frac{\partial U}{\partial z} = -\frac{\alpha}{2}U - \sum_{m\geq 2} \frac{j^{m-1}\beta_m}{m!}\frac{\partial^m U}{\partial t^m} + j\gamma\left(1 + \frac{j}{\omega_0}\frac{\partial}{\partial t}\right) \times \left(U(z,t)\int_{-\infty}^{+\infty} R(t')\left|U(z,t-t')\right|^2 dt' \right)$$

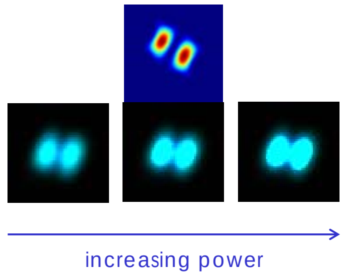
Loss — Dispersion — Kerr — Self steepening — Stimulated Raman Scattering



- For short distances the spectrum exhibits features due to SPM.
- The soliton is further red-shifted due to SRS.

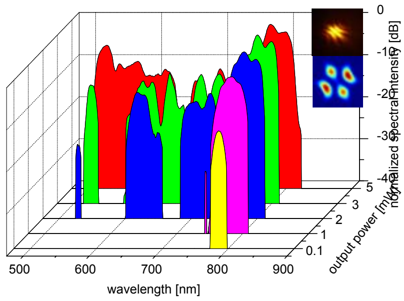
SCG BY HIGH ORDER MODE



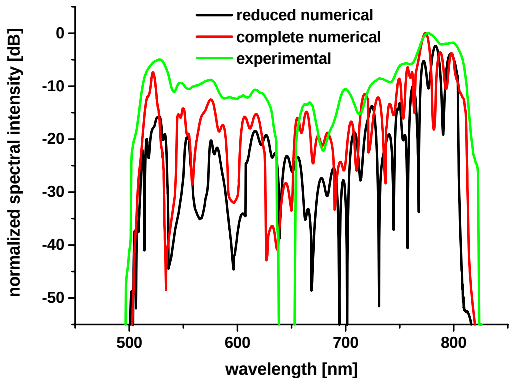


• The zero dispersion is around 600 nm

• The cut-off wavelength of LP_{21} is around 830 nm → no propagation above the cut-off wavelength



SCG BY HIGH ORDER MODE



• The cut-off wavelength for the higher-order modes sets a limit to the spectral broadening on the long-wavelength side.

• the impossibility for the spectrum to broaden to the red side does not halt the generation of a continuum on the blue side.

• The effects of Raman and self-steepening play a negligible role in the observed spectral broadening.

• The effect of higher-order linear dispersion is predominant

SUMMARY & CONCLUSION

PCF concept is having major impact on:

- Fiber optics itself, Non-silica fibers, Dispersion control
- Fiber lasers & amplifiers
- Improved Fiber sensors

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 20, NO. 4, FEBRUARY 15, 2008 279

Dynamic Pressure Sensing Study Using Photonic Crystal Fiber: Application to Tsunami Sensing

Yogesh Subhash Shinde and Harneet Kaur Gahir

- Nonlinear optics: SC generation, Solitons at new frequencies, Fsec pulses in hollow core
- Particle, atom & molecule guidance : Trapping, transport and manipulation possible
- Improved Gas-laser interactions

RETHINK DEVICE APPLICATIONS OF FIBERS
(Anything you can do PCF can do better)

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