EUROPHYSICS LETTERS 15 January 2006
Europhys. Lett., **73** (2), pp. 218–224 (2006)
DOI: 10.1209/epl/i2005-10371-0

Observation of superluminal and slow light propagation in erbium-doped optical fiber

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received 1 September 2005; accepted in final form 9 November 2005
published online 2 December 2005

PACS. 42.65.-k – Nonlinear optics.
PACS. 42.81.Dp – Propagation, scattering, and losses; solitons.

Abstract. – We observe both extremely slow and superluminal pulse propagation speeds at room temperature in an erbium-doped fiber (EDF). A signal at 1550 nm is sent through an erbium-doped fiber with varying powers of a 980 nm pump. The degree of signal delay or advancement is found to depend significantly on the pump intensity. We observe a maximum fractional advancement of 0.124 and a maximum fractional delay of 0.089. The effect is demonstrated both for a sinusoidally modulated signal and for Gaussian pulses. The ability to control the sign and magnitude of the pulse velocity could have important implications for applications in photonics.

There has recently been much interest in optical processes that can lead to unusually small or unusually large group velocities of propagation through material systems. Such situations can lead to many possible applications, such as the development of variable optical delay lines for use in telecommunication systems. As the expression for the group velocity of light is given by $v_g = c/(n + \omega\frac{\partial n}{\partial \omega})$, where n is the phase index, materials with highly dispersive regions can exhibit group velocities that are very low, very large, or even negative [1–3]. As regions of high dispersion are coupled to sharp absorption peaks according to the Kramers-Kronig relations, studies have focused on techniques that are capable of producing these features in the absorption spectrum. Electromagnetically induced transparency (EIT), a technique that creates a narrow transparency window for a probe pulse via the application of a strong pump field at a different frequency, has been shown to produce slow light in several material systems [4–7]. Additionally, by making use of the phenomenon of coherent population oscillations (CPO), researchers have produced slow or fast pulse propagation effects in ruby [8], alexandrite [9], and low-temperature semiconductor quantum wells [10].

Still another procedure for slowing the velocity of light is to make use of the rapid variation of refractive index that accompanies the gain associated with the processes of stimulated Brillouin scattering [11–13] and stimulated Raman scattering [14].

In the present work, we show that both slow and fast light propagation can occur in erbium-doped optical fiber, occurring through the process of coherent population oscillations. The widespread use of erbium-doped fiber amplifiers at the 1550 nm signal wavelength used in the telecommunications industry suggests that slow and fast light effects in this system could lead to important applications. The technique described here works at room temperature. Additionally, the fiber system has a very simple experimental setup and allows for the possibility of long interaction lengths and high intensities, both of which can lead to large time delays. Moreover, while pulses can be delayed without a separate pump field, the easy integration of a pump at 980 nm enables the propagation speed to be tuned continuously, leading to either significant delay or significant advancement for appropriate pulse widths. Previous workers had observed phase delays of modulated light fields in EDFA's [15–17]. The present research extends this work by showing that both delays and advancement are possible for either modulated or pulsed light fields. We also develop a theoretical model that describes our experimental results with high accuracy.

Coherent population oscillations occur when the ground state population of a saturable medium oscillates at the beat frequency between two applied optical fields. The oscillation creates a narrow hole in the absorption spectrum having a linewidth on the order of the inverse of the excited-state lifetime; this hole is susceptible to power broadening. The original theoretical prediction of spectral holes from CPO was made in 1967 by Schwartz and Tan [18], and was based upon an analysis of the density matrix equations of motion. Some additional insight may be gained by considering the problem in the time domain, where the slow light effect of a CPO hole can be seen as the saturation of the medium by the leading edge of the pulse, allowing the remainder to be transmitted with less attenuation. The resulting pulse in this case would be delayed, but reduced in overall intensity. Oppositely, a medium exhibiting saturable gain produces an advanced pulse. The ground state recovery time of the system is determined by the lifetime of the metastable state, which places a lower bound on the pulse duration for which anomalous propagation effects can be observed. This explanation of the effect was first used by Basov *et al.* in 1965 [19] and was explored in more theoretical detail by Selden in following years [20, 21].

We can model the propagation of intensity-modulated 1550 nm light through an erbium-doped fiber in the presence of a 980 nm pump using a rate equation analysis [16]. The energy levels in erbium can be approximated as a three-level system, and under the additional approximation of rapid decay from the upper pumping state to the metastable state, we obtain the rate equation for the ground state population density n:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\rho - n}{\tau} + \left(1 - \frac{n}{\rho}\right)\beta_s I_s - \frac{n}{\rho}\,\alpha_s I_s - \frac{n}{\rho}\,\alpha_p I_p, \tag{1}$$

where ρ is the Er^{3+} ion density, τ is the metastable level lifetime (10.5 ms), I_p is the pump intensity in units of photons/area/time, I_s is the signal intensity, β_s is the signal emission coefficient, and α_p and α_s are the pump and signal absorption coefficients. We solve this equation for n, since the absorption is proportional to the ground state population density. First, we note that the steady-state solution to eq. (1) is given by $n_0 = (\rho/\tau + \beta_s I_s)/\omega_c$, where we have defined the "CPO center frequency" as

$$\omega_c = \frac{1}{\tau} + \frac{\alpha_p I_p}{\rho} + \frac{(\alpha_s + \beta_s) I_s}{\rho}. \tag{2}$$

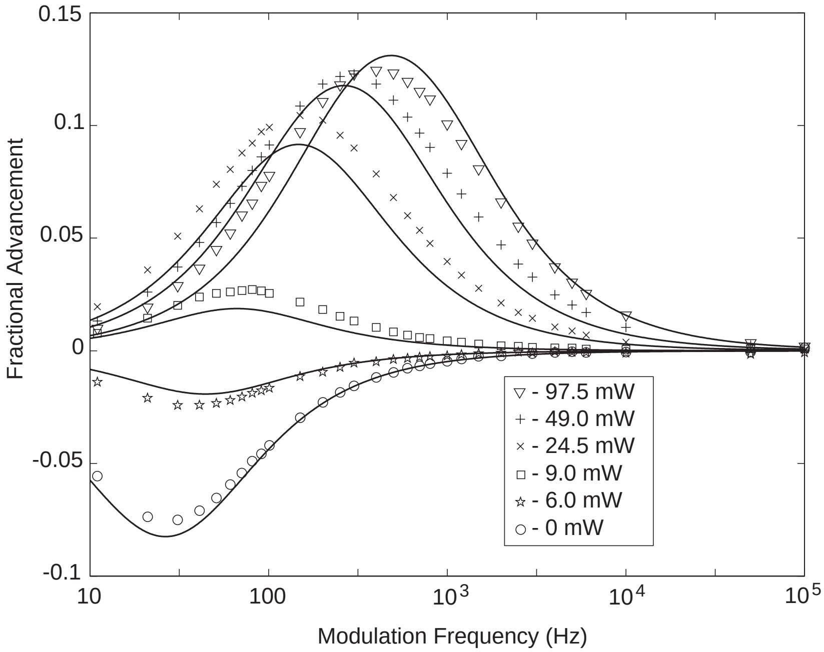

Fig. 1 – Frequency and pump power dependence of the fractional delay observed in propagation through erbium-doped fiber. The input was sinusoidally modulated beam at 1550 nm with an average power of 0.8 mW. Results of the numerical model are shown as solid lines along with the experimental data points. The different curves represent different pump powers. In all cases, the ratio $I_m/I_0 = 0.08$.

We will see that this frequency determines the width of the spectral hole. Its width is the inverse of the metastable-state lifetime, with additional terms that allow for power broadening by the pump and signal fields. Because a single intensity-modulated beam can be expressed in the frequency domain as a field with two sidebands separated by the modulation frequency, it can provide the input fields for CPO. If we modulate the signal intensity as $I_s = I_0 + I_m \cos(\Delta t)$, we find that the ground state population density oscillates as $n(t) = n_0 + \delta n(t)$, where

$$\delta n(t) = \left(\frac{\omega_c \cos(\Delta t) + \Delta \sin(\Delta t)}{\omega_c^2 + \Delta^2}\right) I_m g \tag{3}$$

and we have additionally defined the gain coefficient as

$$g = -\frac{n_0}{\rho}(\alpha_s + \beta_s) + \beta_s. \tag{4}$$

We then find that, neglecting second-order terms in the modulated signal, the propagation equation can be written as

$$\frac{\mathrm{d}I_m}{\mathrm{d}z} = gI_m - \alpha_1(I_m, I_p, I_0)I_0, \tag{5}$$

where

$$\alpha_1(I_m, I_p, I_0) = \left(\frac{\alpha_s + \beta_s}{\rho}\right)\left(\frac{\omega_c}{\omega_c^2 + \Delta^2}\right) I_m g. \tag{6}$$

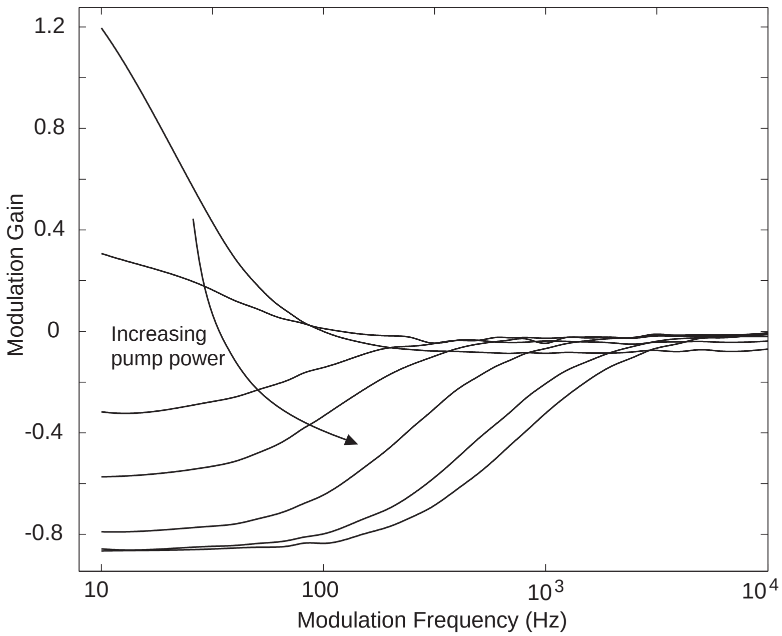

Fig. 2 – Modulation gain, $\ln\left[\frac{(I_m/I_0)_{out}}{(I_m/I_0)_{in}}\right]$, showing the holes in the absorption and gain spectra, plotted for the same traces as in fig. 1. From largest to smallest low-frequency gain, the curves represent pump powers of 0, 6.0, 9.0, 24.5, 49.0, and 97.5 mW.

The phase shift of the modulation is described by

$$\frac{\mathrm{d}\phi}{\mathrm{d}z} = \frac{I_0}{I_m}\alpha_2(I_m, I_p, I_0), \tag{7}$$

where

$$\alpha_2(I_m, I_p, I_0) = \left(\frac{\alpha_s + \beta_s}{\rho}\right)\left(\frac{\Delta}{\omega_c^2 + \Delta^2}\right) I_m g. \tag{8}$$

Here we notice that the modulation absorption coefficient α_1 is taken from the cosinusoidal part of δn, while the phase shift α_2 comes from the sinusoidal part, which is out of phase with the original signal modulation. We also notice that the signs of both α_1 and α_2 are fixed by the sign of the gain coefficient g, which itself is determined by the balance between the net gain and absorption experienced by the signal. Furthermore, from the expression for α_2, we can see that the peak of the phase shift will occur when $\Delta = \omega_c$. In this simplified approach, we have neglected the effect that the time-dependent part of the signal field will have on the pump field, including only the spatial modulation due to I_0.

The experimental setup used to observe this effect consists essentially of an erbium-doped fiber amplifier in the reverse-pumped configuration. The signal source is a tunable diode laser, operating at 1550 nm. The beam is coupled into a fiber and sent through 13 m of EDF which is pumped by a counter-propagating beam from a 980 nm diode laser. Two percent of the input light is split off before the EDF for use as a reference. For experiments using a sinusoidally modulated input, the current of the laser is modulated directly by a function generator. To create Gaussian pulses, the beam was passed through a rotating wheel with a narrow slit,

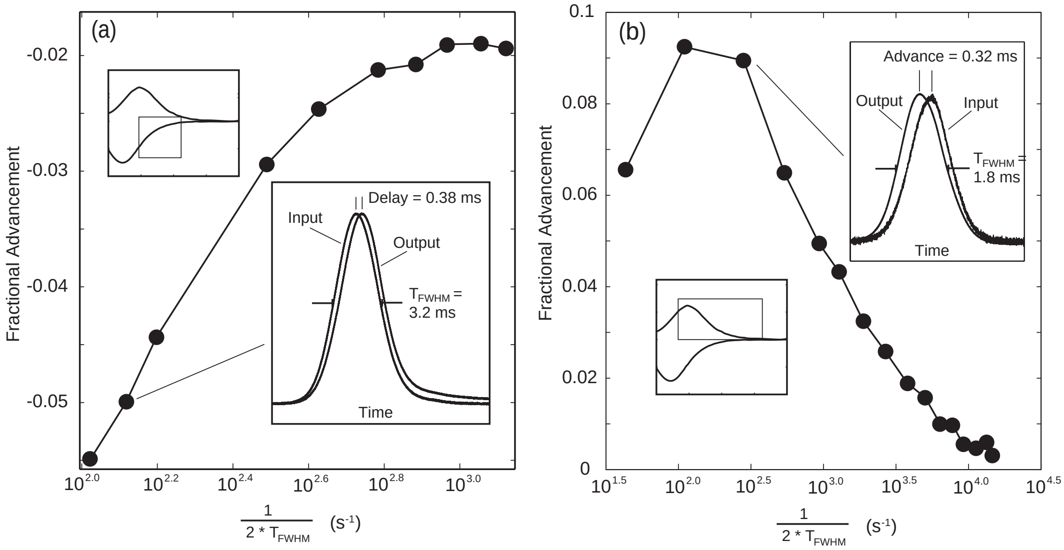

Fig. 3 – Fractional advancement *vs.* the log of the inverse pulse width in the regimes of slow light (a) and superluminal propagation (b). The x-axis is the log of the inverse of the pulse width, so that the width data may be easily compared to modulation frequency data, as shown in the inset. Other insets show sample time traces of the pulses. For the slow light case, the peak input power was 0.8 mW and there was no pump. Power transmission was about 0.1%. For the fast light data, the pump power was 12 mW and the signal power was weak enough to make negligible its contributions to hole broadening and pulse delay. In this case, the signal experienced a total gain factor of 5. Fractional advancement/delay was calculated with respect to twice the FWHM.

before being coupled into the single-mode fiber. This process converts a continuous beam with a Gaussian spatial profile into a series of pulses with Gaussian time profiles. In each experiment, we subtracted from the raw data a trace taken with 13 m of undoped silica fiber replacing the EDF, to compensate for any inherent response difference between the InGaAs photodiodes used to detect the signal and reference fields.

A series of experiments showing the fractional delay or advancement of a modulated input field is shown in fig. 1. Traces are plotted against the log of the modulation frequency and are taken with varying pump powers, with slow light being recorded with little or no pump and superluminal propagation being demonstrated for higher pump powers. Anomalous propagation speeds are observed over roughly 1.5 decades of bandwidth, with the peak of the effect being pushed to higher frequencies with increasing pump power. However, the effect appears to saturate, with a doubling of pump power from 49 mW to 97.5 mW producing only a modest increase in peak frequency, and we do not observe large modulation advancements above 10 kHz for any value of pump power. Notably, for a given frequency, increasing the pump power can significantly increase the fractional advancement. For example, at 31 Hz a signal with a fractional delay of 0.08 unpumped will have a fractional advancement of 0.04 with 20 mW of 980 nm pump, and can be tuned continuously by varying the pump power in this range. The largest fractional advancement recorded was 0.125 at a pump power of 97.5 mW, while the largest fractional delay shown is 0.075 and is obtained with no pump. By increasing the signal power from 0.8 mW to 1.2 mW, the fractional delay can be increased to 0.089 demonstrating the signal power dependence predicted theoretically.

Theoretical curves are produced through numerical solution of the propagation equations (5)-(8) and show good agreement with the experimental data. The effective absorption and emission coefficients and the erbium ion density are found by a fit to the fractional advancement data. Parameters used for the calculation are $\alpha_p = 0.11\,\mathrm{m}^{-1}$, $\alpha_s = 0.54\,\mathrm{m}^{-1}$, $\beta_s = 1.00\,\mathrm{m}^{-1}$, $\rho = 1.78 \times 10^{24}\,\mathrm{m}^{-3}$, $\tau = 10.5\,\mathrm{ms}$, mode field diameter $= 2.75\,\mu\mathrm{m}$. By examining the gain or loss on the modulated signal, we can directly observe the hole in the absorption or gain spectra due to CPO. Figure 2 shows the relative modulation attenuation plotted against the log of the modulation frequency for different pump powers. Interestingly, the modulation experiences relative gain over the DC signal for low pump powers, when the EDF is acting as a saturable absorber, and relative loss at higher pump powers, when the medium behaves as an amplifier.

In accordance with what would be expected from the modulation data, we observe that Gaussian pulses propagate through an EDF with an effective velocity that is either slow or superluminal depending on the pump power. Figure 3 shows plots of fractional advancement as a function of pulse width. In one case, the EDF was pumped at 12 mW, and in the other, the pump was turned off. Insets show sample time traces of the advanced and delayed pulses (with normalized intensity) and windows indicating the corresponding domains of the modulation data for comparison with fig. 1. For the unpumped case, the maximum fractional delay recorded was 0.055, corresponding to an effective pulse velocity of $c/(1.2 \times 10^4)$. The largest fractional advancement observed was 0.092, or a pulse velocity of $c/(-5600)$. For pulses slightly shorter than the inverse of the CPO hole bandwidth, we notice significant distortion in the transmitted pulse envelope.

In our work we have observed only relatively small fractional advancements and delays. Even these small timing changes could be useful for certain technological applications, such as centering a data pulse into a time window, an important step in the process known as data stream regeneration. For certain other applications, larger fractional delays or advancements are desirable. The delays and advancements that we observed are limited primarily by pump depletion effects. Greater delays and advancements could be obtained by pumping the erbium-doped fiber from both ends or by cascading several fiber stages.

In summary, we have demonstrated slow and superluminal light propagation speeds in an erbium-doped fiber, the effect being tunable from one regime to the other by varying the pump power. We were able to achieve significant fractional delays and advancements for pulses at the technologically important wavelength of 1550 nm. Our technique exploits the phenomenon of coherent population oscillations, which allow for the delay or advancement of a pulse by burning a narrow spectral hole in an optically saturable medium.

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This work was supported by NSF grant ECS-0355206 and by DARPA/DSO.

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