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Group velocity manipulation using cross gain modulation in erbium-doped fibers with co-direction structure

Fangying Tao [a], Li Zhan [a,*], Kai Qian [b,*], Zhiqiang Wang [a], Liang Zhang [a], Le He [a]

[a] Department of Physics and Astronomy, Key Laboratory for Laser Plasmas (Ministry of Education), State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China
[b] School of Information Engineering, Hubei University for Nationalities, Enshi, Hubei Province 445000, China

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ABSTRACT

We experimentally demonstrated tunable delays using mutrally modulated cross-gain modulation (MM XGM) in erbium-doped fiber (EDF) with a new co-direction structure. The group velocity of the signal light can be controlled by the saturating light at an arbitrary wavelength in the EDF gain bandwidth. We have observed slow light propagation with a group velocity as low as 146.4 m/s, which means a 88.8 ms delay, and an advancement of 11.2 ms after a 13 m EDF at the same time. This provides a greater enhancement on the delay or advancement compared to the previous experiment. Furthermore, we confirmed the influence on delay or advancement by varying the pump power, the input power of the saturate light. Also, we discussed the influence of recovery time, the modulation depth of the saturating light and the modulation frequency on the modulation gain. This attractive approach could be one of the suitable solutions for real applications.

1. Introduction

One of the basic bottlenecks in the all-optical telecommunications and information processing communities is short of a device that can buffer or delay the arrival of the information via light by light interactions. Obviously, controlling the group velocity of light propagation in optical materials provides an exceptional solution. Over the past decade or more, as we have seen, the field of slow- and fast-light has been studied intensely by researchers who expect to control the group velocity of modulated or pulsed light by a variety of nonlinear effects [1–13]. Also, the reason for the increasing interest in this field is its inviting applications in controllable optical delay, random access memory, data synchronization, sensing, pattern correlation, and true time delay methods for synthetic aperture radar. To date, many methods have been proposed to demonstrate the phenomena of slow- and fast-light propagation. But most of these schemes are achieved by using either material resonances or structural resonances worked at the well defined wavelengths in absorbing media [14,15], hot atomic vapors [16,17], photonic crystals [18], fiber Bragg gratings [19], corrugated waveguides [20], left-hand materials [21], and saturated absorbing medias [22,23]. Meanwhile, superluminal or even negative group velocity propagation has also been widely researched in both theory and experiment [24–28]. However, the fast light is usually achieved in the strong absorbing band, which makes it experience strong loss and thus limits the long-distance propagation. Real applications for all-optical communication systems require slowing or advancing to be operated under normal environmental conditions in optical fibers, and at telecommunication wavelengths. There are some eligible methods, such as stimulated Brillouin scattering (SBS) [1,2], stimulated Raman scattering [29], parametric amplification [30], and cross-gain modulation (XGM) in active fibers [31]. In particular, the SBS scheme has attracted much attention due to its incomparable advantages of low pump power, operating at arbitrary wavelength, and capacity of obtaining large delay [1,2]. Nevertheless, the operating wavelengths in SBS scheme need to be accurately set at the Brillouin-stokes frequency.

Cross-gain modulation is a well-known nonlinear effect in which a modulation is impressed onto a non-modulated beam

* Corresponding authors.
E-mail addresses: lizhan@sjtu.edu.cn (L. Zhan), kaiqian@sjtu.org (K. Qian).

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owing to its interaction with another modulated beam in active media, such as in a semiconductor optical amplifier [32]. Recently, Sternklar et al. demonstrated ultra-slow propagation in fibers using Brillouin mutually-modulated cross-gain modulation (MM XGM), which gave an arbitrary absolute delay with respect to the linear propagation time, but it also has the setting wavelengths problem [11,12,33–35]. Otherwise, Kai Qian has demonstrated group velocity manipulation from ultraslow to superluminal propagation in the erbium-doped fibers (EDFs) using XGM [31].

In this paper, we experimentally demonstrated tunable delays using MM XGM in EDF with a new co-direction structure. The group velocity of the signal light can be controlled by the saturating light at an arbitrary wavelength in the EDF gain bandwidth, including the telecommunication wavelengths, with low-loss performance and low production cost. By controlling the modulation phase of saturating light, we can observe ultraslow or superluminal light propagation. We have observed slow light propagation with a group velocity as low as 146.4 m/s, which means a 88.8 ms delay, and an advancement of 11.2 ms after a 13 m EDF at the same time. This provides a greater enhancement on the delay or advancement compared to the previous experiment [31]. Furthermore, we confirmed the influence on delay or advancement by varying the pump power, the input power of the saturate light, as well as the value of the parameter $G\beta/\alpha$. Nevertheless, there are some other questions need to be solved, such as distortions, especially when the real telecom signal is used as the signal light, and when they are done, this attractive approach could be one of the suitable solutions for real applications.

2. Theory analysis

The theory of XGM in EDFs has been proposed in the past [31], and is reviewed briefly here. The fields of modulated saturating and signal lights propagating in the same direction in EDF are given as follows, respectively: $E_1(z,t) = A_1(z,t)e^{i(k_1 z+\omega_1 t)} + c.c.$

$E_2(z,t) = A_2(z,t)e^{i(k_2 z+\omega_2 t)} + c.c.$

where c.c. denotes complex conjugate. And the slowly varying amplitudes are given as:

$$A_1(z,t) = A_1 + \frac{a_1}{2}e^{i(\mathrm{K}z+\Omega t)} + c.c. \tag{1a}$$

$$A_2(z,t) = A_2 + \frac{a_2}{2}e^{i(\mathrm{K}z+\Omega t)} + c.c. \tag{1b}$$

A_i and a_i denote the dc and ac components, respectively, of the amplitude. Ω is the modulation frequency, $K = \Omega n/c$ is the modulation wavenumber, where n is assumed to be the background linear refractive index in EDF, and $\beta = 2a_2(0)/A_2(0)$ is the modulation depth of the signal light.

The nonlinear equation that describes the signal amplitude calculated from the nonlinear schrödinger equation is

$$\frac{\partial A_2(z,t)}{\partial z} + \frac{1}{v}\frac{\partial A_2(z,t)}{\partial t} = \frac{g(z,t)}{2}A_2(z,t) \tag{2}$$

where v is the group velocity. $g(z,t)$ is the gain coefficient modulated by the saturating light. It can be assumed as $g = g_0[1+\alpha\cos(\Omega t + Kz + \varphi)]$, where g_0 is the dc component which can be controlled by the pump and saturating light power, α is the gain modulation depth that depends on the modulation depth of the saturating light, and φ is the modulation phase boundary condition.

By solving the above equation, the time delay is acquired:

$$t_d = \frac{Ln}{c} + \frac{\varphi + \theta_B}{\Omega} \tag{3}$$

where L is the active EDF length, $\theta_B = \tan^{-1}\left(\frac{H\cos\psi}{1+H\cos\psi}\right)$, $H = G\beta/\alpha \sin c(KL)$, $G = g_0 L$ and $\psi = -(KL+\varphi)$. Thus, controllable time delay or advancement after light propagation can be obtained through varying G, α, β and φ.

Theoretical analysis [36] show the variation of the gain modulation depth to the power of the saturating light, the recovery time and the modulation frequency as follows: The gain modulation depth (α) increases upon the increase of the power of the saturating light and the recovery time, while it decreases upon the increase of the modulation frequency. Therefore, the effect of the decrease of the gain modulation depth (α) caused by the increase of the modulation frequency can be compensated by means of increasing the power of the saturating light and the recovery time. Similarly, the upper limit of the modulation frequency can be increased via changing the gain modulation depth (α). But, taking the whole situation into account, the modulation frequency influences the delay of the signal light most, but the influence can be compensated by changing other parameters.

As for the delay time and the fractional delay, we know that they increase upon the increase of the gain modulation depth (α). However, the increase of the gain modulation depth (α) is limited by the recovery time of the EDF when the modulation frequency approaches around 1 MHz. This makes the recovery time the critical factor in the increase of the delay time.

3. Experiments setup

Fig. 1 illustrates our experiment setup to demonstrate the delay or advancement effects. Light from the tunable laser source (TLS) laser operating at 1544 nm is served as the saturating light, while the distributed feedback laser (DFB) laser operating at 1550.380 nm as the signal light. Respectively, they are sinuously amplitude modulated by electro-optic modulators (EOM) which are driven by the same function generator with channel 1 and channel 2. Then, the saturating light is amplified by an Er-doped fiber amplifier (EDFA) before it is coupled into a 13 m long EDF with the signal light. Two 980 nm laser diodes are used for pumping this 13 m EDF in opposite directions. To monitor the temporal traces of the signal light by an oscilloscope after photoelectrical conversion, we separate the saturating light and the signal light with a dense wavelength division multiplexing (DWDM), and only the signal light gets through the DWDM before it is transferred into the photoelectrical detector. Finally, the signal is shown on the oscilloscope together with the trigger from channel 1 of the function generator.

As compared to the experimental setup used in [31], we adopt the co-direction structure so as to supplement the propagation situations in which the signal light and the saturating light may propagate in the same direction or opposite direction. Nevertheless, our co-direction structure has the convenient of applications and is more suitable for the practical communication system.

4. Results and discussions

Initially, the TLS wavelength is set at 1544 nm, while the DFB wavelength at 1550.380 nm which is just in the central wavelength of the DWDM filter. To measure the maximum value of the delay, we set the modulation frequency at 10 Hz, and the input power of the signal light is 0.958 mW, as well as the saturating light is 8.2 mW. Also the output peak to peak amplitude of channel 1 is 1 V, and for channel 2, it is 3 V. Varying the modulation phase of channel 2, the modulation phase difference (varying from $-\pi$ to π) between channel 1 and channel 2 is obtained, and the signal delay can be measured. Fig. 2 shows the measured delay variation in a modulation period. Controllable group delay or advancement