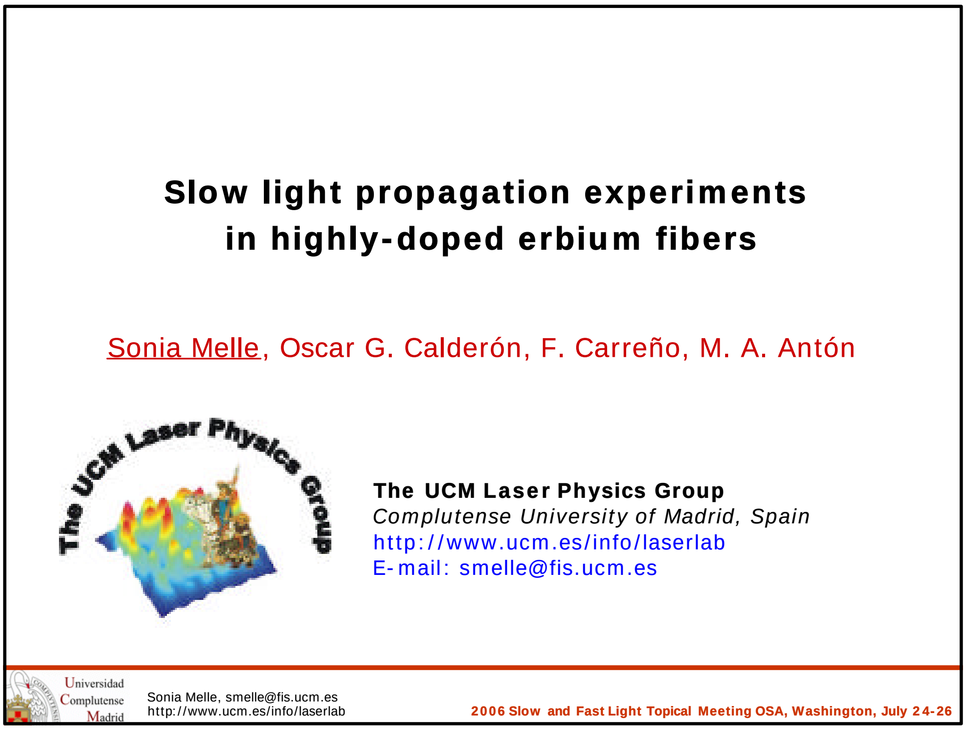

Slow light propagation experiments in highly-doped erbium fibers

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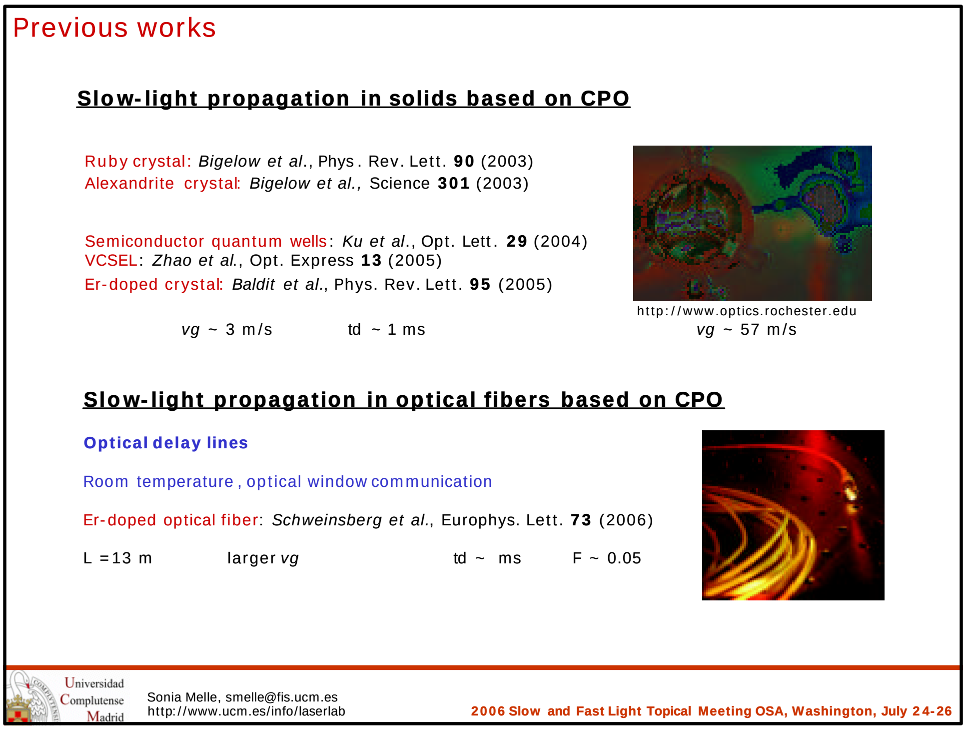

Previous works

Slow-light propagation in solids based on CPO

Ruby crystal: *Bigelow et al.*, Phys. Rev. Lett. **90** (2003)
Alexandrite crystal: *Bigelow et al.*, Science **301** (2003)

Semiconductor quantum wells: *Ku et al.*, Opt. Lett. **29** (2004)
VCSEL: *Zhao et al.*, Opt. Express **13** (2005)
Er-doped crystal: *Baldit et al.*, Phys. Rev. Lett. **95** (2005)

vg ~ 3 m/s td ~ 1 ms

http://www.optics.rochester.edu
vg ~ 57 m/s

Slow-light propagation in optical fibers based on CPO

Optical delay lines

Room temperature, optical window communication

Er-doped optical fiber: *Schweinsberg et al.*, Europhys. Lett. **73** (2006)

L =13 m larger *vg* td ~ ms F ~ 0.05

Motivation

How to achieve larger delays with small fiber lengths?

Increasing ions concentration !!

Objective:

Optimize the slow light propagation effect in HIGHLY-DOPED ERBIUM FIBERS

Er-doped fibers properties

Fiber code	Peak absorp. (dB/m)	Ions dens. (m^{-3})	Conc. (ppm)
Er20	20 ± 2	1.6 x 10^{25}	800
Er30	30 ± 3	2.1 x 10^{25}	1050
Er40	40 ± 4	2.7 x 10^{25}	1350
Er80	80 ± 8	6.3 x 10^{25}	3150
Er110	110 ± 10	8.7 x 10^{25}	4350

Manufactured by Liekki

Ions density 10-50 times greater than in Europhys. Lett. **73** (2006)

L =1 m

MFD @ 1550nm = 6.5 ± 0.5 µm
Cladding = 125 ± 2 µm
Coating = 245 ± 15 µm
NA =0.2 ± 0.02

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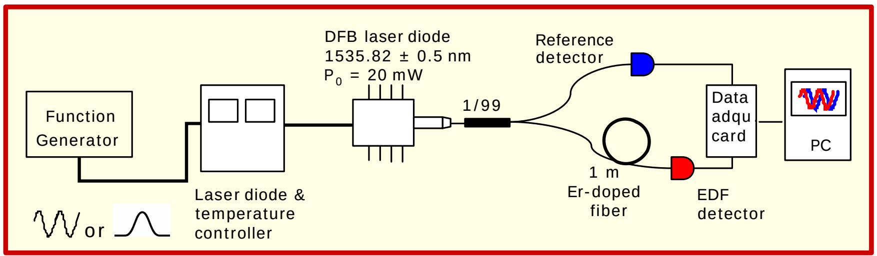
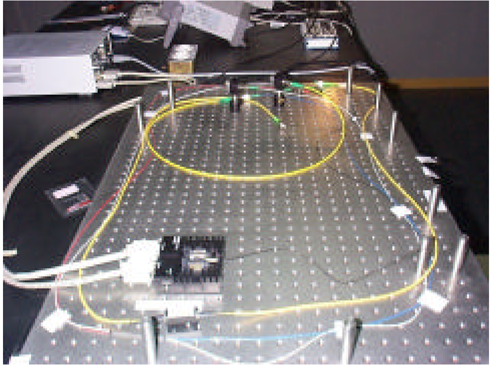
Experimental setup





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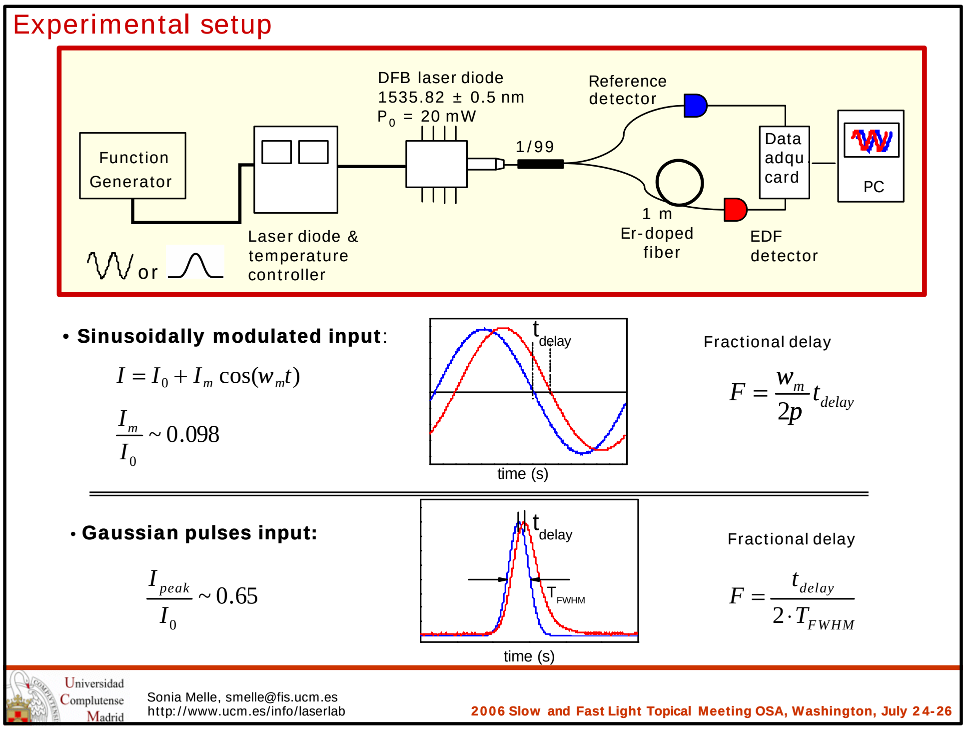


Experimental setup

- **Sinusoidally modulated input**:

$$I = I_0 + I_m \cos(w_m t)$$

$$\frac{I_m}{I_0} \sim 0.098$$

Fractional delay

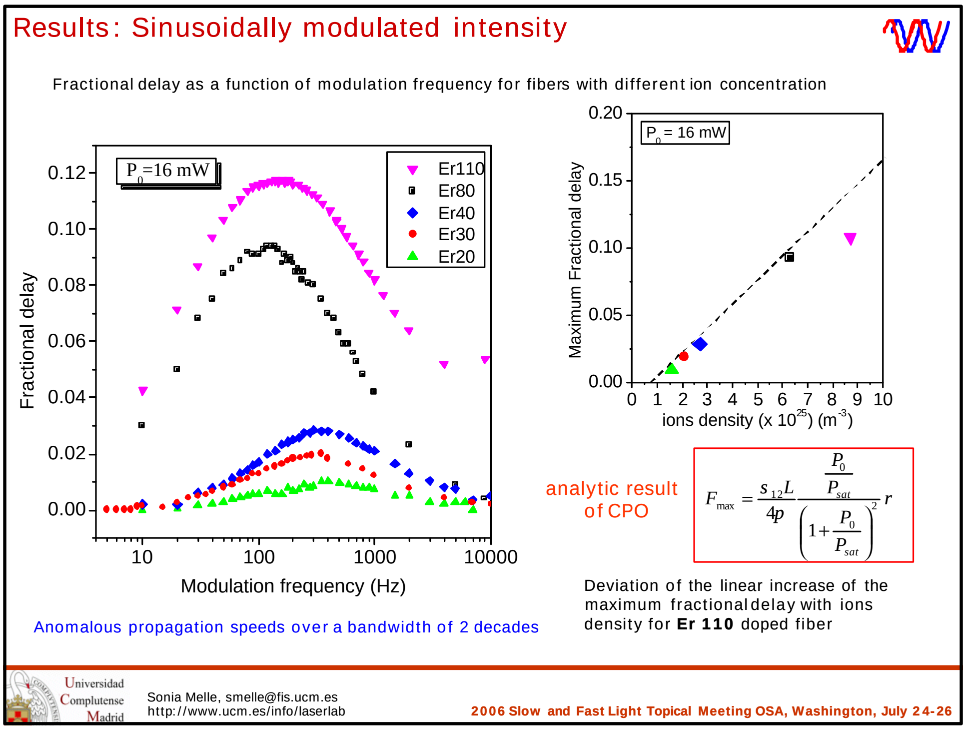
$$F = \frac{w_m}{2p} t_{delay}$$

- **Gaussian pulses input:**

$$\frac{I_{peak}}{I_0} \sim 0.65$$

Fractional delay

$$F = \frac{t_{delay}}{2 \cdot T_{FWHM}}$$



Results: Sinusoidally modulated intensity

Fractional delay as a function of modulation frequency for fibers with different ion concentration

Anomalous propagation speeds over a bandwidth of 2 decades

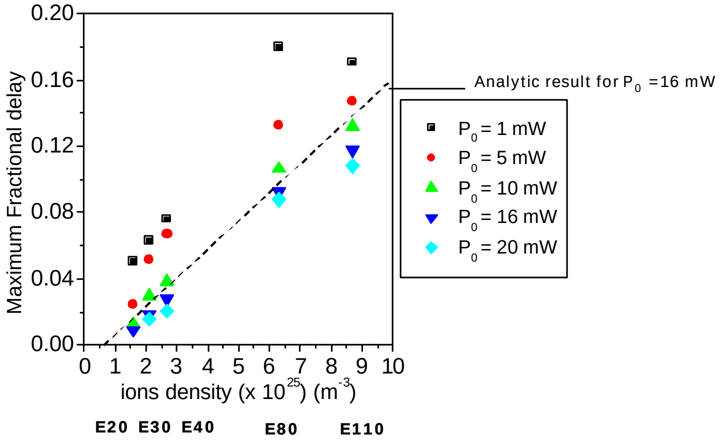
analytic result of CPO

$$F_{\max} = \frac{s_{12} L}{4p} \frac{\frac{P_0}{P_{sat}}}{\left(1 + \frac{P_0}{P_{sat}}\right)^2} r$$

Deviation of the linear increase of the maximum fractional delay with ions density for **Er 110** doped fiber

Results: Sinusoidally modulated intensity

Maximum fractional delay as a function of fibers concentration for different laser powers



Saturation of the maximum fractional delay for the ultra-highly doped fiber E110 more pronounced for smaller laser powers.

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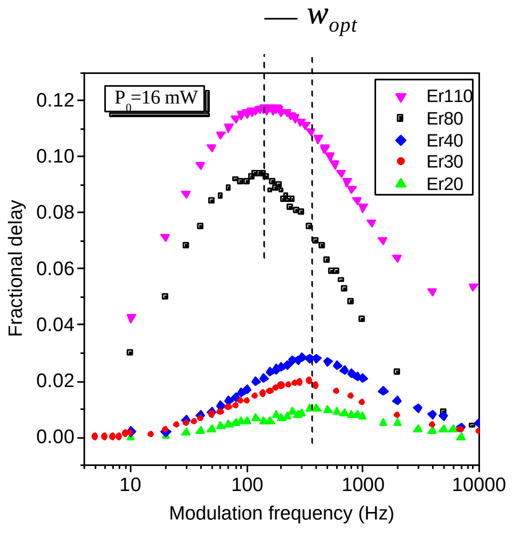
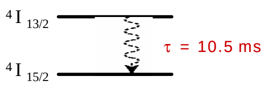
Results: Sinusoidally modulated intensity

Fractional delay as a function of modulation frequency for fibers with different ion concentration



Highly doped fibers (**Er20** → **Er40**) follow the analytic result of CPO

$$\boxed{w_{opt} = \frac{1}{t}\left(1+\frac{P_0}{P_{sat}}\right)} \Rightarrow w_{opt} \sim 370 \text{ Hz}$$



$$w_{opt}^{EXP} \sim 150 \text{ Hz}$$

Ultra-highly doped fibers (**Er80** and **Er110**) deviate from the expected behavior

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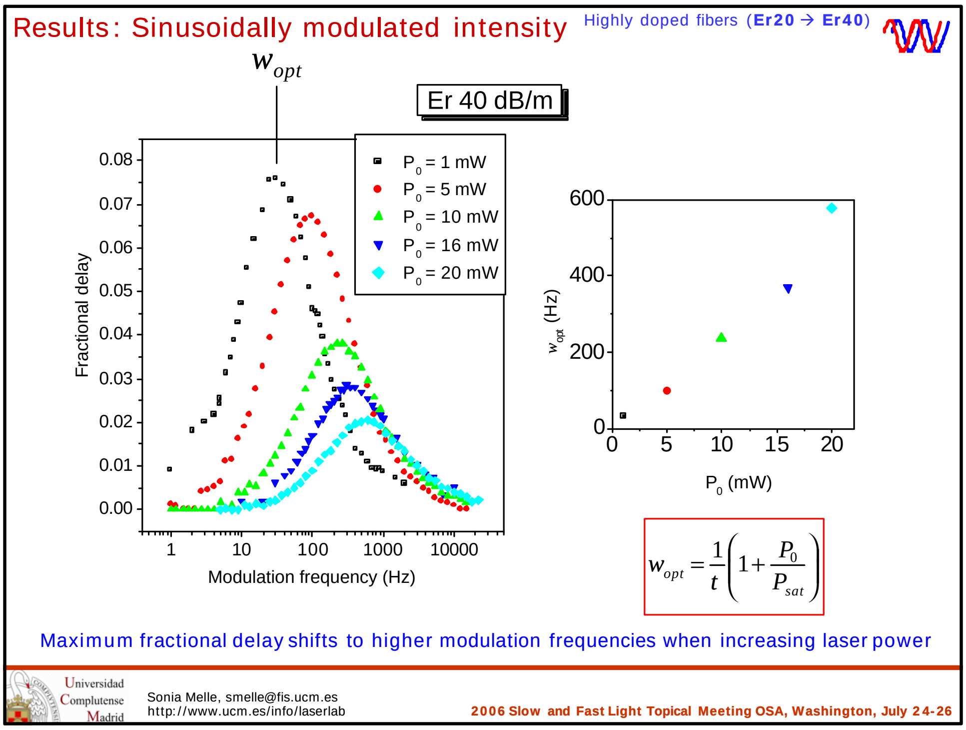

Results: Sinusoidally modulated intensity

Highly doped fibers (**Er20** → **Er40**)

$$w_{opt} = \frac{1}{t}\left(1 + \frac{P_0}{P_{sat}}\right)$$

Maximum fractional delay shifts to higher modulation frequencies when increasing laser power

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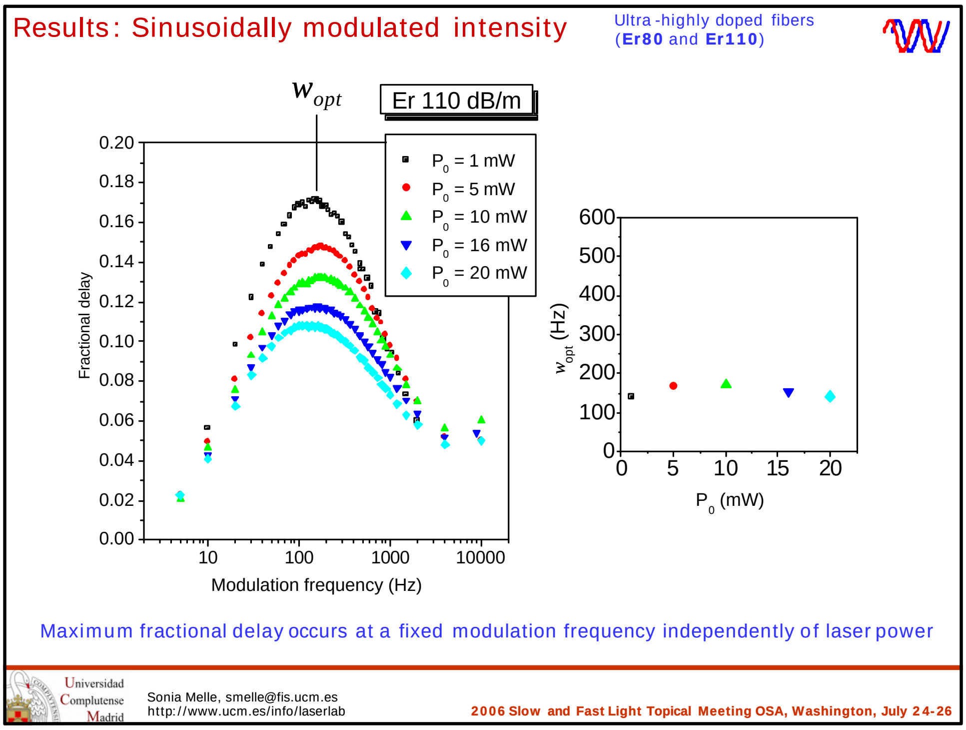

Results: Sinusoidally modulated intensity

Ultra-highly doped fibers
(**Er80** and **Er110**)

Maximum fractional delay occurs at a fixed modulation frequency independently of laser power

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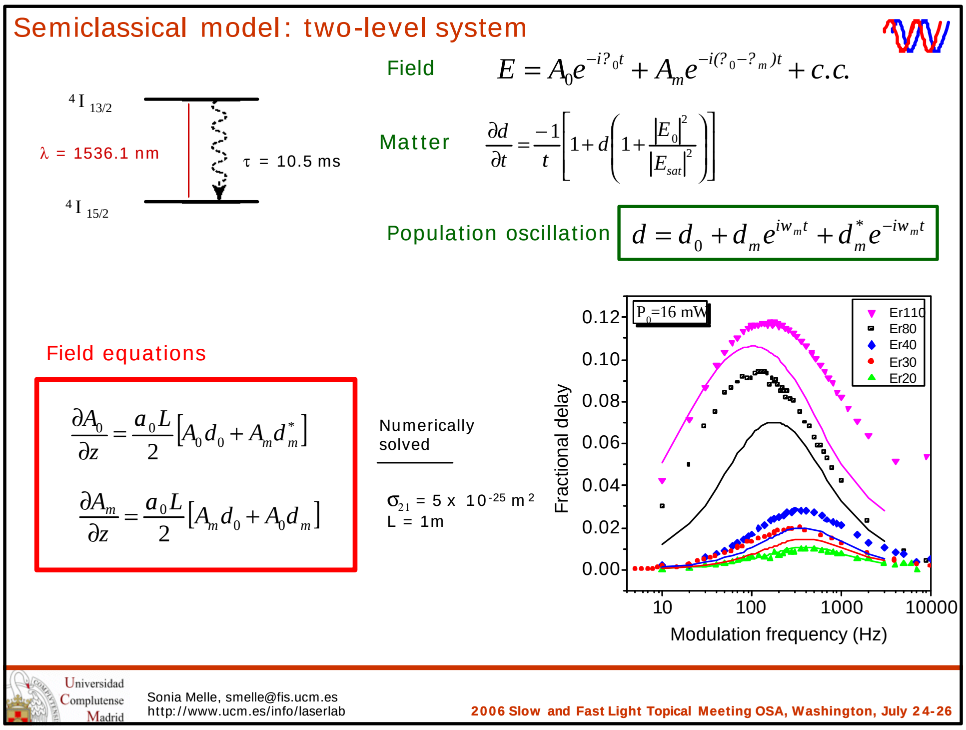

Semiclassical model: two-level system

Field $$E = A_0 e^{-i?_0 t} + A_m e^{-i(?_0 - ?_m)t} + c.c.$$

Matter $$\frac{\partial d}{\partial t} = \frac{-1}{t}\left[1 + d\left(1 + \frac{|E_0|^2}{|E_{sat}|^2}\right)\right]$$

Population oscillation $$\boxed{d = d_0 + d_m e^{iw_m t} + d_m^* e^{-iw_m t}}$$

Field equations

$$\frac{\partial A_0}{\partial z} = \frac{a_0 L}{2}\left[A_0 d_0 + A_m d_m^*\right]$$

$$\frac{\partial A_m}{\partial z} = \frac{a_0 L}{2}\left[A_m d_0 + A_0 d_m\right]$$

Numerically solved

σ_{21} = 5 x 10^{-25} m^2
L = 1m

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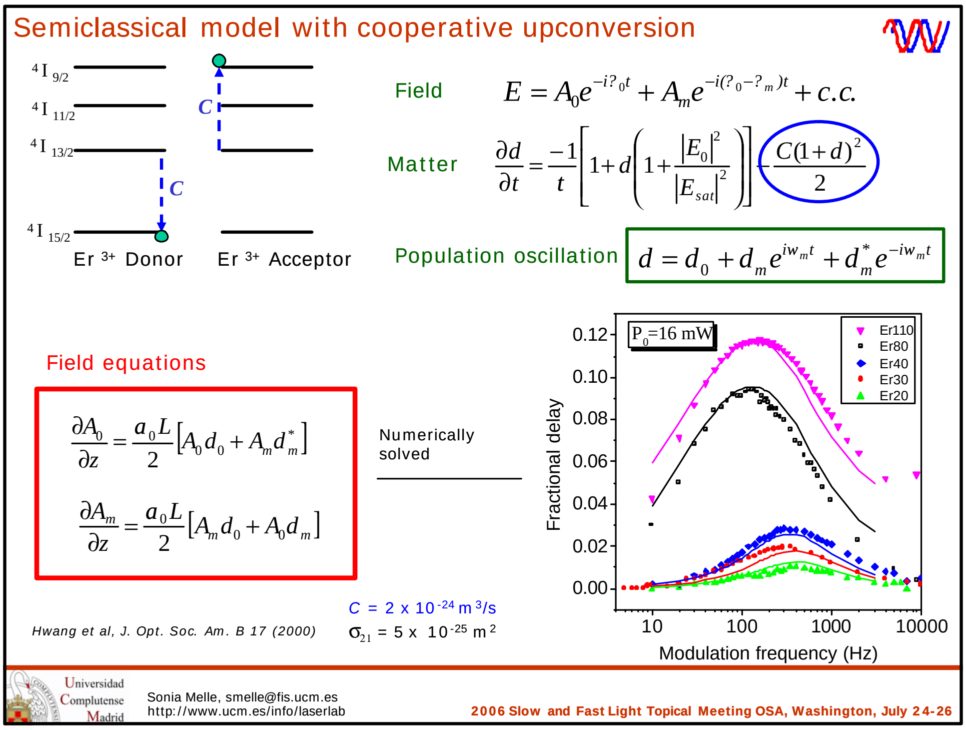

Semiclassical model with cooperative upconversion

Field $$E = A_0 e^{-i?_0 t} + A_m e^{-i(?_0 - ?_m)t} + c.c.$$

Matter $$\frac{\partial d}{\partial t} = \frac{-1}{t}\left[1 + d\left(1 + \frac{|E_0|^2}{|E_{sat}|^2}\right)\right] - \boxed{\frac{C(1+d)^2}{2}}$$

Population oscillation $$\boxed{d = d_0 + d_m e^{iw_m t} + d_m^* e^{-iw_m t}}$$

Field equations

$$\frac{\partial A_0}{\partial z} = \frac{a_0 L}{2}\left[A_0 d_0 + A_m d_m^*\right]$$

$$\frac{\partial A_m}{\partial z} = \frac{a_0 L}{2}\left[A_m d_0 + A_0 d_m\right]$$

Numerically solved

Hwang et al, J. Opt. Soc. Am. B 17 (2000)

C = 2 x 10^{-24} m^3/s
σ_{21} = 5 x 10^{-25} m^2

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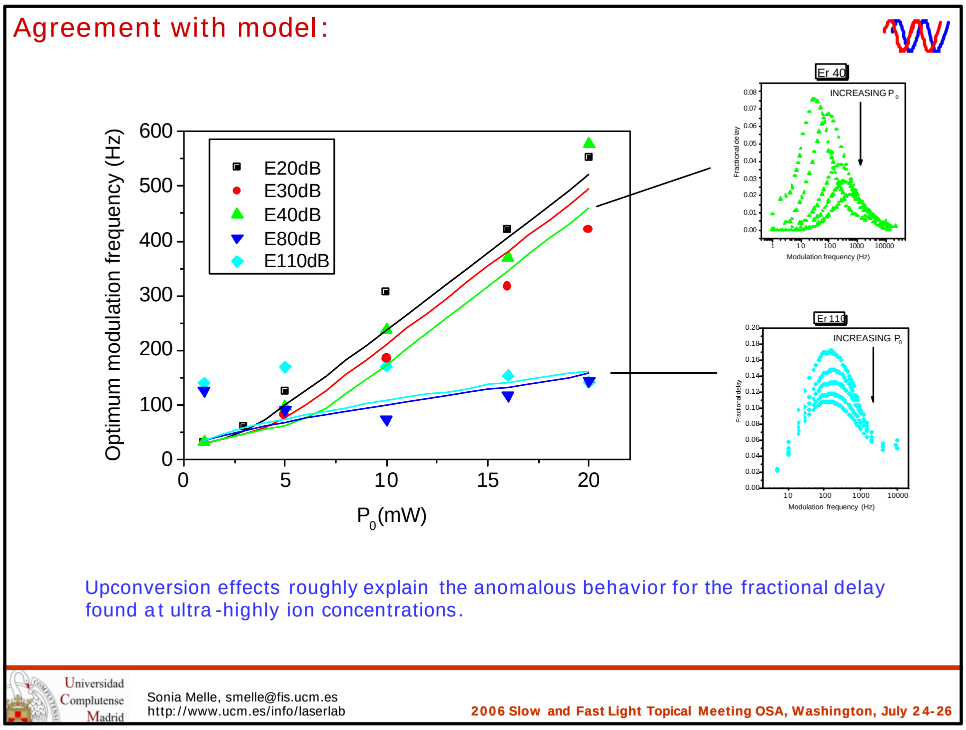

Agreement with model:

Upconversion effects roughly explain the anomalous behavior for the fractional delay found at ultra-highly ion concentrations.

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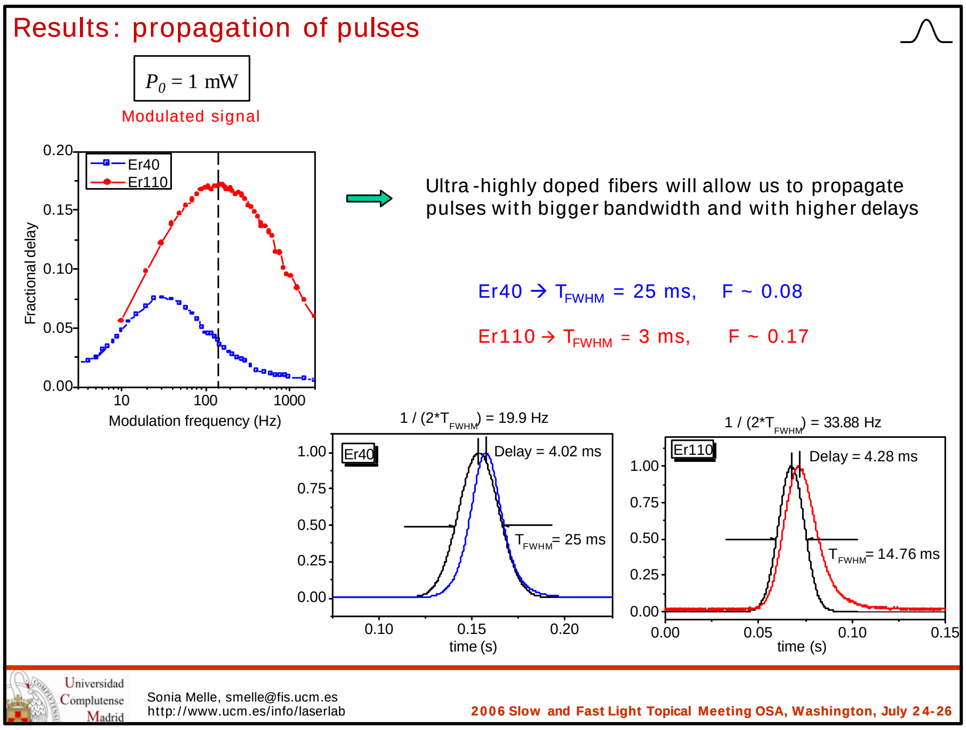

Results: propagation of pulses

$P_0 = 1$ mW

Modulated signal

Ultra-highly doped fibers will allow us to propagate pulses with bigger bandwidth and with higher delays

Er40 → T_{FWHM} = 25 ms, F ~ 0.08

Er110 → T_{FWHM} = 3 ms, F ~ 0.17

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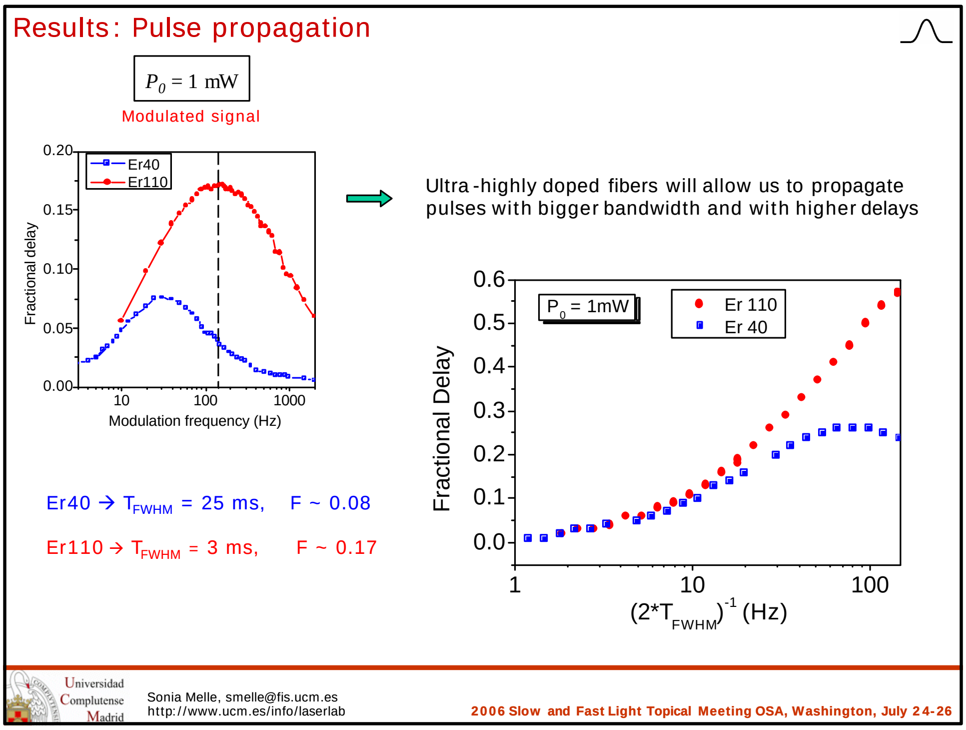

Results: Pulse propagation

P_0 = 1 mW

Modulated signal

Ultra-highly doped fibers will allow us to propagate pulses with bigger bandwidth and with higher delays

Er40 → T_{FWHM} = 25 ms, F ~ 0.08

Er110 → T_{FWHM} = 3 ms, F ~ 0.17

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Conclusions

- Larger fractional delays with shorter fiber lengths have been found.

  F ~ 0.17 (L = 1 m)

  Schweinsberg et al.
  F ~ 0.07 (L = 13 m)

- Fractional delay increases with ion concentration although this increase is sublinear at ultrahighly doped fibers.

- Two different behaviors have been found for the optimum modulation frequency when changing ion concentration:

  A) For highly-doped fibers **(Er20 → Er40)** the optimum frequency increases linearly with laser power

  B) For ultra-highly doped fibers **(Er80 and Er110)** the optimum frequency remains unchanged independently of laser power

- Ultra-highly doped fibers allow us to propagate pulses with bigger bandwidth and with higher delays Er110 → TFWHM = 3 ms, F ~ 0.17

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Thank you for your attention!!

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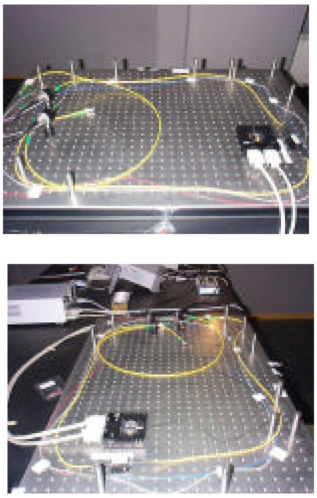

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