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Fast and slow light property improvement in erbium-doped amplifier

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Abstract

This work experimentally demonstrates improvement of the fast light property in erbium-doped amplifiers at room temperature. The difference between the signal power and the pump power associated with bending loss is used to control the signal power at the different positions of the erbium-doped fiber (EDF) to improve the fast light property. Periodic bending of the EDF increases the time advance of the probe signal by over 288%. Additionally, this concept also could improve the fast light property using coherent population oscillations in semiconductor optical amplifiers.

(Some figures may appear in colour only in the online journal)

1. Introduction

'Fast light' and 'slow light' have recently attracted substantial interest because they have important applications, as in optical signal processing, optical buffers, optical communication, optical data synchronization, optical memories, and phase-array antenna systems [1–9]. In recent years, slow light has been demonstrated in electromagnetically induced transparency, coherent population oscillations, and stimulated Brillouin and Raman scattering. A group velocity of 9600 $\mathrm{m\ s^{-1}}$ has been demonstrated in semiconductor quantum wells using coherent population oscillations at $T = 10$ K [10]. A group velocity of less than 200 $\mathrm{m\ s^{-1}}$ in a sample with 15 GaAs QWs at $T = 10$ K has also been proposed [11].

Erbium-doped fiber amplifiers (EDFAs) have attracted considerable interest because they have a wide range of applications in optical fiber communication systems [12–17]. Coherent population oscillations (CPOs) have been reported to induce slow light and fast light in an erbium-doped fiber at room temperature [18–20]. In the CPO mechanism, the group velocity in an erbium-doped fiber amplifier is controlled by varying the signal power and gain. However, as the signal is transmitted through an EDFA, the signal power and the signal gain per unit length of the EDF increases and decreases, respectively, with the length of the transmitting EDF. Accordingly, the fast light effect is weakened at the end of the EDF and the signal power is high.

Substantial effort has been made to develop an erbium-doped waveguide amplifier (EDWA) using ion exchange technology in planar glass integrated optics [21–24]. The advantage of an erbium-doped waveguide amplifier over an erbium-doped fiber amplifier is its higher erbium doping concentration. This advantage provides high optical gain with a very short length. The erbium-doped waveguide amplifier has the potential to generate ultrafast light and ultraslow light in the waveguide.

This paper is composed of two related parts. First, the improvement of fast light property in an EDFA is experimentally demonstrated. Second, fast light and slow light in an EDWA are investigated. Finally, section 4 summarizes the results of this research.

2. Erbium-doped fiber amplifier

The group velocity of an optical signal through a waveguide is given by

$$v_{\mathrm{g}} = \frac{c}{n_{\mathrm{g}}} \tag{1}$$

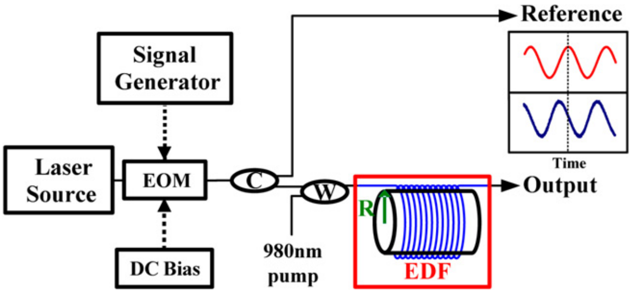

Figure 1. Experimental setup. (EOM, electro-optic modulator; C, optical coupler; W, 980/1550 WDM coupler; EDF, erbium-doped fiber.)

where n_g is the group index and c is the speed of light in a vacuum. The group index that is determined by the coherent population oscillations is given by [20]

$$n_g = n_{bk} - \frac{gcT}{2}\frac{I_0}{(1+I_0)^3} \qquad (2)$$

where n_{bk} is the background refractive index of the optical fiber; g is the unsaturated gain coefficient; T is the relaxation time of the population inversion of the erbium amplifier, and $I_0 = I/I_{sat}$ is the light intensity, normalized to the saturation intensity I_{sat} of the erbium amplifier. Therefore, the group index can be controlled by varying the input signal power and the 980 nm pump power. However, increasing the signal power will decrease the gain, resulting in reduction of the fast light effect. In order to improve the time advance, the bending loss is used to control the signal power in the different position of EDF. Moreover, a 1550 nm lightwave experiences more bending loss than a 980 nm lightwave. Therefore, the signal gain from the EDF cannot be obviously affected by the bending fiber.

Figure 1 shows the experimental setup for measuring the time variation of the signal transmitted over the erbium-doped fiber, which consists of an erbium-doped fiber, a 980 nm pump laser and a 980/1550 nm WDM coupler. The 980 nm pump laser is driven by a current source. Moreover, the inset of figure 1 shows the waveforms when the frequency and power of the probe signal are 0.5 kHz and −3 dB m, respectively. The length of the EDF is 10 m, and the bending radius (R) of the EDF is 7.5 mm. In fast light measurements, the wavelength of the probe signal is 1550 nm. The optical signal is generated by a tunable laser and modulated using an electro-optical modulator. The electro-optical modulator is modulated by applying a sinusoidal signal from a function generator. The modulation depth of the optical signal is 0.1. The optical signal is split into two paths. One is sent to a photodetector as a reference signal. The other signal is sent to the erbium-doped fiber amplifier.

Moreover, the time advance was measured at the different signal frequencies, as shown in figure 2. We compare the EDF with and without periodic bending. The improvement in the time advance can be clearly seen when the bending loss is used to control the signal power in the EDF. The maximum signal advance is 940.7 μs, when the 980 nm pump power and the frequency of probe signal are 100 mW and 0.5 kHz, respectively. The time advance is increased over 288% by

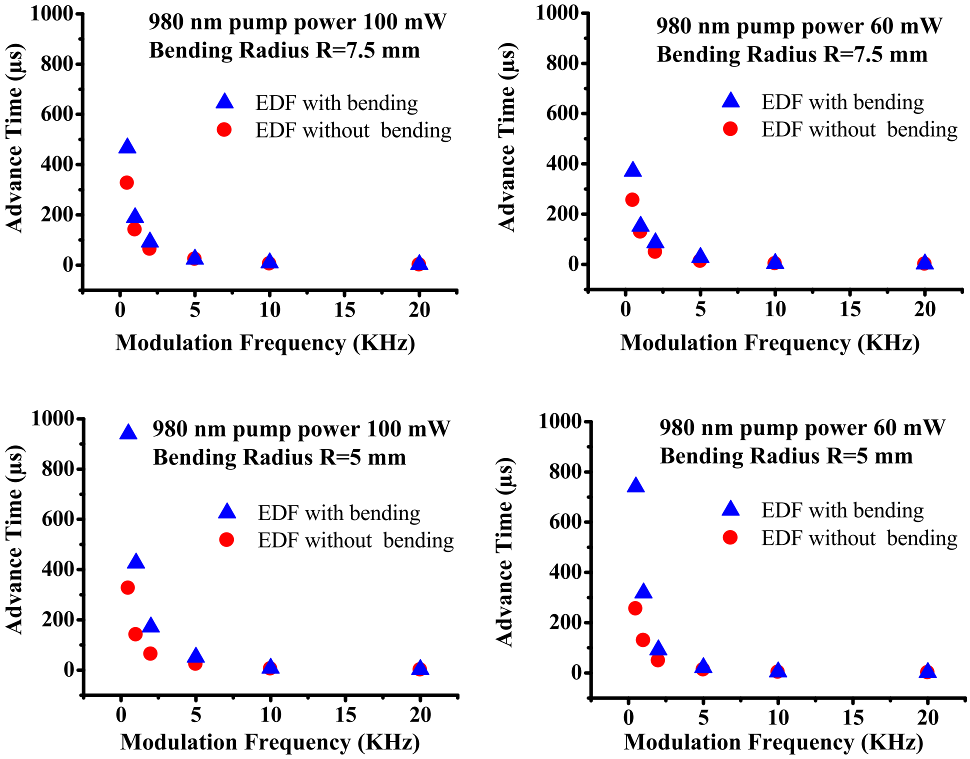

Figure 2. The relationship between the time advance and the modulation frequencies of probe signals.

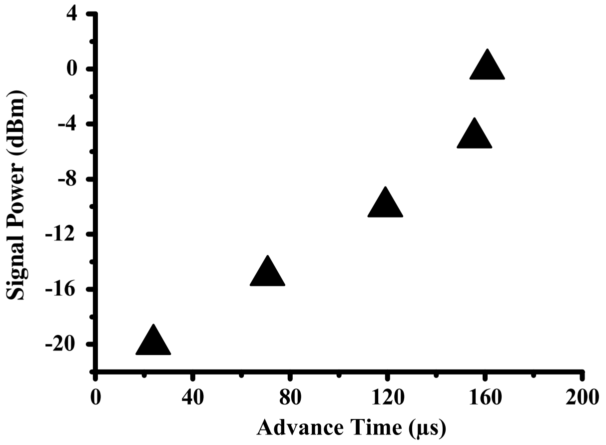

Figure 3. The relationship between the time advance and the power of probe signal.

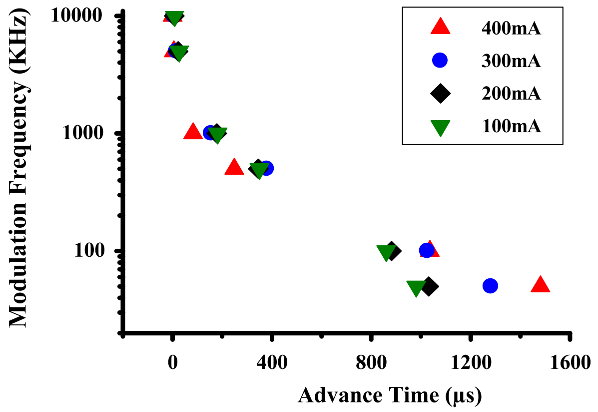

Figure 4. The relationship between the time advance and the modulation frequencies of probe signals.

the periodic bending of the EDF, and the bending radius of the EDF is 5 mm. This advance time corresponds to a group velocity of about -1.06×10^4 m s^{-1}.

3. Erbium-doped waveguide amplifier

The erbium-doped waveguide amplifier is very attractive for use in 1.55 μm communication systems because of its compactness, low processing cost, and compatibility with other optical devices. Additionally, the erbium-doped waveguide amplifier has the advantage of the fundamental qualities of an erbium-doped fiber amplifier, such as a low noise figure, negligible polarization dependence, and the absence of inter-channel crosstalk [21–24]. The erbium-doped waveguide amplifier consists of an erbium-doped waveguide, two optical isolators, a 980 nm pump laser, a 980/1550 nm WDM coupler, and a pump filter. The 980 nm pump laser is driven by a current source.

In fast light and slow light measurements, the wavelength of the probe signal is 1550 nm. The optical signal is generated by a tunable laser and modulated using an electro-optical modulator. Then the electro-optical modulator is modulated by applying a sinusoidal signal from a function generator. The optical signal is split off and is sent to a photodetector for use as a reference signal. The other signal is sent to the erbium-doped waveguide amplifier.

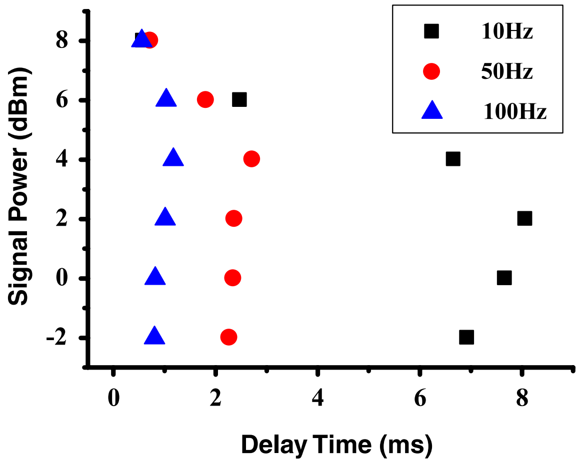

Figure 5. The relationship between the time delays and the power of probe signals.

A digital oscilloscope records the output signal from the erbium-doped waveguide amplifier and the reference signal. For the fast light, the erbium-doped waveguide with a 980 nm pump power is driven by a current source, and for the slow light, the 980 nm pump power is turned off. Figure 3 plots the relationship between the time advance and the power of the probe signal when the modulation frequency of the probe signal is 1 kHz. Increasing the signal power from −20 to 0 dB m increases the time advance of the probe signal.

Figure 4 plots the time advance measured at the different frequencies. The maximum signal advance is 1.481 ms. This advance time corresponds to a group velocity of about -67.5 m s^{-1}, and the group index changes to about -4.44×10^6. Figure 5 plots the time delays as functions of modulation frequencies and optical power of the probe signal, when the 980 nm pump power is turned off. The maximum signal delay is 8.067 ms. This delay corresponds to a group velocity of about 12.4 m s^{-1}, and the group index changes to about 2.42×10^7. The proposed scheme yields greater time advancements and delays than the erbium-doped fiber amplifier.

4. Conclusion

This investigation experimentally demonstrates the fast and slow light property improvement in erbium-doped amplifiers. Since the lengths of the interaction in the erbium-doped fiber amplifier are large, the bending loss can be utilized to control the signal power in various positions of the fiber to improve the fast light property. The time advance is increased by more than 288% by the periodic bending of the erbium-doped fiber. Fast and slow light in an erbium-doped waveguide amplifier is also investigated because the erbium-doped waveguide amplifier has a greater erbium doping concentration than an erbium-doped fiber amplifier. Accordingly, it has potential to provide a larger time advance and delay in a compact system.

Acknowledgments

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