Pulse width depending group velocity on Erbium-doped fibers

Francisco Arrieta-Yáñez, Oscar G. Calderón, Sonia Melle, F. Carreño,
M. A. Antón
Escuela Universitaria de Óptica, Universidad Complutense de Madrid, Arcos de Jalón s/n,
28037 Madrid, Spain
franarrieta@fis.ucm.es

Abstract: We report a change in the propagation regime (subluminal-superluminal) of light pulses in a pumped erbium doped fiber. We explain this behavior as a propagation effect. A pulse-width separator based on this effect is proposed.

OCIS codes: (190.4370) Nonlinear optics, fibers; (060.4510) Optical communications; (060.2410) fibers, Erbium

1. Introduction

Light pulse group velocity in Erbium doped fibers (EDFs) is a subject of interest nowadays due to the potential applications in telecommunications. Slow light in EDFs occurs due to Coherent Population Oscillations (CPO) [1], based on the creation of a narrow hole in the absorption spectrum. Fast light occurs in pumped EDFs (EDF amplifier, EDFAs) and it's based on the creation of a transparency hole in the gain spectrum [2]. In previous works, such as [3], the effect of ion concentration on slow light propagation was studied, as well as transitions from sub- to superluminal light varying the pump power [2], and the modulation frequency [5]. In this work we observe a change in pulse propagation from sub- to superluminal with the spectral width of the input pulse, and we study the broadening of the pulse at the end of the fiber.

2. Experimental setup

The experimental setup is depicted en Fig 2. of reference [4], used to observe both fast and slow light in a 1 m long EDF with a 977 nm beam co propagating with a 1536 nm signal. The fiber has an erbium concentration of $\rho = 8.7{\cdot}10^{25} m^{-3}$, which is a high concentration compared with previous works about CPO in fibers ([2], [4], [5]). The injection current of the laser signal was modulated with a function generator in order to get width-controlled pulses. Thus the signal power injected to the fiber was $P_s = P_{sc} + P_{sa}\exp\left(-t^2/2\sigma_{in}^2\right)$, where σ_{in} is the variance of the distribution of the Gaussian input pulse. We define then $\tau_{in} \equiv 2\sqrt{2\log 2}\sigma_{in}$ as the full-width at half the maximum of the input pulse. Spectral width is defined by $f_w = 1/\tau_{in}$. We used a constant pulse height/background ratio of 0.2. The measurement of the delay t_d of the fiber pulse is made by measuring the distance between the delayed and reference pulse peaks. Fractional delay is obtained from $F = t_d/\tau_{in}$.

The measurement of the pulse width is made by two ways. The first one consist in take directly the half-width of the pulse. The other way is calculating the variance of the distribution given by the delayed pulse.

3. The model

We have used propagation equations for the pump and signal powers on an erbium three level system (all the powers are normalized to the saturation power), where the signal can be written as $P_s(t) = P_{sc} + \int \tilde{P}_{sa}(\Omega)\exp\left(-i\Omega t\right)d\Omega$, where $\tilde{P}_{sa}(\Omega)$ is the Fourier transform of $P_{sa}(t)$. This modulation induces a population modulation as $n_2(t) = n_c + \int \tilde{n}_a(\Omega)\exp\left(-i\Omega t\right)d\Omega$. We obtain the following equations for the propagation of the background powers and the pulse spectrum:

$$\frac{\partial P_{sc}}{\partial z} = -\alpha_s P_{sc} + 2\alpha P_{sc} n_c; \qquad (1)$$

$$\frac{\partial P_p}{\partial z} = -\alpha_p P_p + \alpha P_p n_c; \qquad (2)$$

$$\frac{\partial \tilde{P}_{sm}}{\partial z} = -\alpha_s\left(-1 + \frac{P_{sc} - 2n_c P_{sc}}{\omega_c - i\Omega\tau} + 2n_c\right)\tilde{P}_{sm} \qquad (3)$$

Where α_s and α_p are the absorbtion coefficients on the fiber for the signal and pump respectively. ω is the central CPO frequency, defined by $\omega_c = 1 + P_{sc} + P_p$, and τ is the decay time for the metastable level.

From the real and imaginary parts of the propagation-dependent integration constant in the equation for the pulse spectrum,we obtain two equations, one for the pulse shape and the other for the complex phase. If we consider pulse spectrum as $\tilde{P}_{sa}(\Omega) = |\tilde{P}_{sa}| \exp(-i\varphi)$, the equation for the phase will be:

$$\frac{\partial \varphi}{\partial z} = \alpha_s \left(\frac{P_{sc} - 2n_c P_{sc}}{\omega_c^2 + (\Omega\tau)^2} \right) \Omega\tau; \tag{4}$$

4. Experimental results and discussion

Pump effect: In Fig. 1 (left), fractional delay is plotted against the input pulse spectrum width. We use a constant signal background of $P_s = 3.57$ mW and different pump powers. Due to the great absorption of the fiber, a minimum pump is needed in order to observe a outgoing signal. A maximum fractional delay of $F = -0,26$ is observed for a spectral width of 186 Hz. For low pump powers, only delay is observed. But for a pump power high enough (about 72 mW) we observe advancement for narrow pulses. Maximum advancement is obtained for higher pump powers.

Signal effect: In Fig. 1 (right) fractional delay is plotted against the input pulse spectrum width, for a constant pump of 102.87 mW and different signal backgrounds. We observe that transition is only possible for low signals

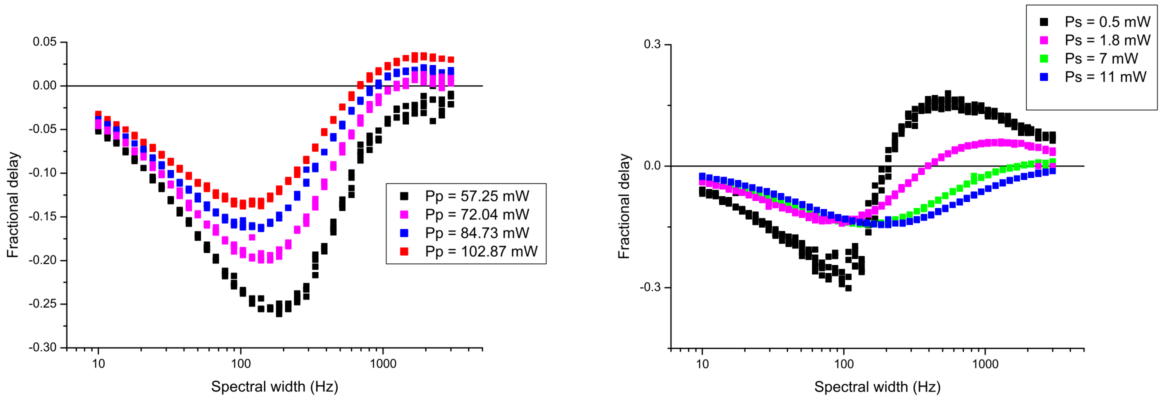

Fig. 1. (left) Fractional advancement dependence with spectral width for different pump (left) and signal powers (right). Pulse peak - background ratio was 20 %.

These results are consequence of a competition between absorbtion and amplification processes in the fiber. Thus, we postulate that the combination of an amplification stage followed by an absorption stage (without the needing of propagation), with an appropriate selection of the background and pump powers, can be a good device for separating different pulses depending on their width. The combination of both processes can lead to configurations where some of the frequencies are delayed and some are advanced, resulting in an advanced or delayed pulse depending on the width. Next step in the development of this device for our group will be the consideration of absorbtion and amplification dependence of slow and fast light in semiconductors.

We have also studied how pulses are broadened in the different propagation regimes. In Fig. 2 we have plotted the reference Gaussian pulse and the corresponding delayed pulse after propagating through the fiber, for different widths. They correspond to the pink points in Fig. 1 (right) ($Ps = 1.8$ mW, $Pp = 102.87$ mW), a case where both superluminal and subluminal behaviors are observed. Fig. 2 (left) shows a pulse of spectral width of 100 Hz, where a fractional delay of -0,14 was observed. We can see the characteristics of a delayed pulse shape, a high pulse broadening. Fig. 2 (center), shows a pulse of spectral width of 395 Hz, where fractional delay is nearly 0. Fig. 2 (right) corresponds to an advanced pulse

Using the half-width at half maximum (HWHM), we obtain that the ratio between the fiber pulse and the reference pulse increases with spectral with until the transition to superluminal, when it decreases.

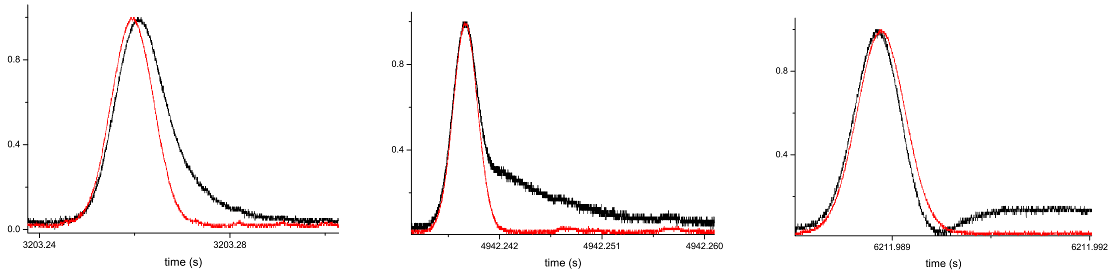

Fig. 2. (left) Normalized EDF Pulse shapes (black) and reference pulse (red) for a delayed pulse (left), a pulse in the transition between subluminal and superluminal (center) and an advanced pulse (right).

Using the variance of the distribution, we obtain that the pulse is always broadened in both propagation regimes.

This work has been supported by Projects no. PR34/07-15847 (UCM/BSCH), CCG07-UCM/ESP-2179 (UCM-CM), CCG08-UCM/ESP-4220 and FIS2007-65382 (MEC) from Spain.

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