Group velocity manipulation in active fibers using mutually modulated cross-gain modulation: from ultraslow to superluminal propagation

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Received January 13, 2011; revised May 3, 2011; accepted May 3, 2011; posted May 5, 2011 (Doc. ID 141094); published June 6, 2011

We propose and experimentally demonstrate the propagation of slow/fast light in an erbium-doped fiber (EDF) using mutually modulated cross-gain modulation. The group velocity of the light signal can be manipulated by the effect of gain cross-saturation modulation by a saturating light at an arbitrary wavelength in the gain bandwidth of the EDF. The ultraslow propagation with a small group velocity of $5.6 \times 10^{-3}c$ ($c$ is the light speed in free space) and superluminal propagation with a negative group velocity of $-1.1 \times 10^{-6}c$ has been observed under different modulation phases. © 2011 Optical Society of America
OCIS codes: 190.4370, 060.2520, 060.4980.

Controlling the group velocity of light has attracted much interest owing to its potential applications, such as tunable optical buffers, optical memory, improving sensitivity of sensing systems, and enhancing the nonlinear effect. To date, slow/fast light schemes have been widely demonstrated by different methods [1–8]. Also, it has been reported that the light can travel with superluminal propagation (the group velocity $v_g$ exceeds $c$) or even with a negative group velocity [9]. Recent interest in slow/fast light has been focused on optical fibers owing to its inviting applications in all-optical routing systems. In particular, stimulated Brillouin scattering (SBS) slow/fast light in fibers has attracted much attention due to its capacity of obtaining large delay [10–12]. Also, the superluminal propagation in fibers has been demonstrated using SBS lasing [13].

Cross-gain modulation is a well-known effect in active media, such as in the semiconductor optical amplifier, Brillouin and Raman amplifier, and erbium-doped fiber (EDF) [14]. Recently, Sternklaar et al. demonstrated ultraslow propagation in fibers using Brillouin mutually modulated cross-gain modulation (MM XGM). This approach can give an arbitrary absolute delay with respect to the linear propagation time, but it requires the wavelengths of the control and signal lights exactly set at the Brillouin–Stokes frequency [15,16].

In this Letter, we propose and demonstrate slow/fast light propagation using MM XGM in EDFs. The group velocity of the signal light can be controlled by the saturating light at an arbitrary wavelength in the EDF gain bandwidth. Ultraslow or superluminal light propagation has been observed by controlling the modulated saturating light.

The XGM effect also exists in EDFs owing to gain cross-saturation [17]. The fields of modulated saturating and signal lights counterpropagating in EDF can be written as

$$E_1(z, t) = A_1(z, t) e^{i(Kz + \Omega t)} + \text{c.c.} \quad (\text{c.c. denotes the complex conjugate})$$

and

$$E_2(z, t) = A_2(z, t) e^{i(Kz + \Omega t)} + \text{c.c.},$$

respectively, in which, the slowly varying amplitudes are [15]

$$A_1(z, t) = A_1 + \frac{a_1}{c} e^{i(Kz + \Omega t)} + \text{c.c.}, \quad (1a)$$

$$A_2(z, t) = A_2 + \frac{a_2}{c} e^{i(Kz + \Omega t)} + \text{c.c.} \quad (1b)$$

where $A_i$ and $a_i$ are the dc and ac components of the amplitude, $\Omega$ is the modulation frequency, $K = \Omega n/c$ is the modulation wavenumber, $n$ is the refractive index of the EDF, and $\beta = 2a_2(0)/A_2(0)$ is the modulation depth of the signal light. The signal amplitude can be calculated by the nonlinear Schrödinger equation:

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

where $v$ is the group velocity. The gain coefficient $g(z, t)$ is modulated by the saturating light, and it can be written as

$$g = g_0 [1 + \alpha \cos(\Omega t + Kz + \varphi)],$$

where $g_0$ is the dc component and can be controlled by the pump and saturating light power, $\alpha$ is the gain modulation depth that depends on the modulation depth of the saturating light, and $\varphi$ is the modulation phase boundary condition. We solve the equation, and we obtain the time delay

$$t_d = \frac{L n}{c} + \frac{\varphi + \theta_B}{\Omega}, \quad (3)$$

where $L$ is the active fiber length, $\theta_B = \tan^{-1}\left(\frac{H \sin \Psi}{1 + H \cos \Psi}\right)$, $H = G / B \cdot \text{sinc}(KL)$, $G = g_0 L$, and $\Psi = - (KL + \varphi)$. Through varying $G$, $\alpha$, $\beta$, and $\varphi$, we can obtain the time delay or advancement after light propagation.

The experimental setup is shown in Fig. 1. The light from the DFB and TLS laser is sinusuously modulated by EOM1 and EOM2, respectively. The wavelength of the DFB laser is $1544$ nm. The signal generator has two output channels. The EOM1 is driven by channel 1 (Ch1), and EOM2 is done by channel 2 (Ch2). The modulation phase difference between two channels $\varphi'$ can be varied from $-\pi$ to $\pi$. The light from EOM2 is amplified by an EDFA and serves as the saturating light. The signal light from EOM1 passes a $14$ m $400$ ppm EDF, and outputs
from port 3 of circulator 2. The EDF is pumped by two 980 nm laser diodes. The signal delay is measured by the oscilloscope after optoelectrical conversion.

Initially, we set the TLS wavelength at 1560 nm. The modulation frequency is 20 KHz, and the peak-to-peak amplitudes of the Ch1 and Ch2 are 0.8 V. The signal power is 100 μW. The saturating light power is 10 mW. After optoelectric conversion, the observed ac output of the modulator is 0.53 V and the dc value is 13.76 V. Varying the modulation phase of Ch2, we can obtain a 2π modulating phase change of the saturating light. Figure 2(a) shows the output signal change when we vary the modulation phase of the saturating light. We observe the maximum time delay when Ch2 phase is −50° and the maximum advancement when Ch2 phase is −130°. Figure 2(b) shows the output signals with and without saturating light. Controllable group delay or advancement can be obtained when we choose an appropriate phase boundary condition. When the modulation phase difference is −130°, we obtain the advancement up to 7.6 µs by varying the saturating light power from 0 to 10 mW. Note that the phase difference φ and the phase boundary condition qφ exhibit an antiphase relationship, φ = −qφ + C. C varies with the bias voltage of the modulator and the length difference of the two modulators from WDM1. Figure 2(c) shows the theoretical and experimental delay variation with the modulation phase difference when Gβ/α = 1.28. The theoretical model fits well to the experimental data.

Figure 3 shows the experimental results when the amplitude of Ch1 is reduced to 0.4 V. The ac output of the modulator is 0.27 V and the dc value is 13.77 V. Figure 3(a) shows the delay variation in a modulation period. From Fig. 3(b), the maximum delay and advancement are 8.3 and 41.9 µs, respectively. The group velocities are 5.6 × 10^5 cm/s and −1.1 × 10^5 cm/s. Correspondingly, the group indices are 178 and −909. Figure 3(c) plots the theoretical and experimental delay variation when Gβ/α = 0.64. The difference between Figs. 2(c) and 3(c) is mainly caused by the different Gβ/α [16]. When Gβ/α = 1.28, the delay tφ is determined by both φ and θB. When Gβ/α = 0.64, owing to θBmax − θBmin < 2π, the delay is basically determined by the modulation phase difference.

Such group delay variation is also observed when the modulation frequency is 100 and 10 KHz. The lower the modulation frequency used, the larger the group delay or advancement obtained.

We also prove the effect of gain bandwidth on the delay. Figure 4 shows the signal light transmission power and the fractional delay variation with the saturating light wavelength. Controlling the group velocity through XGM can be observed at any wavelength in the EDF gain bandwidth both for signal and saturating lights. However, the delay is not obvious when the wavelength is below 1537 nm or beyond 1567 nm. This can be explained as follows: the gain compression depth varies with the wavelength [17], thus, G and the delay vary with the saturating light wavelength. Because of the flat gain of EDF on saturation status, the group delay variation with the saturating light wavelength is negligible in the range

Fig. 1. (Color online) Experimental setup: DFB, distributed feedback laser; TLS, tunable laser source; PC, polarization controller; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; D1, D2, detectors; WDM, wavelength division multiplexer.

Fig. 2. (Color online) Experimental results when the Ch1 amplitude is 0.8 V. (a) Output signal with different modulation phases. (b) Output signal with and without saturating light. (c) Theoretical and experimental group delay variation.

Fig. 3. (Color online) Experimental results when the Ch1 amplitude is 0.4 V. (a) Output signal with different modulation phases. (b) Output signal with and without saturating light. (c) Theoretical and experimental group delay variation.
from 1537 to 1567 nm. However, the 1530 nm gain peak in EDF should be avoided, because it is a different gain band to the 1550 nm band.

In the scheme, the modulated saturating light causes the modulation of signal gain, and thus different parts of the signal pulse undergo different gain. Controlling signal light group velocity can be achieved by varying the modulation phase, the power and the modulation depth of the saturating light. The delay asymmetry in Figs. 2(c) and 3(c) is mainly caused by $G\beta/\alpha$. The population recovery time of erbium atoms may influence the gain modulation depth $\alpha$, when the saturating light and signal light works at higher frequency. When the modulation frequency exceeds 1 MHz, $\alpha$ tends to 0, which leads to limiting the signal bandwidth and delay time. It seems that our work is similar to the ones based on the coherent population oscillation (CPO) in EDF [18,19]. All these works utilized the periodic gain modulation, but the sources of slow/fast light are different. The gain modulation in CPO strongly depends on population recovery time, and it is hard to obtain obvious delay or advancement when the frequency exceeds 1 KHz. The periodic gain modulation here results from the MM XGM, in which, $\alpha$ weakly depends on the population recovery time, because the total population inversion level for two light beams in EDF is almost unchanged under weak modulation. A large delay or advancement was observed at 20 KHz and even 100 KHz frequency. It should be noted that the delay variation with the modulation phase difference is a unique property of XGM slow/fast light. Moreover, this approach is suitable for any active media.

In conclusion, we have demonstrated slow/fast light in EDF using MM XGM. Our approach has advantages such as larger signal bandwidth, larger fractional delay, and working at any wavelength in EDF gain band. Ultraslow light with $1.69 \times 10^8$ m/s group velocity and superluminal propagation with $-3.3 \times 10^5$ m/s were observed. Larger group delay or advancement can be obtained by using a lower modulation frequency. With the large group index variation obtained, this technique may find potential applications in optical sensing [16].

The authors acknowledge the support from the National Natural Science Foundation of China (NSFC) (grant 10874118), the key project of the Ministry of Education of China (grant 109061), and the “SMC Young Star” Scientist Program of Shanghai Jiao Tong University.

References