Tunable delay slow-light in an active fiber Bragg grating

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Abstract: We proposed and experimentally demonstrated an extremely simple and feasible slow-light technique to achieve tunable optical delay by using the Er/Yb codoped fiber Bragg grating (FBG). The signal light experiences strong dispersion when it is launched into the reflection edge of FBG, and the group delay value is determined by the signal wavelength and the pump power. In the experiment, a controllable delay of 0.9 ns can be obtained through changing the 980nm pump power. The group velocity can be slowed down to $5.6 \times 10^7$ m/s, which is 19% of the speed of light in free space. It provides a very simple approach to control the light group delay, which is likely to have important implications for practical applications.

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References and links


1. Introduction

Controlling the group velocity of light has been attracting more interests owing to its potential application as tunable optical buffer in all-optical router commutation and optical computing. Thus, the techniques of tunable slow-light have been widely studied, such as electromagnetically induced transparency (EIT) [1], coherent population oscillation (CPO) [2–5], coupled resonator induced transparency (CRIT) [6], stimulated Raman scattering (SRS) [7], fiber optical parametric amplifier (OPA) [8] and hybrid approach employing wavelength conversion with the linear dispersion [9,10]. Stimulated Brillouin scattering (SBS) slow light has attracted much attention because it can generate large delays at any wavelength and only requires low-power pump [11–14]. However, its narrow bandwidth does not allow delaying the narrow pulses [15], and thus SBS slow-light usually requires a relatively complicated system to improve the operating bandwidth [15–17].

FBGs have been applied as key fiber components in many fields such as dispersion compensators, wavelength converters and phase conjugators for their versatility and unique filtering capabilities [18]. In 2005, D. Janner, etc. reported the group velocity reduction by using Moiré fiber gratings [19]. The delay can be tuned when the signal wavelength shifts the center of the transmission band. However, the practical systems don’t allow changing the signal wavelength. In 2006, J. T. Mok, etc. reported the slow light properties of gap solitons in an apodized FBG [20]. Using a high power signal, the optical nonlinearity induces an index change of FBG. Thus, the delay can be modified by varying the signal power. In addition, the dispersion effect can be eliminated through the soliton formation. However, this approach requires very high power signal (~2 kW), which limits its practical implications.

In this paper, a simple technique to obtain tunable delay is experimentally demonstrated by utilizing an active FBG written on Er/Yb codoped fiber. Since the reflection phase of FBG tends to vary rapidly near the band edges, the delay nearby becomes appreciable [21]. The time delay from the FBG reflection varies with the reflection spectrum shift when changing the pump power. In the experiment, we obtain a tunable delay of 0.9 ns for a 200 MHz signal with changing the 980nm pump powers. This scheme is very simple, and cost-effective. It may have important implications in the practical systems, such as data synchronization and optical phase array antenna [22–24].

2. Theory

The characteristics of FBG can be calculated using the coupled mode theory [21,25]. The reflection coefficient can be written as

\[
P = \frac{-\kappa \sinh(\sqrt{\kappa^2 - \sigma^2} L)}{\sigma \sinh(\sqrt{\kappa^2 - \sigma^2} L) + i \sqrt{\kappa^2 - \sigma^2} \cosh(\sqrt{\kappa^2 - \sigma^2} L)}. \tag{1}
\]
where $\kappa = \pi n_i / \lambda$ is the coupling coefficient, $n_i$ the spatial modulation amplitude, and $\lambda$ the wavelength, $\hat{\sigma}$ is the AC coupling coefficient and $\hat{\sigma} = \delta + i\alpha$, $\alpha$ is the gain (or loss) constant, $\delta = 2\pi n_{\text{eff}} \left( \frac{1}{\lambda} - \frac{1}{\lambda_{dB}} \right)$ is the detuning to the Bragg wavelength $\lambda_{dB} = 2n_{\text{eff}} \Lambda$, $\Lambda$ is the period, $n_{\text{eff}}$ is the effective index, and $L$ is the FGB length. The group delay reflected by the FGB is

$$
\tau = -\frac{\lambda^2}{2\pi c} \frac{d\phi}{d\lambda},
$$

where $\phi$ is the phase of the reflection coefficient and can be expressed as

$$
\phi = -\alpha \tan \left[ \frac{\sqrt{\kappa^2 - \hat{\sigma}^2}}{\hat{\sigma}} \coth(\sqrt{\kappa^2 - \hat{\sigma}^2} L) \right].
$$

Fig. 1. Calculated reflection spectrum (solid line) and group delay (dash dot line) in FBG.

We calculated the reflection spectrum and the group delay of a 3.5-cm-long FBG with the Bragg wavelength of 1545.611 nm and the spatial modulation amplitude of $0.53 \times 10^{-3}$. As shown in Fig. 1, the group delay becomes appreciable near the edges of the reflection band. Since the core refractive index of the active fiber varies with the pump power [26], the reflectivity spectrum may be changed if varying the pump power. Thus, for a signal with the central wavelength near the band edges of the FBG, an appreciable tunable optical delay can be obtained with different pump powers. Although the same effect can be obtained by thermal or mechanical means, these approaches are not compatible with practical systems for their long response time. This optical approach is considered owing to the short response time of optical signal processing.

3. Experiments and results

Figure 2 shows the experimental setup to achieve the tunable slow-light in the active FBG. The continuous light from a tunable laser source is modulated by an electro-optic modulator to produce the signal of 200 MHz sinusoidal pulse train, whose average power is 3mW. A ~3.5-cm FBG written on 2-m-long Er/Yb codoped fiber is pumped by a 980 nm laser diode. The pulse train is reflected by the FBG and output from the port 3 of the circulator. The tunable delay of the probe pulse reflected by the FBG is measured by a high-speed oscilloscope after opto-electrical conversion.
In the active fiber, the core refractive index changes as a consequence of the variation of the pump power [26]. The Bragg wavelength of a FBG is linearly proportional to the effective index, which is approximately equal to the core refractive index in the uniform FBG. Figure 3 shows the measured reflection spectra of the FBG with different pump powers. When the pump power increases from 0 mW to 160 mW, the reflection spectrum shift is about 0.01 nm. The estimated core index change $\Delta n$ is $\sim 9.4 \times 10^{-6}$. The threshold of active fiber relies on the active fiber length. When the pump power is close to the threshold, the index variation is relatively sensitive [26]. In fact, the threshold pump power is only several milliwatts for this about 3.5-cm-long active FBG. Thus, several milliwatts pump power is adequate to control the signal. However, 2-m-long Er/Yb codoped fiber used here enhance the threshold to several tens of milliwatts. The long active fiber used here contributes to the improvement of the output power and the signal quality.

Figure 4 shows the traces of the signal pulses for different wavelengths. From Fig. 4(a), without pumping, when the signal wavelength is tuned to the reflection edges of the FBG, 1545.622 and 1545.698 nm respectively, about 0.3 ns delay for both situations can be obtained compared to the case of the Bragg wavelength of 1545.660 nm. As shown in Fig. 4(b), when the pump power is 160 mW, the wavelength of the reflection edges is 1545.635 and 1545.711 nm respectively. The Bragg wavelength is 1545.673 nm. About 0.013 nm reflection spectrum shift can be observed. In addition, under zero pump power, the signal reflected from the FBG band edges experiences large distortion because the power is too low to detect, which is shown in Fig. 4(a). When the pump power is 160 mW, the relatively high signal power can be obtained. The signal distortion can be optimized.
Figure 5 shows the signal traces under different pump powers when the signal wavelength is set at 1545.704 nm. This wavelength is on the first right side lobe of the FBG reflection band when zero pump power. When the pump power increases to 100 mW, about 0.5 ns delay is obtained. The delay decreases gradually when the pump power increases from 100 mW to 130 mW. The pulses experience 0.4 ns advancement when the pump power is 160 mW. In short, when the pump power increases from 100 mW to 160 mW, up to 0.9 ns controllable delay has been obtained. From the parameters mentioned above, the group velocity can be estimated about $5.6 \times 10^7$ m/s, which is about 19 percent of the speed of light in free space.

Figure 6 shows the theoretical simulation for this process. We assume the delay spectrum shift is proportional to the pump power. The assumption is reasonable for the pump power is close to the threshold. The signal wavelength is set near the first right side lobe of the reflection spectrum. The calculated delay value varies with pump power. It increases from 0.17 ns to 0.42 ns when pump power rises from 0 mW to 100 mW, but declines to 0.25 ns when pump power continues to rise from 100 mW to 130 mW and to 0.16 ns when pump power is 160 mW.

The above theory, in which the reflection spectrum shift owing to the pump variation is considered as the only factor to influence the delay, can explain the variation tendency of delay; especially why the maximum delay occurs when the pump power is ~100 mW. The discrepancy between the theory and the experiment is probably due to the shape changing of the reflection spectrum line in the active FBG.
Fig. 6. Calculated delay spectrum shift for the FBG with different 980 nm pump powers. The inset illustrates the details of the delay varying with the reflection spectrum shift.

Compared with other approaches, this slow-light approach has many advantages. First, only a 980 nm pump and an active FBG are used to generate tunable delay. It is an extremely simple and very feasible slow light technology to achieve tunable delay. Besides, the delay value and the signal bandwidth rely on the characteristics of FBG. For example, shorter FBG length leads to broader bandwidth and smaller delay value. Actually, there is a trade off between the group delay and the signal bandwidth [27], but this should be further improved through optimizing the FBG parameters. The fractional delay is 18% in our experiments. Note that the delay here doesn’t depend on the bit rate of the signal. The larger fractional delay may be obtained using the higher bit rate signal. On the other hand, larger fractional delay can be obtained by cascading the grating in a serial manner. In addition, the signal is amplified in the active fibers, which provides a lossless or even gain slow-light approach.

4. Conclusion

We have experimentally demonstrated a very simple tunable delay slow-light scheme. Up to 0.9 ns delay is achieved by using a cheap and accessible and controllable active FBG by varying the pump power. The group delay generated by the FBG reflection becomes appreciable near the band edges of the reflection spectrum, and the reflection spectrum of the active FBG shifts with the pump power. We believe that this simple, feasible, cost-effective slow light approach will have a great future in developing optical data synchronization and optical phase array antenna.

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