New light sources based on nonlinear photonic crystal fibers

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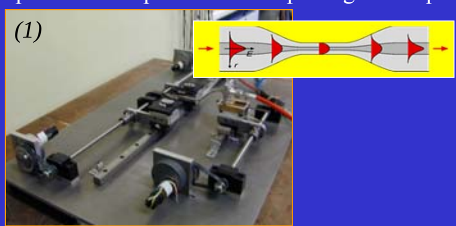
Vniversitat de València

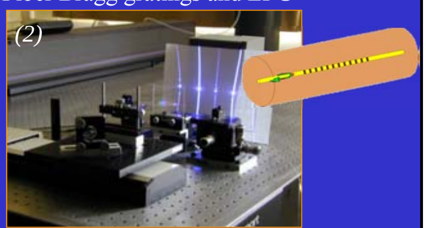
Laboratorio de Fibras Ópticas

Fiber-optics components technologies

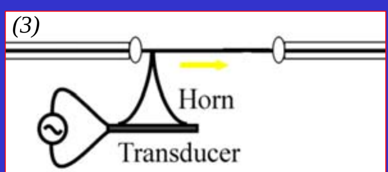
- **Fabrication of fiber-optics components**
  - Optical fiber tapers: fusion & pulling technique



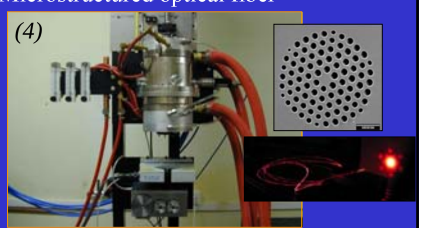
  - Fiber Bragg gratings and LPG



  - In-Fiber acousto-optic devices



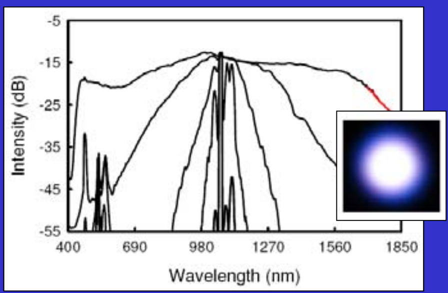
  - Microstructured optical fiber



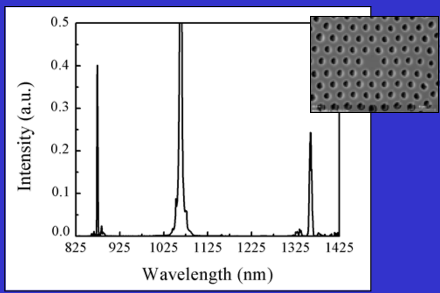
- **Applications:**
  - All-fiber light sources
  - Optical communications and microwave photonics
  - Optical fiber sensors

Objective

- **The development of optical fiber light sources based on non linear photonic crystal fibers**
  - Photonic crystal fibers can be designed with specific dispersion properties for an efficient exploitation of in-fiber non linear effects
  - Some postprocessing techniques permit an accurate control and a fine adjustment of the dispersion
  - Our work has focused on supercotinuum generation and photon pairs generation



Supercontinuum generation in a tapered fiber



Photon pairs generation through FWM

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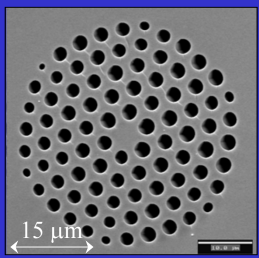
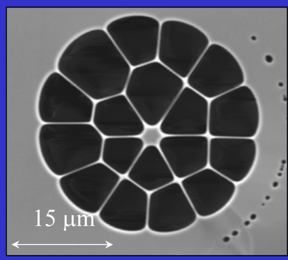
Supercontinuum and photon pairs generation in photonic crystal fibers

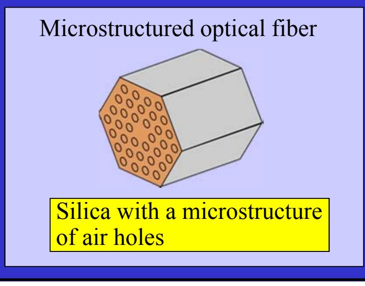
VNIVERSITAT DE VALÈNCIA — Laboratorio de Fibras Ópticas

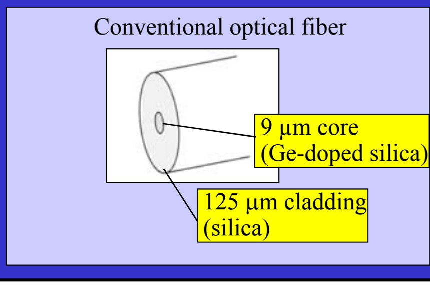
• Some examples of microstructured optical fibers





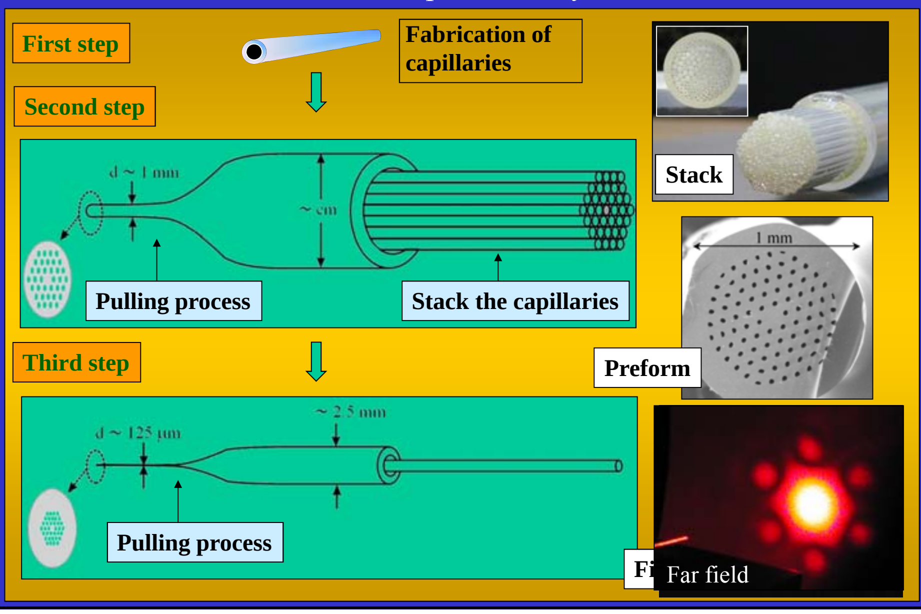
• Guidance mechanisme





VNIVERSITAT DE VALÈNCIA — Laboratorio de Fibras Ópticas

• Fabrication of photonic crystal fibers



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I. Introduction

I.1. Fabrication of photonic crystal fibers (PCF)

Laboratorio de Fibras Ópticas

VNIVERSITAT DE VALÈNCIA

I. Introduction

I.1. Fabrication of photonic crystal fibers (PCF)

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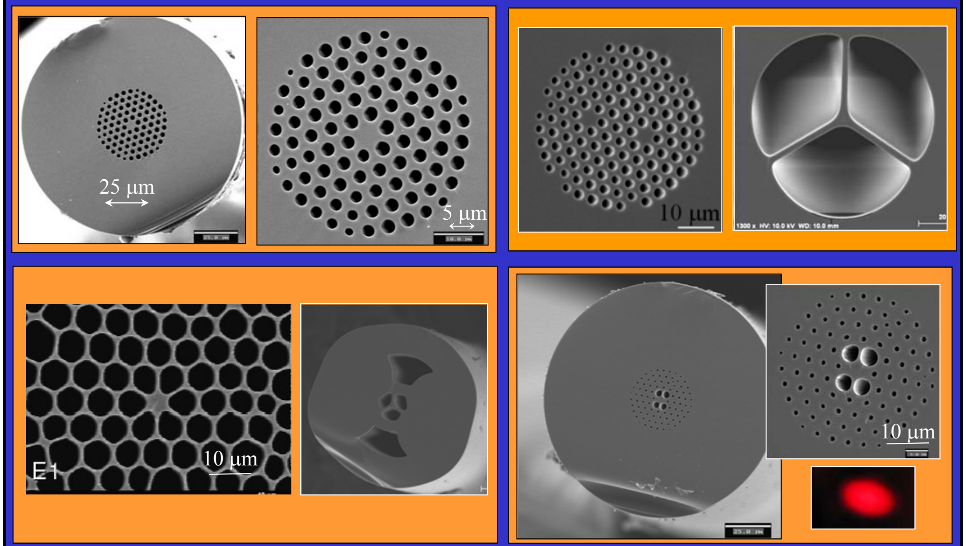
Vniversitat de València — I. Introduction — I.1. Fabrication of photonic crystal fibers (PCF) — Laboratorio de Fibras Ópticas

• Fabrication of photonic crystal fibers



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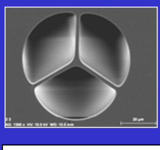
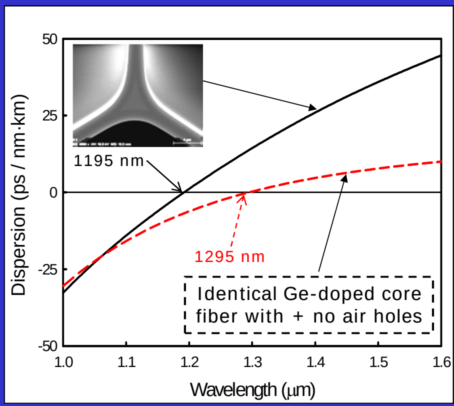
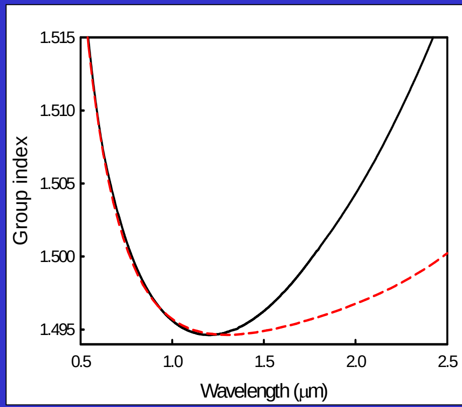
Supercontinuum and photon pairs generation in photonic crystal fibers

• Silica based photonic crystal fibers with special dispersion properties



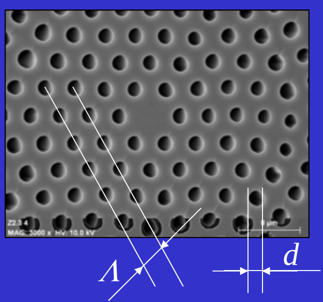
- A highly Ge-doped-core Y-shaped microstructured fiber
- A Ge-doped area of 6.5 μm² with 20 %w of GeO_2
- Enhanced non linear characteristics:
  $n_2 = 1.3 \times n_2$ (SiO2), g_R (12.9 THz) $= 3 \times g_R$ (SiO_2)





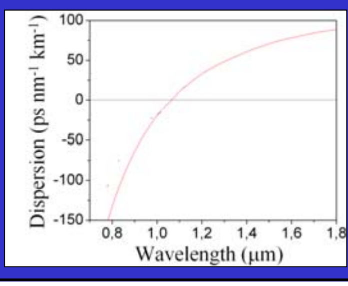
VNIVERSITAT DE VALÈNCIA
I. Introduction
I.2. Fibers with special dispersion properties
Laboratorio de Fibras Ópticas

• Silica based photonic crystal fibers with special dispersion properties



- A set of nonlinear photonic crystal fiber with slightly different zero dispersion wavelength
- Fine adjustment of the dispersion during fabrication

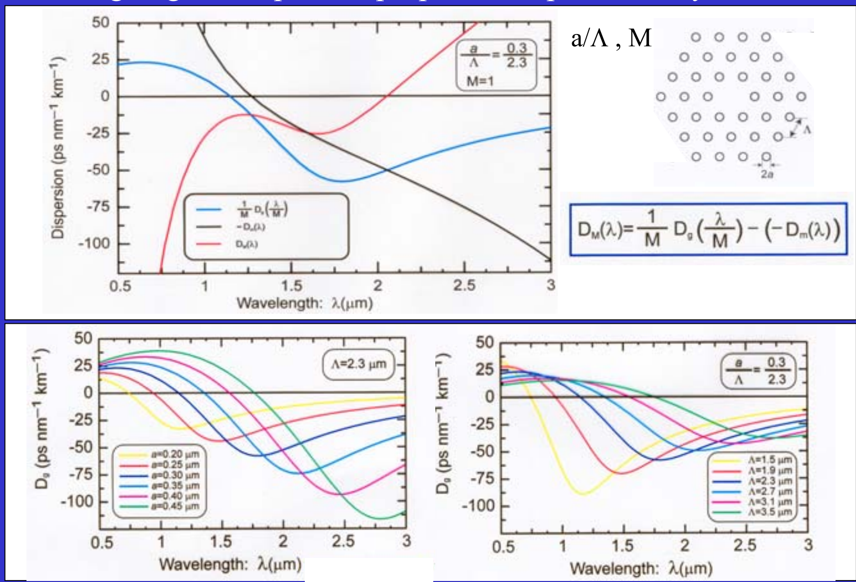
Fiber	Data from SEM images: d (μm)	Data from SEM images: Λ (μm)	λ_{ZDW} (μm)
PCF-A	1.42	3.57	1.082
PCF-B	1.99	4.03	1.070
PCF-C	1.94	3.92	1.065



I. Introduction

I.2. Fibers with special dispersion properties

– Designing the dispersion properties of photonic crystal fibers



Opt. Express, pp. 687-697, 2001

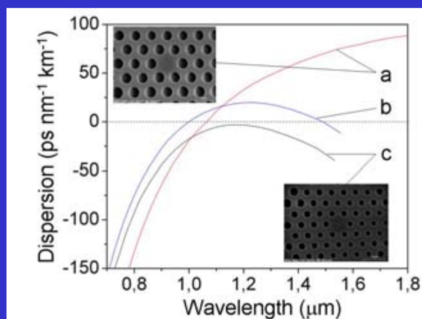
I. Introduction

I.2. Fibers with special dispersion properties

– Control of the dispersion properties during fabrication

– A series of PCF produced from a given preform

Fiber	Data from SEM images	
	d (μm)	*Λ* (μm)
PCF-a	1.56	2.61
PCF-b	0.72	1.73
PCF-c	0.63	1.70



- PCF-a: One zero dispersion wavelength at ~ 1050 nm
- PCF-b: Two zero dispersion wavelengths at 1000 and 1450 nm
- PCF-c: Completely normal dispersion PCF

Contents

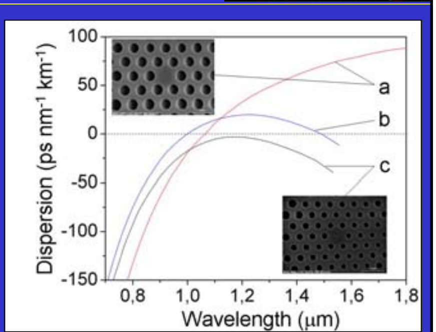
Supercontinuum and photon pairs generation in photonic crystal fibers

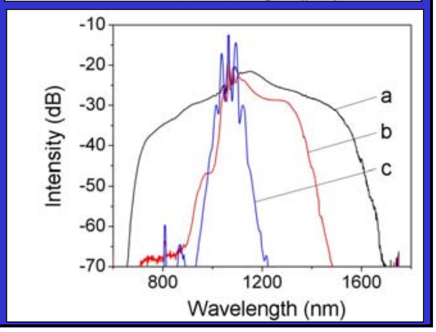
- Supercontinuum generation with a pulsed laser: 1064 nm, 0.7 ns

• PCF-a (5 mW)
- One zero dispersion wavelength at ~ 1050 nm
- Anomalous dispersion, modulation instability, solitons, self frequency shift (SFS)
- Dispersive waves

• PCF-b (5 mW)
- Two zero dispersion wavelengths at 1000 and 1450 nm
- The second zero dispersion wavelength limits the anomalous dispersion region and prevents the SFS mechanism to extend the spectrrum beyond 1450 nm

• PCF-c (7 mW)
- Completely normal dispersion PCF
- Raman bands





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Supercontinuum and photon pairs generation in photonic crystal fibers

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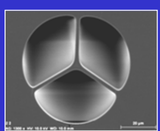
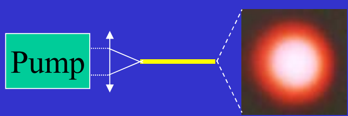
VNIVERSITAT DE VALÈNCIA — **II. Supercontinuum generation** — II.2. A Y-shaped PCF with a Ge-doped core — Laboratorio de Fibras Ópticas

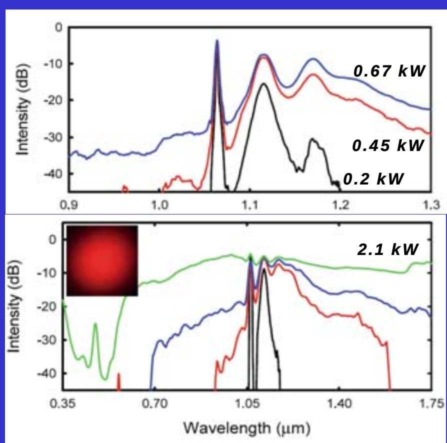
- Supercontinuum generation in a Y-shaped PCF with a Ge-doped core

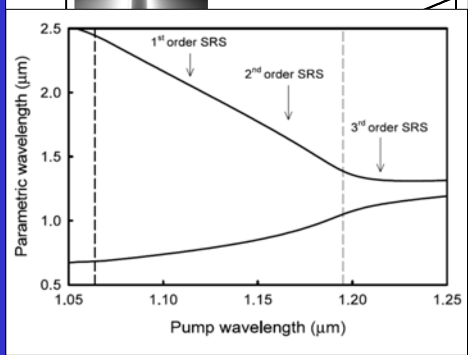


– 1064 nm
– 9 ns pulses
– 5 m length



– Large Raman gain

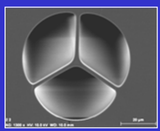




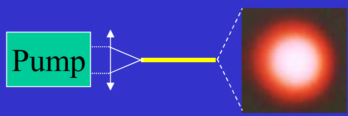
II. Supercontinuum generation

II.2. A Y-shaped PCF with a Ge-doped core

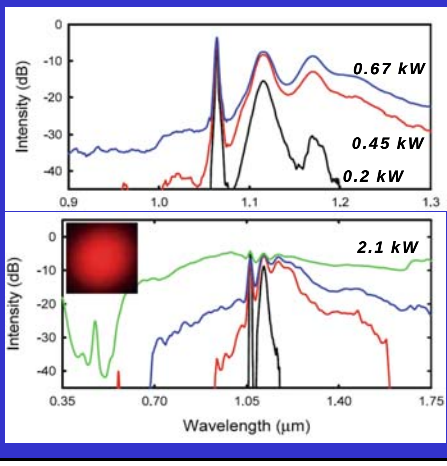
- Supercontinuum generation in a Y-shaped PCF with a Ge-doped core

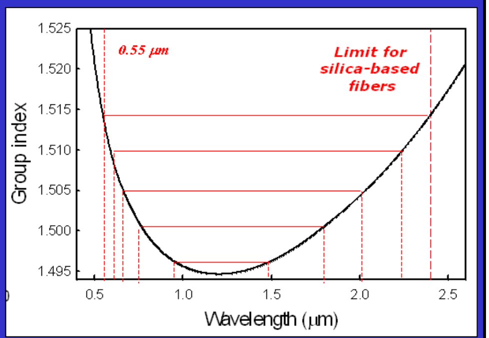


– 1064 nm
– 9 ns pulses
– 5 m length



– SFS solitons produce dispersive waves that couple power efficiently to shorter wavelengths with the same group index





Appl. Phys. B, pp. 371–376, 2010

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Supercontinuum and photon pairs generation in photonic crystal fibers

II. Supercontinuum generation

II.3. Er-doped PCF: Shaping the supercontinuum

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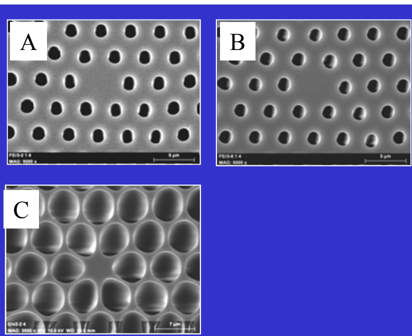
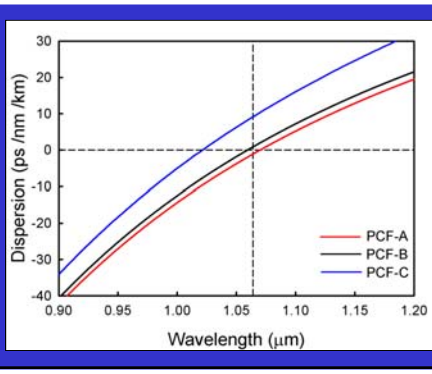
• Erbium doped PCF

	Λ (μm)	d (μm)	D_{core} (μm)	D_{Er} (μm)	Er concentration (ions/m^3)	ZDW (μm)
PCF-A	3.7	1.5	5.6	1.6	1.15×10^{26}	1.071
PCF-B	3.6	1.5	5.6	1.6	1.15×10^{26}	1.058
PCF-C	5.7	0.9	4.5	1.4	1×10^{25}	1.024





II. Supercontinuum generation

II.3. Er-doped PCF: Shaping the supercontinuum

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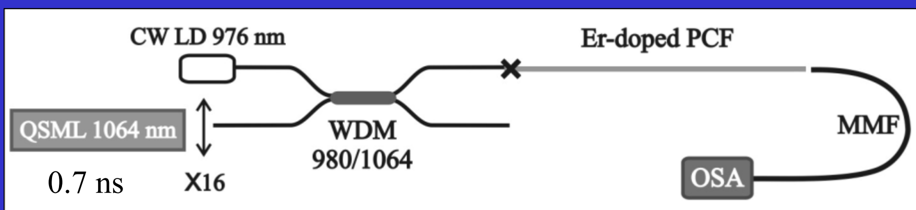
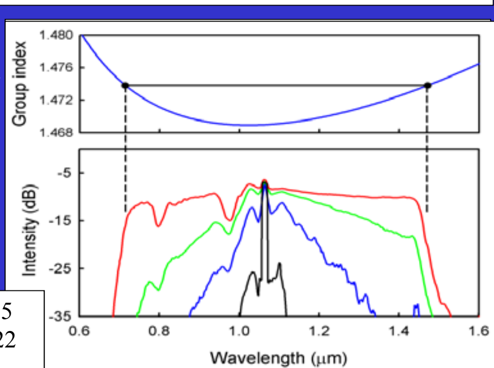
• Erbium doped PCF



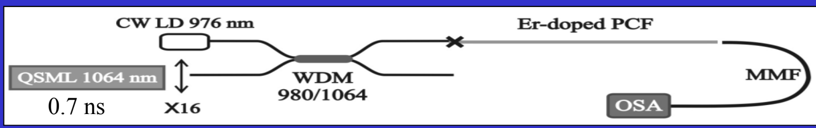
- Supercontinuum spectra generated in 3 m of PCF-B (anomalous regime) when P_{1064}= 20 mW
- Black line: P_{976} = 0 mW
- Red line: P_{976} = 80 mW

- Shaping the spectrum with the absorption band of Er at 1530 nm

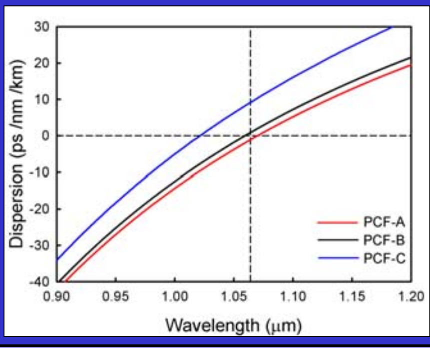


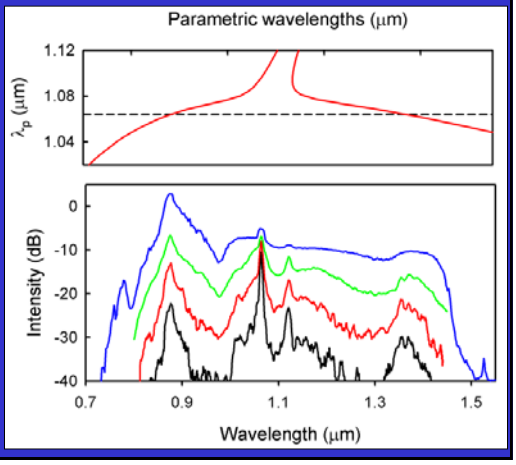
- Supercontinuum spectra generated with 5 m of PCF-B when P_{1064}= 4, 10, 10 and 22 mW

• Erbium doped PCF



- Supercontinuum spectra generated in 5 m of PCF-A (normal regime) when P_{1064}= 4, 10, 22 and 30 mW





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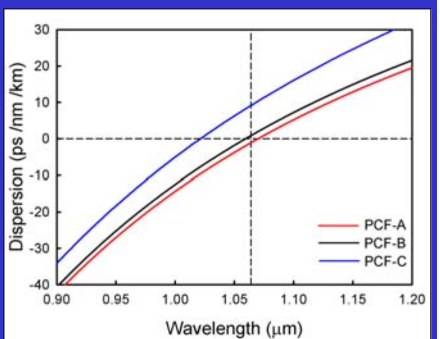
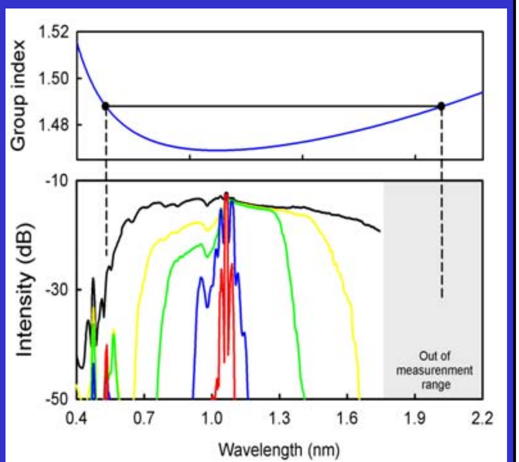
II. Supercontinuum generation
II.3. Er-doped PCF: Shaping the supercontinuum
Laboratorio de Fibras Ópticas

• Erbium doped PCF

- Supercontinuum spectra generated in 3 m of PCF-C (anomalous regime) when P_{1064}= 8, 16, 30, 44 and 66 mW
- The low concentration of Er does not prevent the SFS mechanism to extend beyond 1530 nm





Appl. Phys. B, pp. 559–563, 2012

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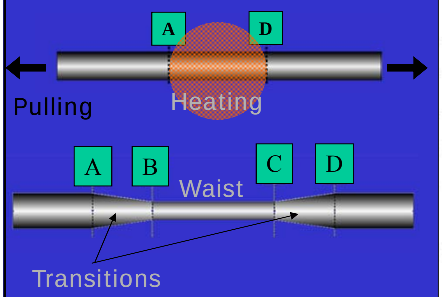
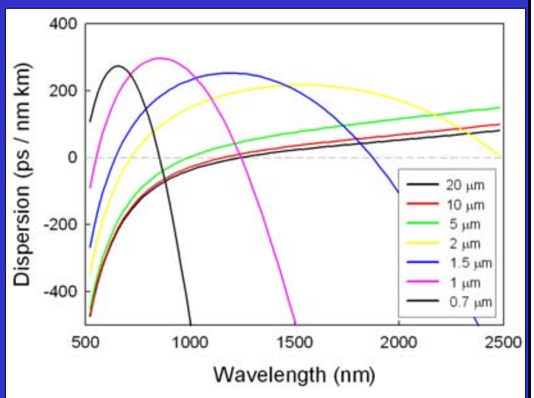
Supercontinuum and photon pairs generation in photonic crystal fibers

- Tapering PCF





- Tapering a PCF the dispersion can be adjusted with a high degree of freedom
- Along the device the dispersion changes: dispersion engineering
- Small core fibers can be spliced to standard fibers with low losses

II. Supercontinuum generation

II.4. Supercontinuum generation in a tapered PCF

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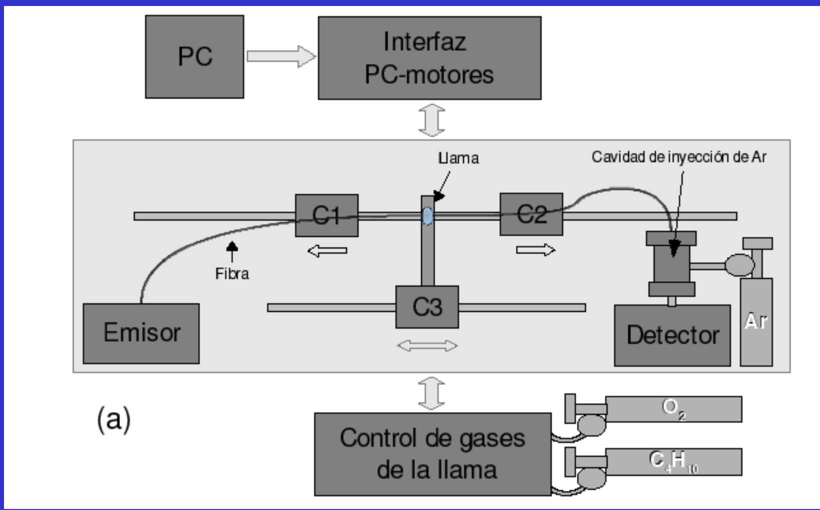
• Tapering PCF



T. A. Birks, Y. W. Li, J. Lightwave Technol. 10, 432-438 (1992)

II. Supercontinuum generation

II.4. Supercontinuum generation in a tapered PCF

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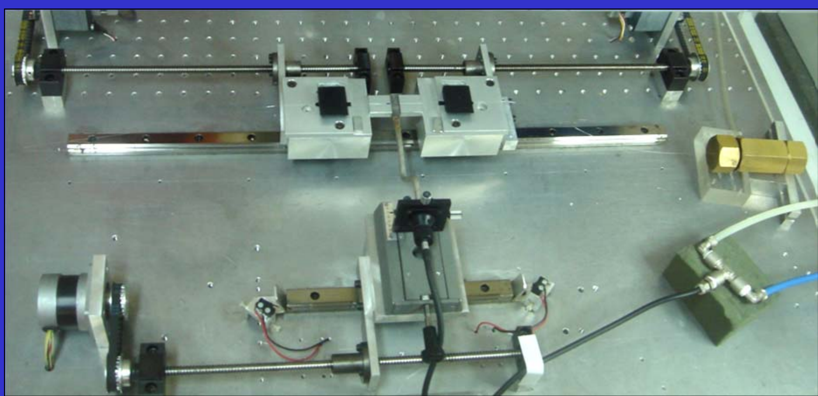
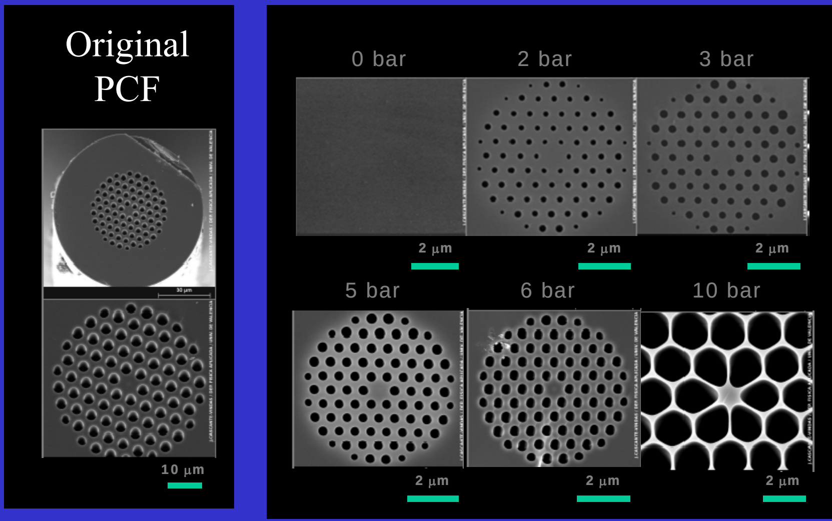
• Tapering PCF



• Tapering PCF



Opt. Commun., pp. 433-438, 2008

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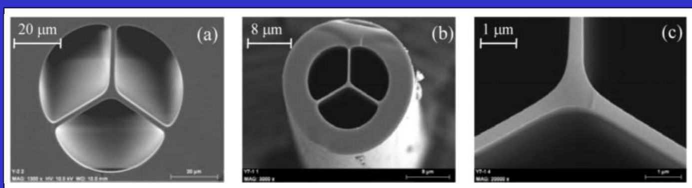
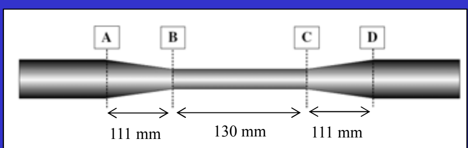
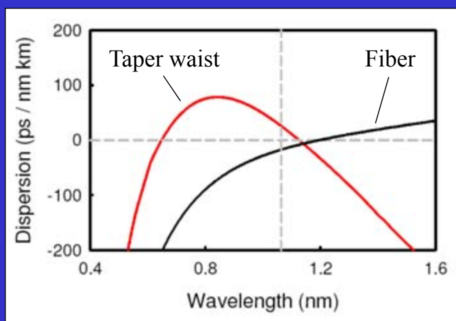
II. Supercontinuum generation
II.4. Supercontinuum generation in a tapered PCF
Laboratorio de Fibras Ópticas

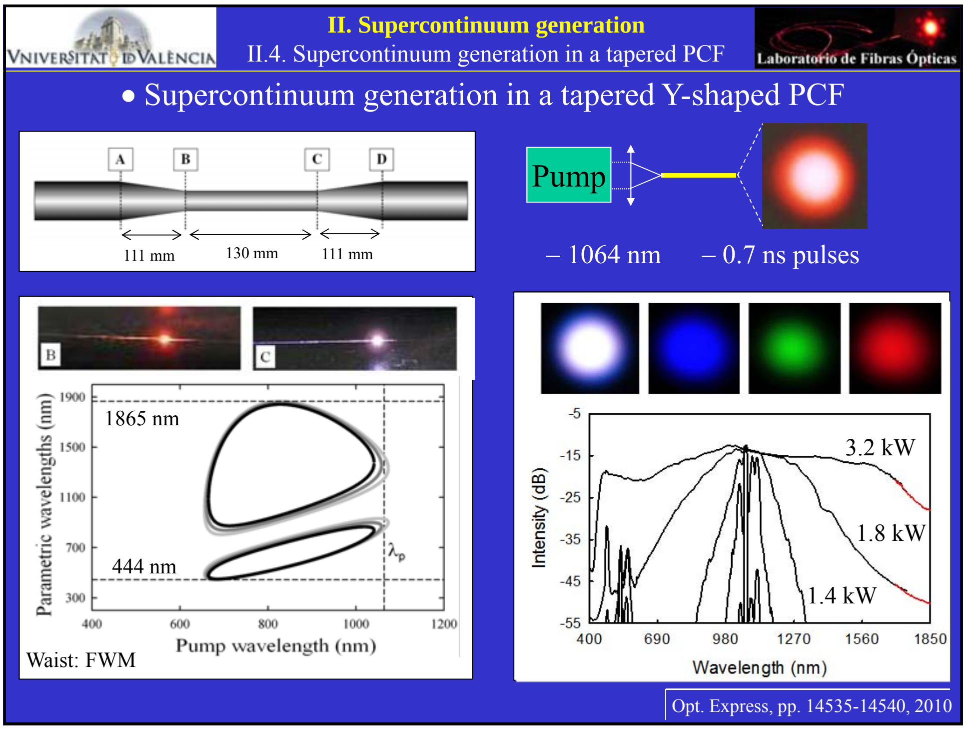
• Supercontinuum generation in a tapered Y-shaped PCF







- At the taper waist, the core diameter was 0.9 µm
- The first zero dispersion wavelength (ZDW) moves from 1195 to 647 nm along the transitions and, at the taper waist, the fiber exhibits two ZDW at 647 and 1127 nm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II. Supercontinuum generation
II.4. Supercontinuum generation in a tapered PCF
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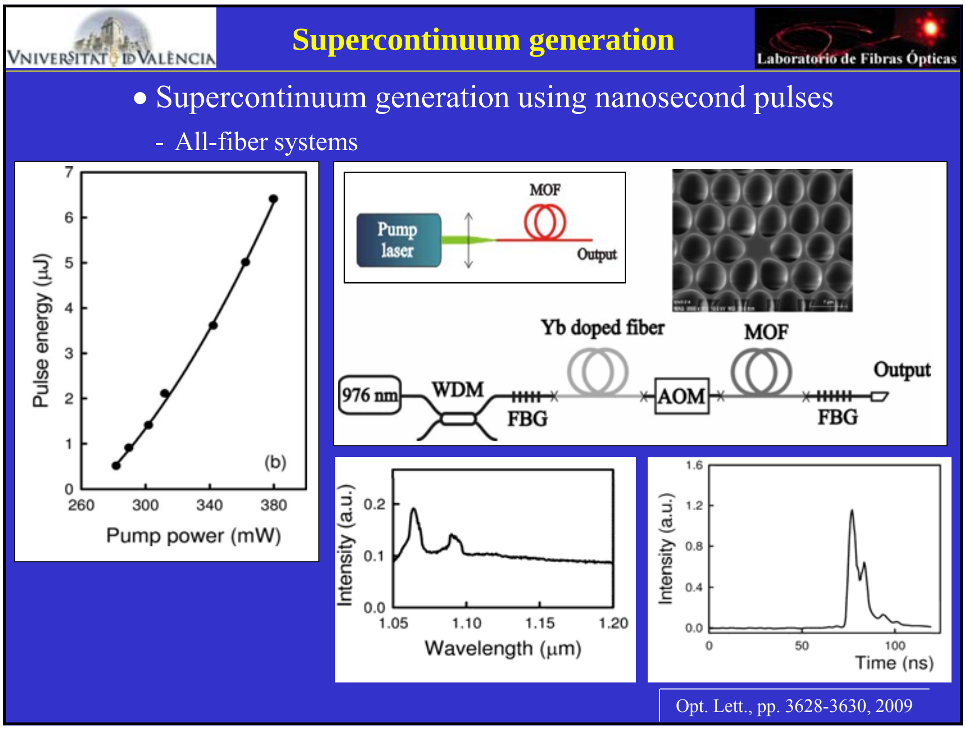
• Supercontinuum generation in a tapered Y-shaped PCF
A
B
C
D
111 mm
130 mm
111 mm
Pump
– 1064 nm
– 0.7 ns pulses
B
C
Parametric wavelengths (nm)
1900
1500
1100
700
300
1865 nm
444 nm
λ_p
400
600
800
1000
1200
Pump wavelength (nm)
Waist: FWM
Intensity (dB)
-5
-15
-25
-35
-45
-55
3.2 kW
1.8 kW
1.4 kW
400
690
980
1270
1560
1850
Wavelength (nm)
Opt. Express, pp. 14535-14540, 2010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Supercontinuum generation
Laboratorio de Fibras Ópticas
• Supercontinuum generation using nanosecond pulses
- All-fiber systems
Pulse energy (μJ)
7
6
5
4
3
2
1
0
260
300
340
380
Pump power (mW)
(b)
MOF
Pump laser
Output
Yb doped fiber
MOF
Output
976 nm
WDM
FBG
AOM
FBG
Intensity (a.u.)
0.2
0.1
0.0
1.05
1.10
1.15
1.20
Wavelength (μm)
Intensity (a.u.)
1.6
1.2
0.8
0.4
0.0
0
50
100
Time (ns)
Opt. Lett., pp. 3628-3630, 2009

Contents

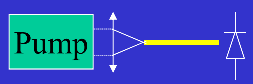
Supercontinuum and photon pairs generation in photonic crystal fibers

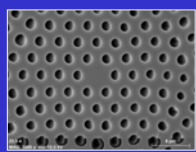
- Photon pairs generation through degenerated FWM

- 1064 nm
- 0.72 ns pulses
- Power average < 160 mW
- 20 kHz repetition rate

$$2 \cdot \omega_p = \omega_i + \omega_s$$

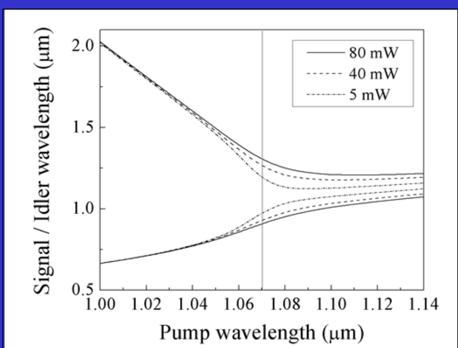
$$\kappa = 2 \cdot \beta(\omega_p) - \beta(\omega_i) - \beta(\omega_s) - 2 \cdot \gamma \cdot P$$

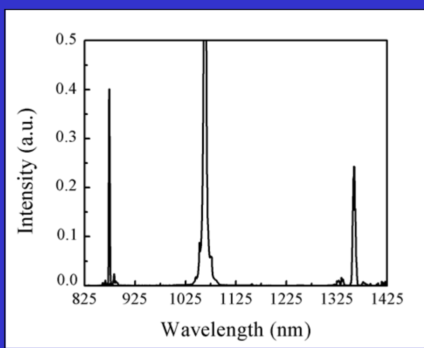




– Fiber length: 0.7 - 1 m

– Fibers with slightly different ZDW



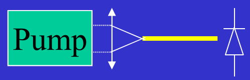


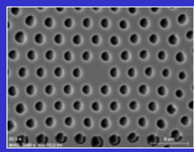
III. Photon pairs generation through FWM

III.1. Pump power induced wavelength shift

• Photon pairs generation through degenerated FWM

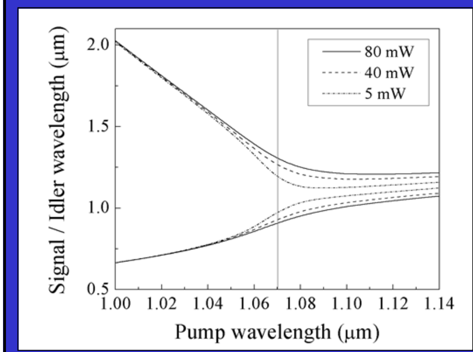
- 1064 nm
- 0.72 ns pulses
- Power average < 160 mW
- 20 kHz repetition rate

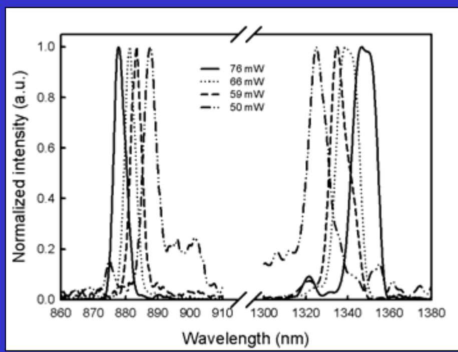




– Fiber length: 0.7 - 1 m

– Fibers with slightly different ZDW

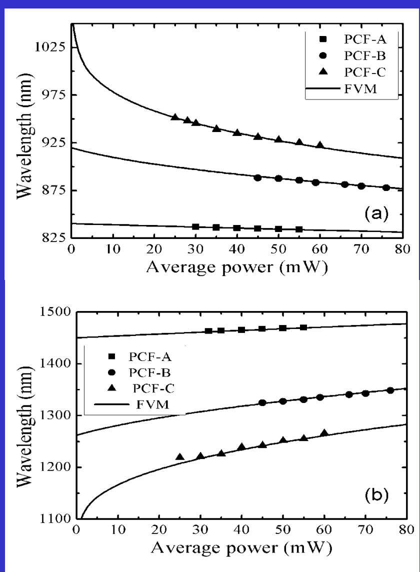




III. Photon pairs generation through FWM

III.1. Pump power induced wavelength shift

• Photon pairs generation through degenerated FWM



Fiber	SEM images		Best fit		λ_{ZDW} (μm)
	d (μm)	*Λ* (μm)	*d* (μm)	*Λ* (μm)	
PCF-A	1.42	3.57	1.410	3.531	1.082
PCF-B	1.99	4.03	1.864	3.771	1.070
PCF-C	1.94	3.92	1.771	3.589	1.065

– The linear properties of the fibers were modeled using a fully vectorial method.

– For PCF-C, the signal and idler bands shifted from 951 nm to 922 nm, and from 1219 nm to 1266 nm, respectively, in a pump power range 35 mW.

– For a 80 mW pump power range, the theoretical calculations predict signal and idler bands shifts of 87 nm and 130 nm.

Photon. Technol. Lett., pp. 1010-1012, 2011

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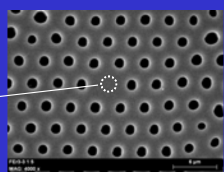
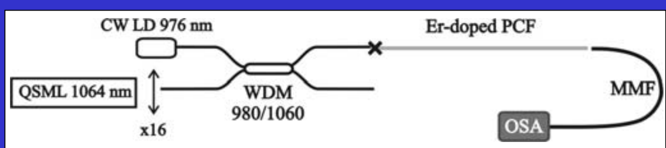
Supercontinuum and photon pairs generation in photonic crystal fibers

III. Photon pairs generation through FWM

III.2. Fine tuning of FWM bands in Er-doped PCF

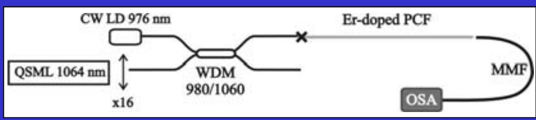
- Normal dispersion Er-doped fiber at 1064 nm: dynamic control by pumping the fiber with a CW 976 nm laser diode
  - Pitch Λ = 3.72 µm
  - Hole diameter d = 1.46 µm
  - Core diameter d_c = 5.55 µm
  - Doped region: 2.23 µm
  - Er concentration: 2300 ppm
  - Zero dispersion wavelength λ_{ZDW} = 1072 nm

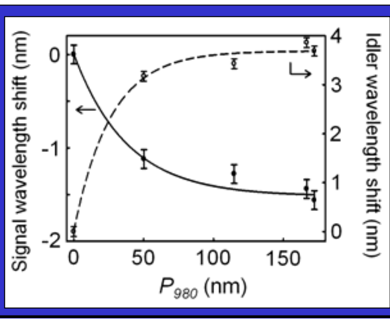


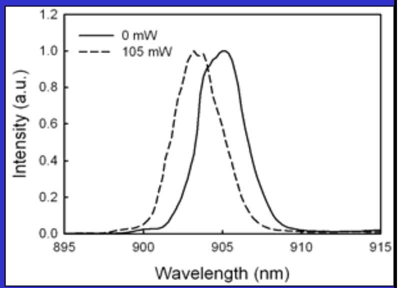


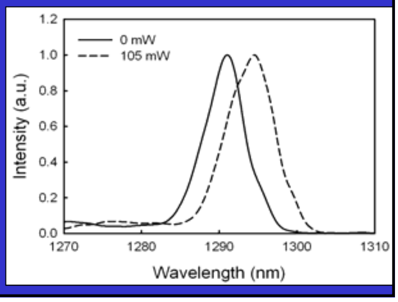
- Q-switched Microchip Nd-YAG laser: 1064 nm, 0.7 ns, 20 kHz, 160 mW
- Pump power coupled to the PCF: 29 mW
- Pigtailed laser diode: 976 nm
- Maximum power coupled to the PCF: 175 mW

- The CW pump at 976 nm has several effects on the PCF that might contribute to the shift of FWM bands:
  - Change of the nonlinear coefficient n_2
  - Change of refractive index produced by absorption changes (Kramers-Kronig)
  - Thermal effects







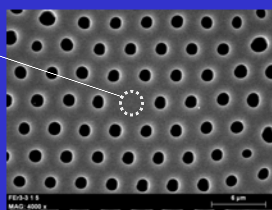


III. Photon pairs generation through FWM
III.2. Fine tuning of FWM bands in Er-doped PCF
Laboratorio de Fibras Ópticas

- Theoretical discussion: non linear refractive index n_2

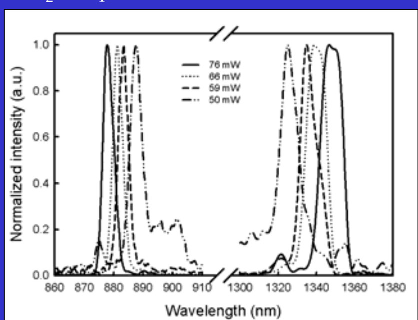
$$\boxed{2 \cdot \beta(\omega_p) = \beta(\omega_i) + \beta(\omega_s) + 2 \cdot \gamma \cdot P}$$

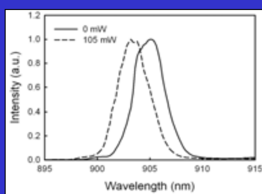
Er-doped region

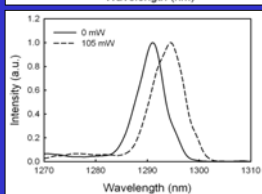


– A small change of the nonlinear refractive index n_2 could be, in principle, responsible for the reported shifts of the FWM bands, but n_2 decreases when pumping the Er-doped fiber* which would shift the bands towards the pump wavelength
** H. García et al., Opt. Lett., pp. 1261-1263, 2005*

– A decrease of n_2 is equivalent to a decrease of P:

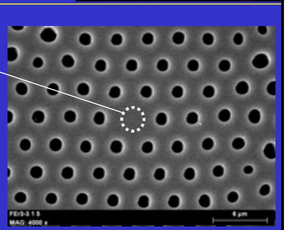






- Theoretical discussion: refractive index changes

Er-doped region



– The thermal effects
– First order of perturbation calculus gives: $\left(\frac{\partial n_{eff}}{\partial n}\right) \cong 2\frac{A_{Er}}{A_{eff}}$

$$\left.\begin{array}{l}\delta n_s \cong \delta n_i \cong \delta n_p \\ A_{eff} \cong \text{constant with } \lambda \\ 2\omega_p = \omega_s + \omega_i\end{array}\right\} \Rightarrow \delta\lambda_i = 0$$

$$\frac{2\pi c}{\lambda_i^2}\left(n_{gs}-n_{gi}\right)\delta\lambda_i = \omega_s\left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_s}\delta n_s + \omega_i\left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_i}\delta n_i - 2\omega_p\left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_p}\delta n_p$$

– Using an accurate calculation of the derivatives:

Δn_g	$(\partial n_{eff}/\partial n_{er})_{\omega_i}$	$(\partial n_{eff}/\partial n_{er})_{\omega_p}$	$(\partial n_{eff}/\partial n_{er})_{\omega_s}$
3.8×10^{-4}	0.45	0.49	0.52

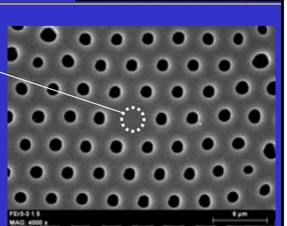
and taking into account the experimental value $\delta\lambda_i$ = 3.7 nm (P_{976} = 160 mW) we can estimate the refractive index increment that would be required: $\delta n = 4.7\times10^{-6}$

This increment of the refractive index in the Er-doped region, with respect to the surrounding glass, corresponds to a temperature difference of about 0.55 K, which would require a pump power 25 times higher (~ 4 W)

III. Photon pairs generation through FWM
III.2. Fine tuning of FWM bands in Er-doped PCF

- Theoretical discussion: refractive index changes

Er-doped region



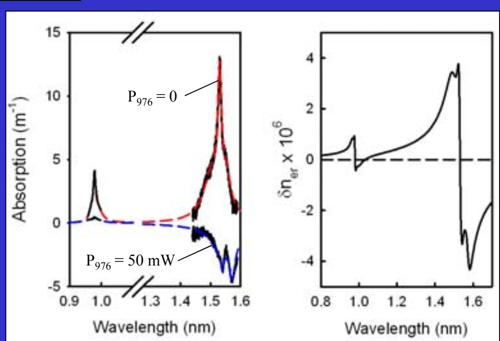
– Which refractive changes would enhance the shift of the parametric bands?
– Taking into account that: $\left(\frac{\partial n_{eff}}{\partial n}\right) \cong 2\frac{A_{Er}}{A_{eff}}$

$$\frac{2\pi c}{\lambda_i^2}\left(n_{gs}-n_{gi}\right)\delta\lambda_i \approx \left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_s}\left(\omega_s\delta n_s + \omega_i\delta n_i - 2\omega_p\delta n_p\right)$$

Therefore, an interesting case is $\delta n_s > 0$, $\delta n_i > 0$ and $\delta n_p < 0$

In fact, this is close to the situation that corresponds to the resonant refractive index changes produced by absorption saturation of the 980 nm band of the Erbium ions.

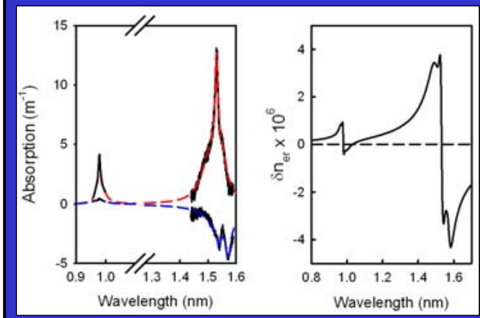
- Using Kramers-Kronig relations:
$\delta n_s = 0.6\times10^{-6}$ at 880 nm
$\delta n_i = 1.2\times10^{-6}$ at 1367 nm
$\delta n_p = 1.0\times10^{-7}$ at 1064 nm



III. Photon pairs generation through FWM

III.2. Fine tuning of FWM bands in Er-doped PCF

- Theoretical discussion: resonant refractive index changes



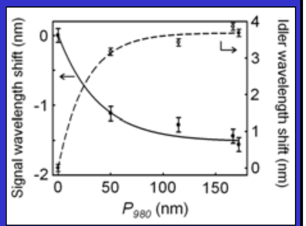
- Resonant change of refractive index produced by absorption changes (Kramers-Kronig):

  $\delta n_s = 0.6 \times 10^{-6}$ at 880 nm
  $\delta n_i = 1.2 \times 10^{-6}$ at 1367 nm
  $\delta n_p = 1.0 \times 10^{-7}$ at 1064 nm

- Estimated shifts $\delta\lambda_s$ = 1.3 nm and $\delta\lambda_i$ = 3.2 nm are in good agreement with the experimental values

$$\Delta n_g \delta\omega_i = \omega_s \left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_s} \delta n_s + \omega_i \left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_i} \delta n_i - 2\omega_p \left(\frac{\partial n_{eff}}{\partial n}\right)_{\omega_p} \delta n_p$$

Δn_g	$(\partial n_{eff}/\partial n_{er})_{\omega_i}$	$(\partial n_{eff}/\partial n_{er})_{\omega_p}$	$(\partial n_{eff}/\partial n_{er})_{\omega_s}$
3.8×10^{-4}	0.45	0.49	0.52



Opt. Lett., pp. 1226-1228, 2012

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IV. Conclusions

- The photonic crystal fiber technology is crucial for the development of novel fiber light sources based on non linear effects
- Fibers with special dispersion properties can be obtained with this technology and, in addition, the tapering technique permits an accurate engineering of the dispersion properties along short sections of the fiber
- Applications: supercontinuum and photon pairs generation