Large tunable fractional delay of slow light pulse and its application to fast optical correlator

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Abstract: The slow light device based on photonic crystal coupled waveguide was fabricated, and a tunable delay of 72 ps was obtained for 2-ps-wide slow light pulses by local heating, which corresponds to a tunable fractional delay of 36. This value was further enhanced to 110 by compressing the output pulses through self-phase modulation and dispersion compensation in external fibers. We applied this device to optical correlator as a delay scanner, where the fractional delay determines the resolution of the delay scanning. Using this correlator, we successfully observed sub-picosecond pulses at a scan frequency up to 2 kHz, which is 100 times faster than that of mechanical scanners in conventional correlators.

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References and links

1. Introduction

Slow light with a group velocity much lower than that in vacuum yields a long delay in a compact device [1–9]. The performance of slow light is often evaluated by the delay-bandwidth product (DBP) and fractional delay. The former is an essential figure-of-merit (FOM) of the device because its bandwidth determines the shortest transmittable optical pulse, and hence the DBP constrains the largest buffering capacity. The latter is a more practical FOM giving the net buffering capacity of pulses broadened by higher order dispersion. If targeting advanced time-domain optical signal processing such as optical buffering, the tunable fractional delay is more crucial. The photonic-crystal coupled waveguide (PCCW) is a promising device because it generates wideband and dispersion-free slow light pulse on a chip at room temperature [10, 11] and its delay can be tuned by sloping the equivalent modal index along the waveguide (chirped structure) [12]. So far, we have obtained fixed and tunable fractional delays of 80 and 22, respectively, in a 280-μm-long PCCW by using local heating [13]. This tunable value is larger than those of any other on-chip slow-light devices (< 10). In a longer PCCW, however, the dispersion became noticeable due to small disordering in the fabricated device, so the values were rather degraded.

In this study, we fabricated the device using e-beam lithography with a higher extraction voltage than in our previous studies. Consequently, the dispersion was reduced and larger fixed and tunable fractional delays were obtained. In addition, we enhanced the fractional delays drastically by compressing output pulses through the self-phase modulation and dispersion compensation in external fibers. Since the pulse spectrum is changed in this case, we cannot count these values as buffering capacities. However, we can consider the tunable value as the resolution of the delay scanning. Therefore, we applied the device to optical correlator as a delay scanner. Optical correlators are widely used to observe fs- to ps-wide optical pulses. They usually use a mechanical delay scanner with a typical scan frequency f of no higher than 10 Hz. A faster scanner is required for high-volume multi-dimensional data acquisition in optical coherent tomography, terahertz time-domain spectroscopy, and so on. A grating-based delay line [14] and thermo-optic effect in Si waveguides [15] have been studied for this purpose. However, the former needs a large and complex optical system, while the latter only achieves a narrow scan range of around 1 ps. In this study, we used the PCCW and successfully observed sub-ps pulses at f < 2 kHz.

2. Tunable delay

Structural details of the PCCW have been reported in Refs [11–13]. It is fabricated on SOI substrate with a Si layer of 210 nm thickness. The photonic crystal slab consists of a triangular lattice of air-holes, with a pitch of 460 nm and diameter of mostly 270 nm. However, some airholes are position-shifted and/or down/up-sized in the range of 120 – 380 nm, particularly around the junctions with input and output (I/O) photonic crystal waveguides (PCWs). In previous studies, the device was fabricated by using 50 kV e-beam lithography. In this study, we employed 100 kV and expected the disordering to be reduced.

Figure 1(a) and (b) show the fabricated device. The magnified view of the photonic crystal suggests the high uniformity of airholes. The PCCW is 400 μm long, and is connected to I/O PCWs of 2700 μm total length. Around the PCCW, air-slots are aligned to enhance the thermal isolation and heating efficiency. Figure 1(c) shows the delay spectrum measured by using the modulation phase shift method at 300 MHz. Raw data of the spectrum exhibit some oscillations, but it is much smaller than previously. In previous studies, we usually used 10 GHz modulation in dispersion analyzer Alnair CDA 2100 although the measurable delay range was limited. If 300 MHz was used, higher coherence severely increased the phase noise caused by the internal reflection and localization of slow light due to the disordering. In this study, on the other hand, we could observe a reasonable spectrum with acceptable noise at 300 MHz. This is evidence that the disordering was reduced by the improved process. The spectrum exhibits a delay peak corresponding to the flat photonic band of the PCCW [11]. Neglecting the delay in the I/O PCWs, the peak group index evaluated after taking the moving
average is 95. The peak delay is 198 ps and the bandwidth (full-width at half maximum: FWHM in the PCCW) is 4.4 nm, which gives the DBP of 110.

The transmission and delay characteristics of short optical pulses were measured using setups in Refs [12, 13], that include mode-locked fiber laser, erbium-doped fiber amplifier (EDFA), band-pass filter (BPF), and a commercial cross-correlator. In this observation, we again confirmed the small disordering of the device from the lower dispersion in the pulse transmission measurement. In previous studies, the low dispersion transmission of 3-ps-wide pulses was observed reasonably for devices shorter than 300 μm. In this study, on the other hand, low dispersion was obtained for < 2-ps-wide pulses even in the 400 μm device. For the tunable delay, the device was locally heated by irradiating the device top with 442 nm laser light. The laser spot was adjusted to an elliptical shape parallel to the PCCW, with major and minor axes of 510 μm and 230 μm respectively by using cylindrical lens. The power \( P \) and central position \( x \) of the laser spot were optimized so that the delay tuning range was maximized while maintaining the low dispersion condition.

Figure 2(a) demonstrates the delay tuning of the slow light pulse. Here, 1.3-ps-wide pulses with center wavelength \( \lambda \sim 1.54 \text{ μm} \) and bandwidth (FWHM) \( \Delta \lambda = 4.5 \text{ nm} \) were incident on the device. The relatively large total delay includes the fixed delay in the long I/O PCWs. The maximum delay in the device was 169 ps, the continuous tuning range was 72 ps, and the average output pulse width (FWHM) \( \Delta \tau \) was 2.0 ps. Thus the fixed and tunable fractional delays are 85 and 36, respectively. In previous studies, the maximum value of the fixed delay was obtained for a narrow pulse width of 0.9 ps. The transmission of such narrow pulse was not observed in this experiment, which may be due to the dispersion in the long I/O PCWs. Nevertheless the long delay and the reasonably narrow pulse slightly improved the fixed fractional delay. On the other hand, the tunable value was enhanced by 1.6-fold than previously by the narrowed average pulse width.
Fig. 2. Cross-correlation waveforms showing the delay tuning of slow light pulse in PCCW by local heating. (a) Result for optimized power $P$ and central position $x$ of the laser heating. (b) Result with pulse compressor in Fig. 3. (c) Animation of measured time shift of waveform in (b) with detailed condition of $P$ and $x$.

Of course, this pulse width is still limited by the bandwidth and the remnant dispersion. As a simple method that breaks this limit, we compressed the output pulse. In this experiment, we amplified the peak power of output pulse from $-6$ to $37$ dBm by an EDFA and expanded its spectrum through the self-phase modulation in highly nonlinear fiber (HNLF). We used a 22 m HNLF with a dispersion of $-1.4$ ps/nm/km ($-0.030$ ps/nm). Then we successively connected 10 m long single-mode fiber (SMF) with a dispersion of 16 ps/nm/km (0.17 ps/nm) to compensate for the total dispersion including the device, other fibers and optics. Consequently, the pulse width was reduced to an average of 0.52 ps. This changes the delay tuning, as shown in Fig. 2(b) and (c). Fixed and tunable fractional delays increased to 290 and 110, respectively. As mentioned above, this tunable value can be regarded as the resolution of the delay scanning in the optical correlator. The correlation is obtained from the convolution integral of two pulses. In this study, we used the cross-correlation method where one pulse goes through the device under test (DUT) and the other is the reference (REF). Therefore, if the REF is narrower, we can measure narrower DUT pulses.

3. Optical correlator

Now we propose an optical correlator using the PCCW and pulse compressor as a delay scanner of the REF pulse, as shown in Fig. 3. Here, $P$ is modulated by a pulsed current from the signal generator (SG) to the laser so that the delay is scanned like a saw-tooth wave. The
interval between currents is set to be sufficiently longer than the thermal relaxation time in the PCCW. The heating position $x$ and the amplification in the EDFA cannot be changed dynamically with $P$. With such limited control parameters, the delay changed nonlinearly and the intensity and dispersion fluctuated nonuniformly. To avoid these problems, we limited the scan range to 22 ps, transformed the pulsed current appropriately, and the cross-correlation trace was calibrated by post-processing of the signal. This scan range is still sufficient for measuring ps to sub-ps pulses. After passing the PCCW, the REF pulse was compressed as mentioned above. Meanwhile, the branched pulse passed through the DUT. Here, fibers with bandwidth- and wavelength-tunable band-pass filter (BPF) were considered as DUT. The correlation waveform was observed through second-harmonic generation (SHG) using photomultiplier (PMT) connected with oscilloscope (OSC).

Figure 3. Cross-correlator using locally heated PCCW and pulse compressor.

Figure 4(a) shows correlation waveforms for different scan frequencies $f$ and scan ranges. Here, the DUT pulse width $\Delta\tau_{\text{DUT}}$ and REF pulse width $\Delta\tau_{\text{REF}}$ were fixed at 0.2 and 0.5 ps, respectively. Assuming these pulses to be Gaussian, the width of the correlation waveform, $\Delta\tau_{\text{corr}}$, is given by the relation $\Delta\tau_{\text{corr}}^2 = \Delta\tau_{\text{DUT}}^2 + \Delta\tau_{\text{REF}}^2$. Therefore, $\Delta\tau_{\text{REF}}$ is dominant in this observation. For a scan range of 22 ps, the waveform was maintained at $f < 1$ kHz, while it trailed at higher $f$ due to the slow thermal response. When the scan range was limited to 5 ps, the tail was not so evident up to $f = 2$ kHz. Figure 4(b) shows the normalized $\Delta\tau_{\text{corr}}$ for different $f$ and scan ranges. The waveform broadened at higher frequencies, but the broadening was suppressed by narrowing the scan range. If 10% broadening in $\Delta\tau_{\text{corr}}$ is acceptable, the highest $f$ reaches 2 and ~3 kHz with scan ranges of 5 and 3 ps, respectively.

To estimate the thermal response time of the delay scan, we modulated $P$ with a step-like current and switched the delay between the REF (0.5 ps) and DUT (0.2 ps) pulses, from completely separated to just overlapped. In this case, the cross-correlation waveform is given by the convolution integral of the ideal waveform and thermal response. The thermal response is derived by deconvoluting the ideal waveform for two Gaussian pulses of 0.2 and 0.5 ps widths from the correlation waveform. Figure 5 shows the normalized separation between two pulses, which corresponds to the delay scan of the REF pulse. The obtained response curve fits well to the exponential function with a 1/e time constant of 19 μs. Taking the Fourier transform of this exponential function, 50 and 90% frequency bandwidths are derived to be 8.3 and 2.8 kHz, respectively. The 90% bandwidth is in good agreement with the result of Fig. 4(b) with the shortest scan range. Within this bandwidth, the error in the delay scan for Fig. 4(a) can be smaller than 10%. The response time is determined by the thermal equilibrium between the PCCW area and outer area. As aforementioned, the heating laser spot was elliptical with a 230 μm width across the PCW. Therefore, the outer area having a larger thermal capacity was heated simultaneously, and this might delay the equilibrium. If the laser spot is narrowed so that only the PCCW area is irradiated, the response time will be shortened and the frequency bandwidth will be enhanced.
Fig. 4. Cross-correlation waveforms and their width Δτ_{obs} for different f. (a) Waveforms with scan range of 22 ps (red) and 5 ps (purple). (b) Δτ_{obs} measured for different scan ranges. Values are normalized by that at f = 100 Hz.

Fig. 5. Measured thermal response (blue) and exponential fit (black) estimated using the step-like heating.

Figure 6 shows the waveforms for different Δτ_{DUT}, which were controlled by changing the bandwidth of the BPF. Here, the small nonlinearity of Δt and intensity fluctuation in the PCCW were calibrated by the waveform at Δτ_{DUT} = 6.0 ps, which was measured separately using a commercial auto-correlator. As Δτ_{DUT} decreased from 6.0 ps, the waveform narrowed and converged at Δτ_{DUT} < Δτ_{REF} = 0.5 ps. It shows that the proposed system functions as a correlator.
4. Conclusion

We improved the tunable slow light characteristics obtained by locally heating the photonic crystal coupled waveguide. A tunable fractional delay of 36 was obtained for picosecond pulses, which is the highest record for on-chip slow light. By compressing output pulses externally, this value was further enhanced to 110. We considered this as a tunable resolution and applied to the delay scanning in the optical correlator. We successfully observed the sub-picosecond pulse with a scan frequency up to 2 kHz, which is at least 100 times faster than mechanical scanners in conventional correlators. It is limited by the thermal response time of 19 μs, and will be improved by limiting the heating area. In this study, we employed the external laser heating, but it can be replaced by integrated heaters. In addition to the delay, heaters can be incorporated to tune the target wavelength in the range of several 10 nm. Such a compact and flexible tunable delay will allow one-chip correlation systems.

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