Slow and fast light based on coherent population oscillations in erbium-doped fibres

2010 J. Opt. 12 104002

(http://iopscience.iop.org/2040-8986/12/10/104002)

IOP Publishing — Journal of Optics

J. Opt. **12** (2010) 104002 (6pp) doi:10.1088/2040-8978/12/10/104002

REVIEW ARTICLE

Slow and fast light based on coherent population oscillations in erbium-doped fibres

Francisco Arrieta-Yáñez, Oscar G Calderón and Sonia Melle

Escuela Universitaria de Óptica, Universidad Complutense de Madrid, Arcos de Jalón 118, E-28037 Madrid, Spain

E-mail: franarrieta@fis.ucm.es

Received 17 March 2010, accepted for publication 21 June 2010
Published 24 September 2010
Online at stacks.iop.org/JOpt/12/104002

Abstract
In this paper we review the main results on slow and fast light induced by coherent population oscillations in optical fibres doped with erbium ions. We explain the physics behind this technique and we describe the experimental realization. Finally, we summarize some recent advances in this field and future goals.

Keywords: slow light, coherent population oscillations, erbium-doped fibres

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The control of light velocity has been a constant challenge during the last few decades. A range of techniques developed in the past decade have made possible to reduce the group velocity of a wavepacket to a few metres per second, and to obtain group velocities greater than c, or even negative, in a controllable way. These techniques include electromagnetic-induced transparency (EIT) [1, 2], based on quantum interference effects in atomic media, and, more recently, techniques that can be realized in solid-state materials at room temperature, such as, for example, stimulated Brillouin scattering (SBS) [3, 4], stimulated Raman scattering (SRS) [5], wavelength conversion and dispersion [6], and coherent population oscillations (CPO) [7, 8]. This last technique has revealed itself as a promising method for slow and fast light. It has been developed in a variety of materials such as solid-state crystals [7, 8], semiconductor structures [9, 10], biological thin films [11] and erbium-doped fibres (EDFs) [12, 13]. In particular, slow and fast light in optical fibres offers a lot of advantages such as long interaction lengths and easy integration with existing optical communication systems [14]. In this review we will focus on the slow and fast light phenomena induced by coherent population oscillations in erbium-doped fibres. We will describe the physics behind this technique and the pioneering works. Finally, we will review some of the latest results achieved in this field.

2. Slow and fast light via CPO: physical processes and pioneering works

2.1. Physical principles

Coherent population oscillations is a technique for slowing down light signals in saturable absorbers. The medium is illuminated by a strong beam (pump beam), resonant with an allowed transition of the material, and a weak beam (probe beam), slightly detuned with the same transition. If the detuning is smaller than the decay rate of the transition (the inverse of the transition lifetime), the interference of the two beams causes an oscillation of the ground-state population of the saturable absorber at the beat frequency. The coupling between the strong beam and the oscillation of the population results in a reduction of the absorption of the probe beam. In other words, the population oscillation generates a temporal modulation of the transmission (a temporal transmission grating) which oscillates at the detuning frequency. The

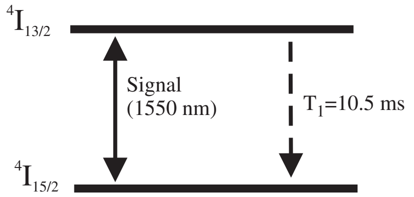

Figure 1. Ground and metastable energy levels of Er^{3+} coupled by a 1550 nm laser beam.

interaction of the pump beam with this temporal grating results in an amplification of the probe beam through a wave mixing process. This can be seen as a narrow 'hole' in the absorption spectrum, that leads, through the Kramers–Kronig relations, to a rapid index variation around the resonant frequency. If the frequency of the probe beam fits in the spectral hole, the probe beam will propagate subluminally along the material.

This process has been described by using the density matrix formalism [15]. Furthermore, when the population inversion decay time T_1 is much longer than the dipole dephasing time T_2, as occurs in most of the studied systems, this process can also be modelled by using a rate equation analysis [16, 17]. This approximation was followed by Schweinsberg *et al* to model CPO in EDFs [12].

Er^{+3} ions can be modelled as two-level systems (see figure 1) when illuminated with a 1550 nm laser beam. The evolution of the metastable level population N_2 (normalized to the total Er^{+3} ion density) driven by a resonant signal of power P_s can be written as

$$\frac{\partial N_2}{\partial t} = -\frac{N_2}{T_1} - \frac{1}{2T_1}\frac{P_s}{P_{sat}}N_2 + \frac{1}{2T_1}\frac{P_s}{P_{sat}}N_1, \qquad (1)$$

where the three terms on the right-hand side of the equation stand for the spontaneous emission, the stimulated emission and the absorption of the signal, respectively. N_1 is the ground-state population and P_{sat} is the saturation power. By defining the dimensionless power $\hat{P}_s = P_s/P_{sat}$, and considering that only ground and metastable levels are involved ($N_1 + N_2 = 1$), the above rate equation is

$$\frac{\partial N_2}{\partial t} = \frac{1}{2T_1}\hat{P}_s - \frac{1}{T_1}(1 + \hat{P}_s)N_2. \qquad (2)$$

The absorption of the signal power along the fibre can be described by the following propagation equation:

$$\frac{\partial \hat{P}_s}{\partial z} = -\alpha_0(N_1 - N_2)\hat{P}_s, \qquad (3)$$

where the absorption coefficient depends on the population difference between the two levels, α_0 being the unsaturated absorption coefficient at 1550 nm. As said before, the signal beam consists of a strong pump field and a weak probe field with a frequency slightly detuned from the pump frequency, δ being the beat frequency. Interference of the pump and probe beams produces an amplitude modulation of the signal, which can be written in terms of the power as $\hat{P}_s(t) = P_{sc} + P_{sm}e^{-i\delta t} +$ c.c. P_{sc} is a constant background, which roughly measures the pump power, and $P_{sm}e^{-i\delta t}$ is the interference term, where P_{sm} stands for the amplitude of the modulation. This interference induces a modulation in the metastable level population at the beat frequency δ. Taking into account that $P_{sm} \ll P_{sc}$, and equating terms with the same time dependence in the power propagation equation, we observe that P_{sc} and P_{sm} propagate with different absorption coefficients:

$$\frac{\partial P_{sc}}{\partial z} = -\frac{\alpha_0}{1 + P_{sc}}P_{sc}, \qquad (4)$$

$$\frac{\partial P_{sm}}{\partial z} = -\alpha_1 P_{sm}, \qquad (5)$$

where α_1 is complex, due to the characteristic response time of the population ($\sim T_1$):

$$\alpha_1' \equiv \mathrm{Re}(\alpha_1) = \frac{\alpha_0}{1 + P_{sc}}\left[1 - \frac{P_{sc}(1 + P_{sc})}{(1 + P_{sc})^2 + (T_1\delta)^2}\right], \qquad (6)$$

$$\alpha_1'' \equiv \mathrm{Im}(\alpha_1) = -\frac{\alpha_0}{1 + P_{sc}}\,\frac{P_{sc}(T_1\delta)}{(1 + P_{sc})^2 + (T_1\delta)^2}. \qquad (7)$$

The real part of α_1 (see equation (6)) stands for the absorption that P_{sm} experiences and the imaginary part of α_1 (see equation (7)) is a spatial phase variation. Assuming that P_{sc} does not vary significantly along the propagation length, i.e. following the so-called undepleted approximation, we can analytically obtain

$$P_{sm}(z) = P_{sm}(0)e^{-\alpha_1' z}e^{-i\alpha_1'' z}. \qquad (8)$$

Thus, the absorption spectrum, given by α_1', shows the CPO hole, as can be seen in figure 2(a). The half-width at half-maximum of this hole is given by $\Gamma \equiv (1 + P_{sc})/T_1$. This width scales with the inverse of the decay time of the metastable level population and it is power-broadened, as can be seen in figure 2(a). The phase shift accumulated by P_{sm} when propagating through the medium, $\alpha_1'' z$, gives the delay time experienced by the modulated part of the beam, $t_d \approx \alpha_1'' z/\delta$. Note that the achieved delay increases with fibre length. However, at long interaction lengths, attenuation of the signals could be relevant due to the residual absorption at the CPO hole (see figure 2(a)). This attenuation can be reduced by means of an additional pump that populates upper levels (such as a 980 nm beam in EDFs). For strong pumps, the CPO induces a dip in the gain spectrum, leading to anomalous dispersion and fast light (group velocity greater than c or even negative).

2.2. *First experiments via CPO*

The most common experimental realization is made with an intensity-modulated pump beam, either sinusoidally or with pulses, so that pump beam and probe beam are not separated beams. The intensity modulation creates frequency sidebands that act as the probe. If modulation frequency and $1/T_1$ have the same order of magnitude, population oscillations will be appreciable and the modulated part of the signal, P_{sm}, will experience delay. In CPO experiments, the goals are to optimize simultaneously the time delay and the bandwidth of the signal to be slowed down [14], and to have an accurate

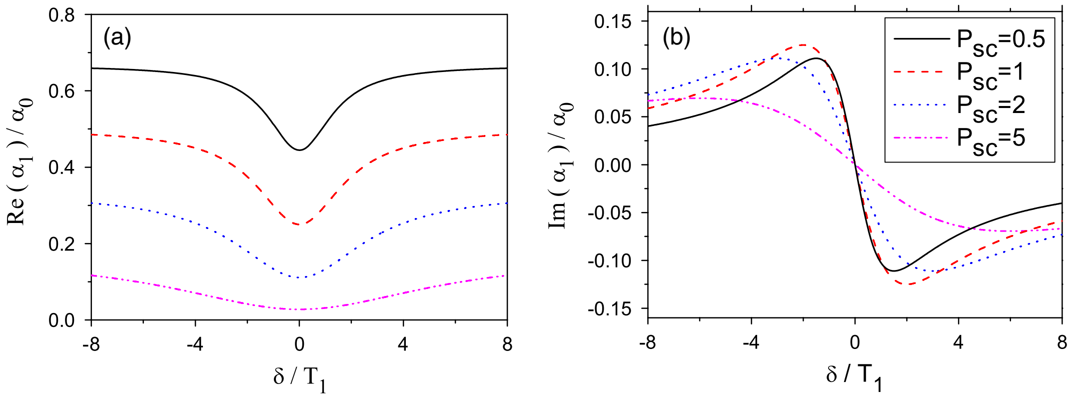

Figure 2. CPO hole (a) and associated index dispersion (b) for different signal powers, given in terms of the saturation power.

control of this delay. The most used measurement unit to characterize the optical buffering of a slow light system is the 'fractional delay', defined as $F \equiv t_d/\tau_{in}$, where t_d is the time delay and τ_{in} is a measurement of the signal characteristic time, that is, the inverse of the modulation frequency for sinusoidally modulated beams, and the full width at half-maximum (FWHM) for pulses.

The first experimental observation of CPO-based slow light was performed by Bigelow *et al* [7] in a 7.25 cm long ruby rod at room temperature. They reported a reduction of group velocity down to 57.5 m s^{-1} by producing a hole as narrow as 36 Hz (HWHM) in the absorption spectrum. They showed that signal power induces broadening of the CPO hole, so that the group velocity can be controlled by changing the input power. A later experiment by the same group [8] achieved slow and fast light with group velocities of 91 and −800 m s^{-1} by using an alexandrite crystal, a material that acts as an inverse saturable absorber for certain wavelengths. They also analysed the propagation of smooth and discontinuous pulses through the above-mentioned materials (ruby and alexandrite) [18]. They found that a discontinuous jump within a pulse propagates at velocities less than or equal to c, whereas the smooth portion of the pulse propagates at the group velocity.

3. Slow and fast light experiments in EDFs

Slow and fast light experiments in optical fibres doped with Er^{3+} ions come motivated by the extended use of EDFs in telecommunications for amplifying a 1550 nm signal by means of a pump beam, usually at 980 nm. EDFs allow propagation of light through long distances, enhancing the interaction length of light with the slow light medium. Apart from optimizing the fractional delay and the available bandwidth, the search for control parameters for group velocity and pulse distortion, and knob parameters that switch the propagation regime from subluminal to superluminal, are recent investigation topics. We summarize here the main results.

The first observation of slow and fast light due to CPO in EDFs was made by Schweinsberg *et al* [12]. They propagated a 1550 nm intensity-modulated beam in a 13 m long fibre, with a counter-propagating 980 nm pump. They measured delays for

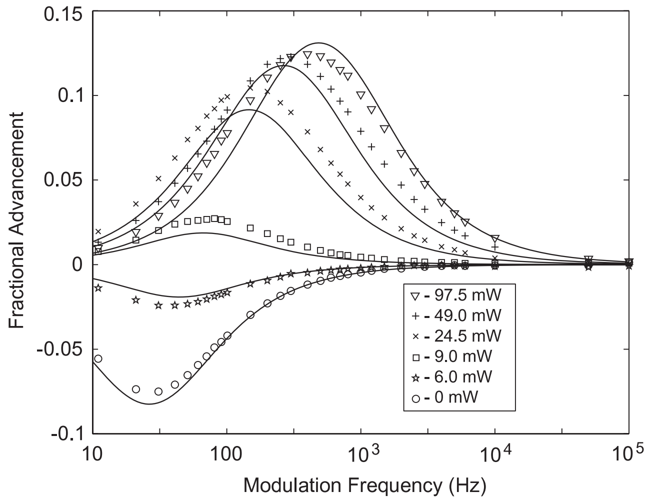

Figure 3. Fractional advancement versus the modulation frequency for different pump powers. A change from subluminal propagation (negative advancement) to superluminal propagation (positive advancement) as the pump power increases is shown. The signal input is a 1550 nm sinusoidally modulated beam with an average power of 0.8 mW and a modulation amplitude of $P_{sm}/P_{sc} = 0.08$. (Reprinted with permission from [12]. Copyright 2006 EDP Sciences.)

sinusoidally modulated signals as well as for Gaussian pulses, looking for the variation of the delay with the pump power and with the modulation frequency or the pulse width. They observed advancement for high enough pump powers (gain regime). Figure 3 shows the most significant results reported in this work. A maximum fractional delay of −0.089 and a maximum fractional advance of 0.124 were obtained. Fast light and 'backwards propagation' (negative group velocities) was analysed in detail by Gehring *et al* in a 9 m long EDF amplifier (EDFA) [13]. They followed the backward movement of a pulse peak inside the EDFA by placing different sensors along the fibre length. Backwards propagation occurs because of reshaping of the pulse profile within the gain medium. Later, Zhang *et al* [19] observed that the maximum fractional delay is achieved when the input signal power reaches the saturation power. Furthermore, they measured the width of the CPO hole to confirm that it is power-broadened. The same group studied the dependence of the delay on the fibre temperature, obtaining

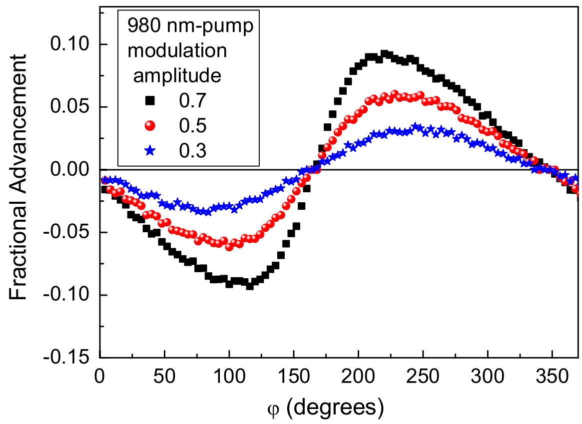

Figure 4. Fractional advancements as a function of the relative phase between pump and signal modulations. The normalized signal power is set to $P_{sc} = 0.24$, the normalized pump power to $P_{pc} = 4.3$ and signal modulation amplitude to $P_{sm}/P_{sc} = 0.5$, for a fixed modulation frequency value of $\delta/2\pi = 20$ Hz [22].

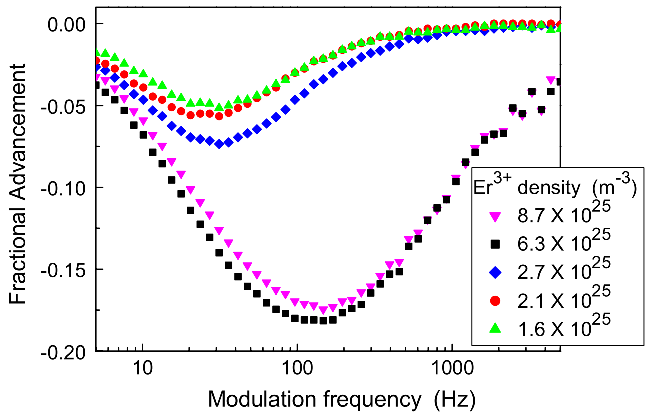

Figure 5. Fractional delay as a function of the modulation frequency for 1 m long fibres with different doping levels [25]. The input signal is a 1550 nm sinusoidally modulated beam with an average power of 0.6 mW and a modulation amplitude of 50%. Ultra-highly-doped fibres show larger bandwidths with higher fractional delays.

the maximum delay at room temperature [20]. The bending loss of the EDF has been used to improve the fast light [21]. This result relies on the control of signal gain by means of bending loss.

Arrieta-Yáñez *et al* have recently developed a novel mechanism for enhancing the fractional delay and advancement of sinusoidally modulated signals by one order of magnitude [22]. They forced the population oscillations by modulating with the same frequency and simultaneously the 980 nm pump beam and the 1550 nm signal beam. They showed that population oscillations are amplified by the pump modulation. Relative phase between both modulations was used as a knob for changing the propagation regime from ultraslow velocities to fast or negative velocities, as can be appreciated in figure 4. The same idea was used by Stepanov *et al* [23] to control the propagation regime of a 1526 nm signal beam by simultaneously modulating this beam and another beam with a different carrier frequency (1568 nm), both within the fundamental absorption spectrum. Numerical calculations have recently shown that the modulation of the 1550 nm signal beam depletes the metastable level population, inducing a modulation on the pump beam [24]. This effect is known as temporal pump depletion (TPD). In a similar way, when the 980 nm pump beam is externally modulated, as in [22], an induced modulation in the 1550 nm signal beam should be expected. In fact, this induced modulation may be responsible for the delay enhancement achieved in [22].

3.1. The effect of high doping levels

Many applications require a minimization of fibre length without a reduction of the achievable fractional delay [14]. A possible way to achieve similar delays with shorter fibre lengths is the use of fibres with a high ion doping level. In long and highly-doped fibres, a strong absorption takes place and the undepleted approximation is no longer valid. This high absorption of the signal and pump beams leads to significant new results in the slow light field. The effect of the doping level of Er^{3+} ions on subluminal and superluminal propagation was studied by Melle *et al* [25]. They used ultra-highly-doped erbium fibres (HEDFs) with ion concentration above 6.3×10^{25} m^{-3} (35 times higher than the concentration of the fibre used by Schweinsberg *et al* [12]). Fractional delays up to −0.7 were observed in a 1 m long HEDF, almost six times greater than the delays reported in [12], where they used a 13 m long fibre. In this work the ion concentration was found to increase the fractional delay and the bandwidth of the delayed signals, at the expense of increasing the absorption (see figure 5). The increase of the delay with ion density confirms the dependence of the delay with the unsaturated absorption coefficient, α_0, proportional to the ion density. Similar results were observed by Zhang *et al* [26, 20].

Furthermore, Melle *et al* observed a transition from subluminal to superluminal light propagation solely increasing the modulation frequency in a 980-pumped HEDF for a fixed pump power [27, 28]. This was interpreted as a combined effect of the spectral hole broadening with pump power and the strong variation of the gain along the fibre length. Due to the strong depletion of the pump beam along the fibre, the intensity-modulated signal changes from being amplified to being absorbed when propagating through it. Then, when a high-frequency signal propagates along the fibre, in the first region of the fibre (where gain is dominant) this signal will undergo strong advancement. As long as it continues travelling through the fibre, attenuation will become dominant so that this high-frequency signal will be slightly delayed in the last part of the fibre. Both contributions will produce a net advancement of the signal at the output of the fibre. Following a similar line of reasoning, low-frequency signals will experience a net delay. These results seem to indicate that the input pulse width could be used as a switching parameter between subluminal and superluminal propagation.

It is well known that HEDFs usually show gain degradation due to upconversion processes via interparticle interactions. Inhomogeneous upconversion or pair-induced quenching (PIQ) is the dominant upconversion process in

HEDFs [29–32]. In this process, one initially excited (energy level $^4I_{13/2}$) erbium ion (donor) donates its energy to the neighbour excited erbium ion (acceptor), producing one upconverted ion and one ground-state ion (energy level $^4I_{15/2}$). The upconverted ion then relaxes rapidly to the initial excited state $^4I_{13/2}$. As a result of this interaction, one excited ion is lost. Calderón *et al* investigated experimentally and theoretically the effect of ion pairs on fast light bandwidth and advancement [33]. They followed the model developed by Li *et al* [32] to explain the effect of ion pairs on the output performance of EDF lasers. They found that an increase of ion doping increases the fractional advancement obtained. However, the presence of erbium ion pairs in HEDFs degrades the bandwidth of the modulated signals that propagates at superluminal velocities.

The role of the pump configuration on the superluminal propagation of intensity-modulated signals through HEDFs has been carried out by Ezquerro *et al* [34]. It is well known that the pumping scheme in an EDFA is an important factor in determining its performance (gain and noise figure). Therefore, as the signal gain changes with the pumping scheme, the advancement of the modulated signal depends on the pumping configuration. They obtained that bidirectional pumping presents larger advancements than co-propagating and counter-propagating configurations. This phenomenon was explained in terms of the gain profile uniformity.

3.2. *Distortion management*

When propagating through an EDF, a light pulse suffers broadening due to gain saturation [35]. Furthermore, in fast light experiments based on CPO, pulses experience anomalous dispersion due to the narrow dip induced in the gain profile. Thus, the spectral wings of the pulse experience more amplification than the central part of the pulse, resulting in pulse compression in the time domain [36]. The pulse distortion in these experiments corresponds to the joint action of these phenomena. Shin *et al* showed that compression and broadening can be balanced to obtain a minimum distortion in fast light propagation by modifying the pulse peak/background ratio [37]. Recently, the same authors have proposed that background and pulse fields can be mutually incoherent, and thus pulse and background powers can be controlled independently to minimize distortion without decreasing significantly the fractional advancement [38]. In figure 6, the distortion and the delay are depicted versus the background to pulse power ratio. The delay does not vary significantly, while distortion has a clear minimum when the background to pulse power ratio is close to one. The results with coherent pulse and background, and mutually incoherent pulse and background, are identical.

The effect of temperature on pulse width distortion has been analysed by Qiu *et al* [20]. They proposed the temperature as a control parameter to reduce distortion.

4. Conclusion and discussion

Erbium-doped fibres constitute a good workbench for slow and fast light, since their use is widely extended, they work in the telecommunications window and the experimental set-ups are easy to produce. Amplification in erbium-doped fibres is a well-studied topic, which leads to fast light propagation. By means of CPO in EDFs, delays up to −0.7 have been achieved to the moment. Fibre properties such as dopant concentration, fibre length or temperature, and signal properties such as power, pulse width or signal modulation frequency can be used to control the group velocity and the distortion of the delayed/advanced signals. The possibility to generate and control slow and fast light propagation at room temperature has several potential applications in telecommunications, interferometry, optical sensing or phased array radars [39].

One of the most promising applications of the slow and fast light techniques is their use in interferometry. Shi *et al* showed experimentally that the spectral sensitivity of an interferometer can be improved by placing a slow light medium within the interferometer [40, 41]. In particular, they showed that spectral sensitivity scales with the group index of the material within a wedged shear interferometer. Besides, superluminal light propagation can improve the spatial resolution of an interferometer, as shown by Shahriar *et al* in a ring-resonator-based optical gyroscope [42]. They achieved an enhancement factor of the sensitivity for measuring absolute rotation as high as 10^6. We believe that these examples can be performed in optical-fibre-based interferometers. Recently, Zhao *et al* [43] proposed a Fabry–Perot fibre sensing system where the sensing process can be controlled by changing the delay in a pumped EDF. Future applications of the above results of CPO in EDFs can go in this direction.

Besides the mentioned direct applications of CPO in optical fibres, most of the experiments developed in EDFs reviewed here can be applied to other CPO systems with faster response, such as semiconductor optical amplifiers (SOAs), in view of signal processing applications. For example, the method that provided a way to change the propagation regime and enhance the fractional delay of signals propagating through an EDF by one order of magnitude [22] has been theoretically extended to commercial SOAs [44], allowing an available bandwidth of GHz (experiments are being carried out during the writing of this review [45]). On the other

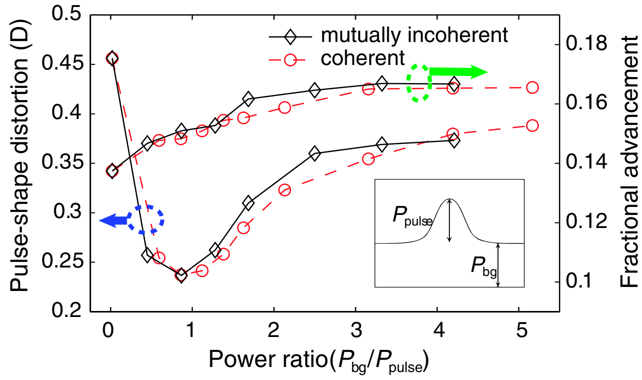

Figure 6. Pulse distortion and delay in a CPO experiment in EDFs measured versus power ratio. (Reprinted with permission from [38]. Copyright 2009 Elsevier.)

hand, CPO cascade systems constitute a well-studied topic in semiconductor optical amplifiers and absorbers [46, 47]. These systems combine stages of absorption and gain, and they are used to control the delay with high tuning speed. These configurations can be studied in EDFs in the future [14].

Acknowledgments

This work has been supported by the project MEC-FIS2007-65382, BSCH-UCM-GR58/08 and FIS2010-22082. FA-Y would like to thank the financial support from the Consejería de Educación de la Comunidad de Madrid and the European Social Fund. We would like to thank M A Antón, F Carreño, J M Ezquerro and E Cabrera-Granado for fruitful discussions and scientific support.

References

[1] Harris S E 1997 *Phys. Today* **50** (7) 36–42
[2] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 *Nature* **397** 594
[3] Okawachi Y, Bigelow M S, Sharping J E, Zhu Z, Schweinsberg A, Gauthier D J, Boyd R W and Gaeta A L 2005 *Phys. Rev. Lett.* **94** 153902
[4] Song K Y, Herráez M G and Thévenaz L 2005 *Opt. Express* **13** 82–8
[5] Sharping J, Okawachi Y and Gaeta A L 2005 *Opt. Express* **13** 6092–8
[6] Sharping J, Okawachi Y, van Howe J, Xu C, Wang Y, Willner A and Gaeta A L 2005 *Opt. Express* **13** 7872–7
[7] Bigelow M S, Lepeshkin N N and Boyd R W 2003 *Phys. Rev. Lett.* **90** 113903
[8] Bigelow M S, Lepeshkin N N and Boyd R W 2003 *Science* **301** 200–2
[9] Su H, Kondratko P and Chuang S L 2006 *Opt. Express* **14** 4800–7
[10] Mørk J, Kjær R, van der Poel M and Yvind K 2005 *Opt. Express* **13** 8136–45
[11] Wu P and Rao D V G L N 2005 *Phys. Rev. Lett.* **95** 253601
[12] Schweinsberg A, Lepeshkin N N, Bigelow M S, Boyd R W and Jarabo S 2006 *Europhys. Lett.* **73** 218–24
[13] Gehring G M, Schweinsberg A, Barsi C, Kostinski N and Boyd R W 2006 *Science* **312** 895–7
[14] Boyd R W, Gauthier D J and Gaeta A L 2006 *Opt. Photon. News* **17** 18–23
[15] Schwarz S E and Tan T Y 1967 *Appl. Phys. Lett.* **10** 4
[16] Basov N G, Ambartsumyan R V, Zuev V S, Kryukov P G and Letokhov V S 1966 *Sov. Phys.—JETP* **23** 16–22
[17] Piredda G and Boyd R W 2007 *J. Eur. Opt. Soc. Rapid Commun.* **2** 07004
[18] Bigelow M S, Lepeshkin N N, Shin H and Boyd R W 2006 *J. Phys.: Condens. Matter* **18** 3117–26
[19] Zhang Y, Qiu W, Ye J, Wang N, Wang J, Tian H, Wang H and Yuan P 2007 *Phys. Lett.* A **372** 2724–9
[20] Qiu W, Zhang Y, Ye J, Wang N, Wang J and Yuan P 2008 *Appl. Opt.* **47** 1781–4
[21] Peng P, Kao W, Lin C, Chen J, Shih P T and Chi S 2008 *Proc. Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conf. OSA Technical Digest (CD)* Optical Society of America, paper JThA2
[22] Arrieta-Yáñez F, Melle S, Calderón O G, Antón M A and Carreño F 2009 *Phys. Rev.* A **80** 011804(R)
[23] Stepanov S and Hernandez E H 2008 *Opt. Lett.* **33** 2242–4
[24] Wen S and Chi S 2008 *J. Opt. Soc. Am.* B **25** 1073–80
[25] Melle S, Calderón O G, Carreño F, Cabrera E, Antón M A and Jarabo S 2007 *Opt. Commun.* **279** 53–63
[26] Zhang Y, Qiu W, Ye J, Wang N, Wang J, Tian H and Yuan P 2007 *Opt. Commm.* **281** 2633–7
[27] Melle S, Calderón O G, Caro C E, Cabrera-Granado E, Antón M A and Carreño F 2008 *Opt. Lett.* **33** 827–9
[28] Calderón O G, Melle S, Antón M A, Carreño F, Arrieta-Yáñez F and Cabrera-Granado E 2008 *Phys. Rev.* A **78** 053812
[29] Sanchez F, Boudec P L, Francois P-L and and Stephan G 1993 *Phys. Rev.* A **48** 2220–9
[30] Wagener J L, Wysocki P F, Digonnet M J F, Shaw H J and DiGiovanni D J 1993 *Opt. Lett.* **18** 2014–6
[31] Wysocki P F, Wagener J L, Digonnet M J F and Shaw H J 1993 *Proc. SPIE* **1789** 66–79
[32] Li J, Duan K, Wang Y, Zhao W, Zhu J, Guo Y and Lin X 2008 *J. Mod. Opt.* **55** 447–58
[33] Calderón O G, Melle S, Arrieta-Yáñez F, Antón M A and Carreño F 2008 *J. Opt. Soc. Am.* B **25** C55–60
[34] Ezquerro J M, Hernández G, Nombela M, Calderón O G and Melle S 2010 *J. Nonlinear Opt. Phys. Mater.* **19** 153–65
[35] Agrawal G P and Olsson N A 1989 *IEEE J. Quantum Electron.* **25** 2297–306
[36] Cao H, Dogariu A and Wang L J 2003 *IEEE J. Sel. Top. Quantum Electron.* **9** 52
[37] Shin H, Schweinsberg A, Gehring G, Schwertz K, Chang H J, Boyd R W, Park Q-H and Gauthier D J 2007 *Opt. Lett.* **32** 906–8
[38] Shin H, Schweinsberg A and Boyd R W 2009 *Opt. Commun.* **282** 2085–7
[39] Boyd R W 2009 *J. Mod. Opt.* **56** 1908–15
[40] Shi Z, Boyd R W, Gauthier D J and Dudley C C 2007 *Opt. Lett.* **32** 915–7
[41] Shi Z, Boyd R W, Camacho R M, Vudyasetu P K and Howell J C 2007 *Phys. Rev. Lett.* **99** 240801
[42] Shahriar M S, Pati G S, Tripathi R, Gopal V, Messall M and Salit K 2007 *Phys. Rev.* A **75** 053807
[43] Zhao Y, Zhao H-W, Zhang X-Y, Yuan B and Zhang S 2009 *Opt. Laser Technol.* **41** 517–25
[44] Antón M A, Carreño F, Calderón O G, Melle S and Arrieta-Yáñez F 2009 *J. Phys. B: At. Mol. Opt. Phys.* **42** 095403
[45] Berger P, Bourderionnet J, Alouini M, de Valicourt G, Brenot R, Bretenaker F and Dolfi D 2010 Experimental demonstration of enhanced slow and fast light by forced coherent population oscillations in an SOA, arXiv:1002.3927v1
[46] Maicas S S, Öhman F, Capmany J and Mørk J 2007 *IEEE Photon. Technol. Lett.* **19** 1589–91
[47] Sedgwick F G, Pesala B, Lin J, Ko W S, Zhao X and Chang-Hasnain C J 2007 *Opt. Express* **15** 747–53