Control of the Group Velocity of Light in Erbium Doped Fibers Via the Modulation Frequency

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Abstract: We report a change from sub- to super-luminal propagation solely upon increasing the modulation frequency of an amplitude-modulated 1550 nm signal when propagating through highly-doped erbium fibers pumped at 980 nm.

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1. Introduction

The ability to control the speed of light in erbium-doped fibers (EDF) is of great interest for their promising applications in telecommunications [1, 2]. It has been recently shown that a change from sub- to super-luminal propagation of an amplitude modulated 1550 nm signal occurs upon increasing pump power in EDFs with low erbium concentration (90 ppm) [3]. In the regime of low/high pump powers only delay/advancement is achieved for all the modulation frequencies. Furthermore, the increase of pump power results in a linear increase of the modulation frequency at which the maximum delay/advancement occurs [3]. Later, a simultaneous increase of the fractional delay and the bandwidth of the signals was reported by increasing ion concentration in EDFs [4]. By pumping this highly-doped erbium fibers, the amplitude-modulated signal changes from being amplified to being absorbed when propagating along the fiber, due to the strong absorption of pump power. So a change in the velocity of light from super- to subluminal could occur along the fiber. In this work we study this point and we report a change in the propagation regime from sub- to super-luminal solely based upon increasing signal modulation frequency at a fixed pump power in highly-doped erbium fibers.

2. Experimental setup and results

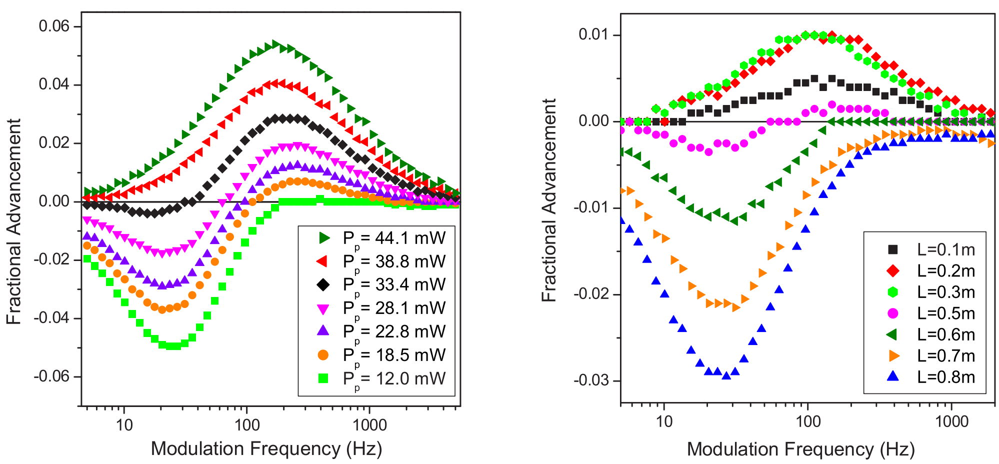

Fig. 1. Fractional advancement versus modulation frequency of a 1550-nm sinusoidal modulated signal with average power P_0= 0.5 mW and modulation amplitude P_0/P_m = 0.5 propagating along fibers with ion concentration of 3150 ppm. (Left) Varying pump power for 1-m fiber length; (Right) Varying fiber length for a pump power of P_p = 8 mW.

We use single mode, Al_2SiO_5-glass-based fibers doped with Er^{3+} ions at a concentration of 3150 ppm ($\rho = 6.3 \times 10^{25}$ m^{-3}). These ultra-highly doped fibers are pumped with a 980 nm signal co-propagating with a 1550 nm signal. A waveform generator sinusoidally modulates the 1550 nm laser power launched into the fiber: $P = P_0 + P_m \cos(2\pi f_m t)$, P_0, P_m, and f_m being the average signal power, the modulation amplitude, and the modulation frequency, respectively. We keep the ratio P_m/P_0 = 0.5 in all the experiments, being 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 $F = t_d f_m$.

In Fig. 1 (left) we plot the fractional advancement versus modulation frequency for an EDF 1 meter in length and for several pump powers, P_p. At low pump levels the signal is absorbed which results in great delays for low frequency signals whilst at high pump levels absorption turns into gain and large advancements for high frequency signals are obtained. Note that for a moderated and fixed pump power (see for example curve corresponding to P_p = 28.1 mW), a net delay or advancement is obtained depending on the value of the f_m. For this pump power the regions where gain or absorption are dominant along the fiber are equally significant so 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 travelling through the fiber, attenuation will become dominant so 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 powers.

To experimentally endorse this explanation we have analyzed the fractional advancement of signals with different modulation frequencies when propagating along fibers of several lengths (see Fig. 1 (right)). Note that for very short lengths ($L < 0.2$ m) advancement is achieved for all the modulation frequencies which indicates that the EDF operates as an amplifier. However, if we increase the fiber length from $L = 0.2$ m to $L = 0.3$ m, the fractional advancement curve does not change which indicates that a transition from superluminal to subluminal propagation takes places. Thus, the advancement accumulated until $L \simeq 0.25$ m will start to decrease due to the additional delay region. At $L = 0.5$ m we observe that solely increasing the modulation frequency switches from delay to advancement. Finally, if we increase the length to $L = 0.6$ m delay is achieved for all the modulation frequencies.

In conclusion, for fixed pump power high-concentration EDFs show a change in regime solely based upon increasing 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. This interesting property could be used to maximize the delay between two signals with close frequencies lying in the change region.

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