Modulation-frequency-controlled change from sub- to superluminal regime in highly doped erbium fibers

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We report a change from sub- to superluminal propagation upon increasing the modulation frequency of an amplitude-modulated 1550 nm signal when propagating through highly doped erbium fibers pumped at 980 nm. We show that the interplay between the pump absorption and the pump-power broadening of the spectral hole induced by coherent population oscillations may drastically affect the fractional advancement or delay of the signal for the considered fibers. © 2008 Optical Society of America

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Controlling the speed of light in telecommunications is a task that has received recent attention. Light propagation at sub- and superluminal velocities through solid-state materials at room temperature has been experimentally demonstrated by means of different mechanisms, such as coherent population oscillations (CPO) [1,2], stimulated Raman scattering [3], and stimulated Brillouin scattering [4,5]. It has been proven that a change of the excitation wavelength can induce the slowdown of the advancement of light in an alexandrite crystal [6]. A modification of group velocity by CPO has also been reported in Er-doped fiber (EDF) amplifiers, where an amplitude-modulated 1550 nm signal copropagates with a 980 nm pump signal [7]. In [7], a change from sub- to superluminal propagation of the 1550 nm signal takes place upon an increase in pump power. In the regime of low or high pump powers only delay or advancement is achieved for all of the modulation frequencies [7]. Furthermore, the increase in pump power results in a linear change of the modulation frequency at which the maximum delay or advancement occurs. In this Letter, we report a change in the propagation regime from sub- to superluminal solely upon an increase in the signal modulation frequency at fixed pump powers in high-concentration EDFs.

The experimental setup consists of a 1 m long EDF pumped with a 980 nm signal copropagating with a 1550 nm signal. A function generator sinusoidally modulates the 1550 nm laser power injected into the fiber, $P=P_0+P_m\cos(2\pi f_m t)$, where P_0, P_m, and f_m are the average power, the modulation amplitude, and the modulation frequency, respectively. We tested that the results reported here do not exhibit significant changes upon a change in modulation amplitude. So we kept the ratio at $P_m/P_0=0.5$ in all cases with $P_0=0.5$ mW. We computed the time delay t_d from the correlation between a reference signal and a signal propagated through the EDF. The fractional advancement is defined as $F=t_d f_m$. We used single mode, Al_2SiO_5-glass-based fibers highly doped with Er^{3+} ions at several concentrations, 800 ppm for the fiber labeled as Er20, 1050 ppm for Er30, 1350 ppm for Er40, 3150 ppm for Er80, and 4350 ppm for Er110. All of these fibers have a nominal mode field diameter at 1550 nm of 6.5 μm, a fiber cladding of 245 μm, and a numerical aperture of 0.2.

We measured the fractional advancement versus f_m for different fibers and for several pump powers, P_p. Figure 1(a) shows the results obtained for the Er20 fiber. Our results agree with those obtained in [7], although they used EDFs with a level of doping ten

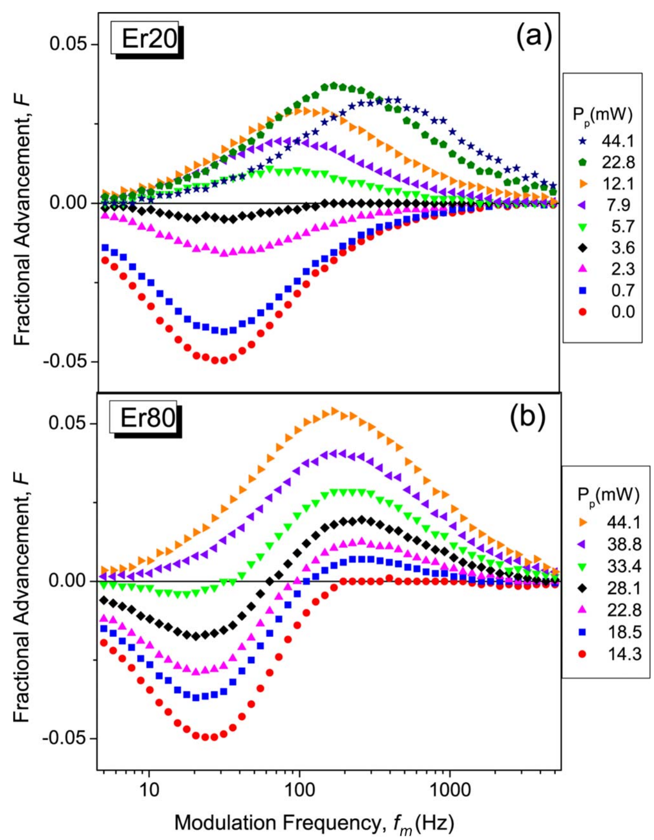

Fig. 1. (Color online) Fractional advancement versus modulation frequency for different pump powers. (a) Er20 fiber and (b) detail of the transition region from sub- to superluminal propagation in the Er80 fiber.

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times lower. There is a transition from sub- to superluminal propagation upon an increase in pump power. Moreover, the increase of pump power results in a linear increase in the optimum frequency (i.e., the modulation frequency at which the maximum delay or advancement occurs) owing to the broadening of the spectral hole with pump power. At low pump levels the signal is absorbed, which results in great delays for low-frequency signals, while at high pump levels absorption turns into gain and large advancements for high-frequency signals are obtained. From these results one can infer that if we use highly doped fibers in which a strong absorption of pump power occurs along the fiber, the signal will experience gain or absorption at different fiber locations when propagating through it.

In Fig. 1(b) we present the results for the Er80 fiber. Note that for a moderated and fixed pump power, a net delay or advancement is obtained depending on the value of the f_m [see curve corresponding to $P_p = 28.1$ mW in Fig. 1(b)]. For this pump power the regions where gain or absorption are dominant along the fiber are equally significant in such a way that both processes compete. When a high-frequency signal propagates along the fiber during the first region of the fiber (where gain will be dominant) this signal will undergo strong advancement. As long as it continues traveling through the fiber, attenuation will become dominant so that this high-frequency signal will be slightly delayed in this last part of the fiber. The sum of both contributions will give a net advancement of the signal at the output of the fiber. Following a similar line of reasoning, low-frequency signals will experience a net delay at the output of the fiber when pumped at this intermediate power. Thus, we found a range of pump powers that will lead to the striking behavior exhibited by the curves displayed in Fig. 1(b) that contains a delay section for low-modulation frequencies and an advancement section for high-modulation frequencies. Upon closer inspection, we notice that all of the fibers reveal their own range of intermediate pumps in which a transition from sub- to superluminal propagation occurs; the greater the ion concentration, the larger the range of pump values and the larger the magnitudes of delay or advancement. The very small magnitudes present in the transition curves for Er20 and Er30 and the very narrow range of pump powers for which they occur make the curves difficult to see at first glance at the delay or advancement versus the frequency graphs.

In Fig. 2 we plot the maximum fractional advancement or delay and the corresponding frequency, where the maximum is achieved versus the pump power for the different fibers. Note that an increase in the ion concentration increases the maximum advancement achievable and the pump power for which the maximum is attained. After this maximum advancement is achieved a saturation regime appears for Er20–Er40. However, the highest tested pump powers are too weak to reach the saturation of the fractional advancement achieved with Er80. We observe that greater delays are also achieved with successively greater doping, as reported in [8]. As the Er ion concentration increases from Er20 to Er80 the transition region enlarges over a large range of pump powers [see inset in Fig. 2(a)]. We also graph in Fig. 2(b) the optimal frequencies versus the pump power. Excluding some small deviation near the transition region, the optimum frequency linearly increases with pump power, although Er80 shows a smaller slope than the ones observed for the Er20–Er40 fibers.

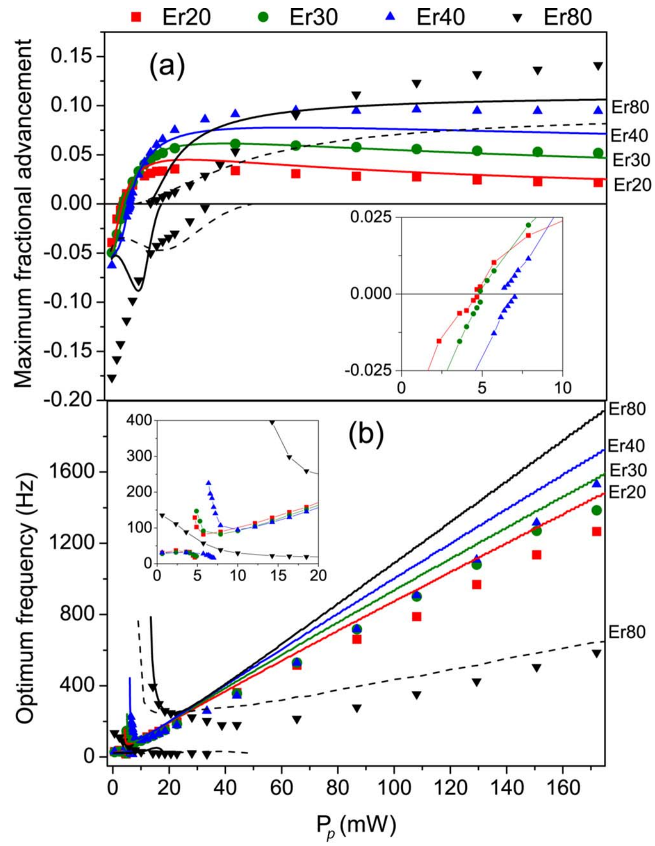

Fig. 2. (Color online) (a) Maximum fractional advancement/delay and (b) optimum frequency versus pump power for different fibers. Symbols, experiments; curves, simulations; dashed curve, simulations with inhomogeneous upconversion for Er80. Insets, experimental data close to the sub- to superluminal transition region.

The theoretical model used to discuss the experimental results is based on a rate equation analysis [1,7–9]. The propagation equations for P_0 and P_p are

$$\frac{\partial \hat{P}_0}{\partial z} = -\frac{\alpha_s(1-\beta_s\hat{P}_p)\hat{P}_0}{1+\hat{P}_0+\hat{P}_p}, \quad (1)$$

$$\frac{\partial \hat{P}_p}{\partial z} = -\frac{\alpha_p\left(1+\frac{\beta_s}{1+\beta_s}\hat{P}_0\right)\hat{P}_p}{1+\hat{P}_0+\hat{P}_p}, \quad (2)$$

where $\hat{P}_0 = P_0/P_{0\mathrm{sat}}$ is the ratio of P_0 to the signal saturation power $P_{0\mathrm{sat}} = \hbar\omega_s A_s/(\tau(\sigma_{21}+\sigma_{12}))$, ω_s is the signal transition frequency, A_s is the signal mode area, τ is the lifetime of the metastable state, and

σ_{21} and σ_{12} are the emission and absorption cross sections, respectively. The ratio between the signal cross sections is $\beta_s = \sigma_{21}/\sigma_{12}$. $\hat{P}_p = P_p/P_{p\text{sat}}$ is the ratio of P_p to the pump saturation power $P_{p\text{sat}} = \hbar\omega_p A_p/(\tau\sigma_{13})$, ω_p is the pump transition frequency, A_p is the pump mode area, and σ_{13} is the absorption cross section at the pump wavelength. $\alpha_s = L\sigma_{12}\rho\eta_s$ is the signal absorption coefficient, L is the fiber length, ρ is the ion density, and $\eta_s = A_c/A_s$, with A_c being the fiber core area. $\alpha_p = L\sigma_{13}\rho\eta_p$ is the pump absorption coefficient, with $\eta_p = A_c/A_p$. The phase delay experienced by the periodic part of the signal due to CPO is given by

$$\frac{\partial\phi}{\partial z} = -\frac{\alpha_s(1-\beta_s\hat{P}_p)\hat{P}_0}{1+\hat{P}_0+\hat{P}_p}\frac{2\pi f_m\tau}{(1+\hat{P}_0+\hat{P}_p)^2+(2\pi f_m\tau)^2}. \quad (3)$$

The fractional advancement can be obtained from $F = \phi(z=1)/(2\pi)$. In Eqs. (1)–(3) the distance z through the fiber is normalized to the fiber length L. Numerical integration of Eqs. (1)–(3) reveals that the peculiar behavior found for the curves of Fig. 1(b) arises from the spatial dependence of $P_0(z)$ and $P_p(z)$, showing that in these fibers amplification and attenuation regions along the fiber are comparable. The continuous curves depicted in Fig. 2 are the results predicted by the numerical simulations showing qualitative and quantitative agreement with the experimental results. The predictions obtained for the Er80 fiber deviate from the experimental findings (see the slope of the optimum frequency with pump power). In this fiber other potential loss mechanisms, such as interparticle interaction effects, could take place [10,11]. Following [11] we have carried out additional numerical simulations by adding the inhomogeneous upconversion process to the model. This process, which can be neglected for the rest of the fibers, is responsible for the decrease of the optimum frequency observed in the highly doped Er80 fiber [see dashed curve in Fig. 2(b)].

Finally, to enlarge the pump powers range at which the transition from sub- to superluminal propagation can be induced when varying the modulation frequency, we used the ultrahighly doped Er110 fiber. In Fig. 3 we plot the fractional advancement versus modulation frequency for different pump powers. In the Er110 fiber we obtained large delays by pumping the EDF. This result contrasts with the results obtained in the rest of the fibers, where the largest delay is achieved with the lowest measured pump powers. Without the pump, a delay accumulates in the front of the fiber, since the signal amplitude will rapidly decrease during propagation owing to the strong absorption of this fiber. However, when slightly pumping the fiber we are able to compensate for the strong absorption, slowing down the signal decay and leading to a greater accumulation of delay. Indeed, the maximum fractional delay and advancement achieved in this fiber are in its transition region, where a small change in frequency can result in a huge fractional delay $F = -0.5$ or a great fractional advancement $F = 0.3$ (see the abrupt transition when pumping this fiber at $P_p = 24.9$ mW). The transition

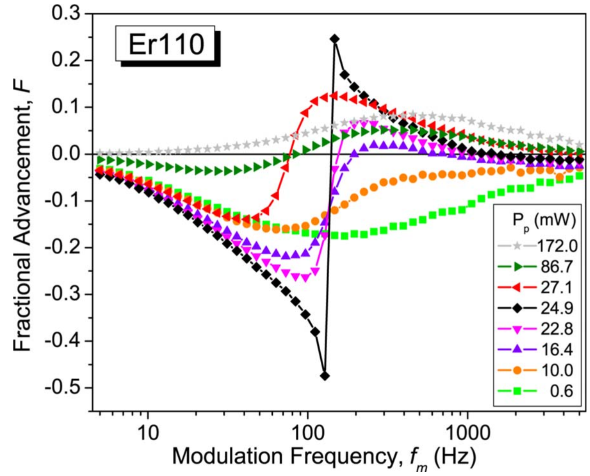

Fig. 3. (Color online) Fractional advancement versus modulation frequency for different pump powers in the Er110 fiber.

region occupies most of the range of pump powers tested with the fiber (see Fig. 3).

In conclusion, fixed pump-power high-concentration EDFs show a change in regime solely based upon increasing the signal modulation frequency. This result is a combined effect of the spectral hole broadening with pump power and the strong variation of the gain along the fiber length. Moreover, we demonstrated that an increase in Er ion concentration (i) increases the values of the fractional delay and advancement, (ii) causes the frequency-dependent regime change to become more abrupt, and (iii) allows the frequency dependency to be visible over a larger range of pump powers. This interesting property could be used to maximize the delay between two signals, with very close frequencies lying in the abrupt change region.

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