Temporal pulse compression by dynamic slow-light tuning in photonic-crystal waveguides

K. Kondo, N. Ishikura, T. Tamura, and T. Baba
Department of Electrical and Computer Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

(Received 25 November 2014; revised manuscript received 27 January 2015; published 25 February 2015)

We demonstrate on-chip pulse compression based on the dynamic tuning in a copropagating slow-light system. Low-dispersion slow-light control pulse in lattice-shifted photonic-crystal waveguides enhances two-photon absorption. Generating free carriers dynamically through the two-photon absorption so as to sweep a signal slow-light pulse, the spectral broadening occurs with a monotonic chirp. The signal pulse is then compressed through the compensation of the chirp by means of integrated heaters. An input pulse of 13.9 ps length was compressed to 1.4 ps, corresponding to a compression factor of 9.9.

DOI: 10.1103/PhysRevA.91.023831 PACS number(s): 42.70.Qs, 42.25.Bs, 42.79.Nv, 42.82.—m

Lattice-shifted photonic-crystal waveguides (LSPCWs) generate low-dispersion slow-light pulses [1,2] and enhance nonlinear effects [2,3]. Depending on structural parameters, they simultaneously generate slow-light pulses whose group delay and dispersion are tunable [4]. Here, we focus on the copropagating slow-light system, in which the low-dispersion slow light and tunable slow light are used as a control pulse and signal pulse, respectively. Adiabatic wavelength conversion [5–11] and fast delay tuning [12,13] in the signal pulse through the nonlinearity of the control pulse have previously been achieved. In this paper, we demonstrate that pulse compression can also be achieved with spectral broadening by optimizing the two pulses and dispersion of the LSPCW.

Two approaches are well known for optical pulse compression. One is the spectral broadening in optical fibers followed by the dispersion compensation using a pair of gratings [14]. The same approach has also been demonstrated on a chip in Si photonic circuits [15]. The other approach is by generating a soliton pulse [16,17]. Even though they are different in terms of separate or simultaneous spectral broadening and dispersion compensation, both need the spectral broadening with a monotonic chirp [Fig. 1(a)]; in both cases, it is obtained by the optical Kerr effect. In recent years, on-chip pulse compression using a photonic-crystal waveguide (PCW) has been investigated as a result of the advancement of slow light. However, when two-photon absorption (TPA) occurs and free carriers are generated, for example, in Si PCW at telecom wavelengths, carrier plasma dispersion and absorption prevent the formation of the monochromatic wavelength chirp and degrade the compression. Soliton compression in a GaInP PCW with a small TPA resulted in a compression factor of 5.2 [18] compared to a factor of only 2.3 in a Si PCW [19]. These small values might also be due to the low flexibility of the process in which the signal pulse tunes itself through the nonlinearity.

In our approach using the copropagating slow-light system in the Si LSPCW, we can improve the flexibility and obtain the spectral broadening with the monotonic chirp by using carrier plasma dispersion instead of the optical Kerr effect. The carrier plasma dispersion is dynamically induced by the TPA of a control pulse; the TPA is enhanced by the spatial compression of the control pulse under the slow-light propagation. The carrier plasma dispersion blueshifts the spectrum of a copropagating signal pulse. Here the control pulse is attenuated by some losses in the propagation. Therefore, when the control pulse slowly overtakes the signal pulse, the amount of the blueshift in the signal pulse is gradually reduced; hence the signal spectrum is broadened from the initial one toward the short-wavelength side resulting in a monotonic chirp [Fig. 1(b)]. Subsequently, the pulse is compressed through the dispersion compensation in the LSPCW whose dispersion is tuned by integrated multiheaters. In this paper, we first show the experimental results and then explain the physical behaviors of the two pulses in detail. We will also discuss the relation between the pulse compression and the other functions of the copropagating slow-light system.

The air-bridge LSPCW with multiheaters is fabricated on the silicon-on-insulator substrate by using a complementary metal-oxide semiconductor (CMOS)–compatible process whose minimum feature size is 180 nm [4], as shown in Fig. 2. The 350-μm-long LSPCW consists of a line defect waveguide in a 210-nm-thick Si photonic-crystal slab with an array of air holes in a triangular lattice (250-nm hole diameter and 450-nm lattice constant). The lattice shift is introduced into third rows of holes on both sides from the line defect to generate the low-dispersion slow light [2,11,13]. Both ends are coupled to external lensed fibers through Si wire waveguides and spot size converters. Seven pairs of TiN heaters are integrated beside the LSPCW and controlled independently by an external controller through Al wires. Figure 3 shows the group delay spectrum of the LSPCW. Without heating (black line), a delay peak appeared at λ ~ 1540 nm, which corresponds to tunable slow light. The flat spectrum on the long-wavelength side corresponds to low-dispersion slow light. When we applied 125 mW of power to each of the four pairs of heaters on the rear side, the delay peak of the heated area shifted to 1548 nm (red line). The shorter side of the peak was flattened due to the delay peak on the front side averaged by the sloped temperature distribution, while the longer side corresponds to the low-dispersion slow-light band that has been redshifted by the heating. At these heating conditions, we launched the signal and control pulses on the LSPCW at peak wavelengths of λs and λc, respectively. At this λs, the passive loss in the LSPCW in the absence of the control pulse was estimated to be 7 dB. Synchronized signal and control pulses with wanted pulse lengths and peak wavelengths were produced using a mode-locked fiber laser, two band-pass filters, an optical attenuator, and a mechanically tunable delay line. The wave form and spectrum of input and output pulses were measured...
by cross-correlator and optical spectrum analyzer, respectively. The pulse length was evaluated as the full width at half maximum (FWHM) of the wave form after deconvoluting from a reference pulse, assuming either Gaussian or sech² profile, which gives a better fit. The detail of the optical setup was the same as those for the adiabatic wavelength conversion [11] and the fast delay tuning [13]. However, as discussed below, we set the signal pulse length to be longer and control pulse length to be shorter than those in Ref. [11]; i.e., the length and the peak power of the signal pulse are 13.9 ps and 0.3 W, respectively, compared to 5.7 ps and 13 W for the control pulse.

Experimental results are summarized in Fig. 4. Figure 4(a) shows the cross-correlation wave form of the output signal pulse for a reference pulse, color map, and pulse length Δτₚ as a function of the relative input timing of the control pulse Δt₀. The white solid line on this color map indicates the output timing of the control pulse. The signal pulse is sharpened along with this line. Δτₚ takes its minimum value of 1.9 ps for Δt₀ = 0.5–2.5 ps, corresponding to a compression factor of 7.0.

Figure 4(b) shows the spectral profile, color map, and width Δλ. Here, the full widths at −3 and −10 dB of the spectral peak are employed as Δλ. The Δλ−3dB does not increase so much although the temporal pulse length is compressed at Δt₀ > 0.5 ps. Here, Δλ−3dB is dominated by the residual unchanged spectral components having a narrower width and higher peak, which is not the spectral behavior of interest. At Δt₀ < 0.5 ps, the spectral broadening in Δλ−3dB becomes clear due to the absorption of the unchanged components by free carriers, but still the unchanged components have an influence. Therefore, Δλ−10dB, which can eliminate the influence, exhibits the spectral broadening more reasonably.

The spectral oscillation that might be caused by the passive transmission spectrum of the LSPCW is observed in the profile and color map. Neglecting the oscillation, Δλ−10dB evaluated from the envelope increases from 0.53 nm at the input end to 4.67 nm at the output end. The broadening mainly occurred toward the short-wavelength side because of the dynamic tuning due to the TPA-induced free carriers; however, a slight broadening is also seen toward the long-wavelength side. The redshifted components at Δt₀ from −2 to 8 ps might be due to the optical Kerr effect, which is known to occur at the leading edge of the control pulse. On the other hand, that at Δt₀ < −2 ps might be due to the depletion (diffusion) of carriers, which is the reverse process of the blueshift due to the generation of carriers. Figure 4(c) shows the peak power and integrated power of the signal pulse normalized by their values without the control pulse. The reduction of the integrated power at small Δt₀ is mainly caused by the free-carrier absorption. At Δt₀ = 2.5 ps, the integrated power is reduced to 0.45 times, which adds 3.5 dB loss to the above-mentioned 7 dB passive loss. However, the peak power is enhanced up to 2.6 times with the pulse compression. A similar compression is observed at Δt₀ from −2 to 7 ps, whereas a smaller loss is observed at larger Δt₀. We estimated the TPA-induced free-carrier density from the equations derived in [3,20] to be of 2 × 10¹⁸ cm⁻³ order (∆n ≈ −0.006) at the input end where the control pulse has the highest intensity, while of 10¹⁶ cm⁻³ order (∆n ≈ −0.0001) order at the output end, due to the attenuation of the intensity.

We repeated the same measurement for many device samples and observed the similar behaviors of the pulse wave
form and spectrum. Figure 5 shows the pulse wave forms showing the highest compression factor of 9.9; a 13.9-ps pulse was compressed to 1.4 ps. This compression factor is higher than those reported previously for any on-chip pulse compression.

We analyze the behaviors of the pulses in the LSPCW and consider the observed pulse compression. The time-space relation between the two pulses depends on the input wavelengths in the group delay spectrum of the LSPCW, the heating power, and the temperature distribution. The group delay spectrum of LSPCWs, $\Delta t(\lambda)$, is expressed as

$$\Delta t(\lambda) = \int_0^L \frac{\partial t [\lambda(z) - a \Delta T(z)]}{\partial z} \, dz, \quad (1)$$

where $L$ is the LSPCW length, $\partial t / \partial z$ is the local delay given by the group delay of the nonheated condition, $\lambda(z)$ is the local wavelength considering the dynamic tuning, $\Delta T(z)$ is the local temperature shift due to the heaters, and $a$ is a spectrum-temperature coefficient. The timing difference of the two pulses, $\Delta t_{\text{comp}}$, at $z$ is given by

$$\Delta t_{\text{comp}}(z) = \int_0^z \left\{ \frac{\partial t [\lambda(z) - a \Delta T(z)]}{\partial z} - \frac{\partial t [\lambda_c - a \Delta T(z)]}{\partial z} \right\} \, dz - \Delta t_0. \quad (2)$$

For these formulas, we first determine $\Delta T(z)$ by fitting the calculated $\Delta t(\lambda)$ with the experimental one, considering $a = 0.082 \text{nm/K}$, as reported for the Si LSPCW [7]. When we assume $\Delta T(z)$ under the heating condition as that shown in Fig. 6(a), $\Delta t(\lambda)$ calculated from Eq. (1) becomes that depicted by the gray line in Fig. 6(b); this also agrees well with the experimentally measured $\Delta t(\lambda)$ (red line). Here, $\Delta T$ at the nonheated region ($z < 125 \mu\text{m}$) becomes $\sim 40 \text{ K}$ due to thermal diffusion. The local group delay spectra are arranged along $z$ based on the $\Delta T(z)$ in Fig. 6(c), where the evolution of the pulses’ spectra are overlaid. While the control pulse continues to propagate in the low-dispersion band, the signal pulse is influenced by the dynamic tuning during the
propagation in the positive-dispersion region and then begins to propagate in the negative-dispersion region with a temporary high group velocity and small local delay. The corresponding variations in group velocities of two pulses in LSPCW. (d) Variation in group velocities of two pulses in LSPCW. (e) Relative delay, $\Delta t_{\text{cc}}$, of signal pulse components with 1-ps interval. $\Delta t_0 = -4\text{ ps}$ and $\Delta t_t = 12\text{ ps}$ are assumed. The positive value of $\Delta t_{\text{cc}}$ shows that the signal pulse is delayed from the control pulse. The change of line color beyond $\Delta t_{\text{cc}} = 0$ schematically expresses the blueshift due to the dynamic tuning.}

We experimentally estimated the values of $\Delta \lambda_{\text{cc}}$ and $z_0$ to be $-3.5\text{ nm}$ and $160\mu m$, respectively. The signal pulse components overlap at $\Delta t_{cc} = 0$ from the back end in sequence; thus, the blueshift is gradually reduced from the back end to the front end, forming a monotonic wavelength chirp, as depicted in Fig. 1(b). The chirped pulse is broadened in the positive-dispersion region. It is then focused in the negative-dispersion region at $z > 175\mu m$ and compressed around the point where $\Delta t_{cc} = 5\text{ ps}$ at the output end. According to Fig. 6(f), the pulse duration within $\pm 4\text{ ps}$ contributes to the compression, whereas the outer components do not. However, some outer components do contribute to the compression because the control pulse has a finite length. The experimental results are well explained by Fig. 6(f).

As the signal pulse is as long as $13.9\text{ ps}$ at the input end, similar pulse compression occurs in the range of approximately $-5 < \Delta t_0 < 5\text{ ps}$. However, the front end and back end of the signal pulse are not involved in the compression for other $\Delta t_0$. Note that the integrated pulse intensity is greatly reduced at $-5 < \Delta t_0 < 0\text{ ps}$ [Fig. 4(c)]. In this situation, signal components launched later than the control pulse are attenuated by the free-carrier absorption, which might look like a more compressed pulse.

Finally, let us summarize the functions achieved by means of the dynamic tuning in the copropagating slow-light system. Previously, we have reported large adiabatic wavelength shift [11] and fast delay tuning [13] using this system. The pulse compression fundamentally utilizes the same system, but

![Diagram of pulse compression](image)

**FIG. 6.** (Color online) Analysis of the pulse compression. (a) Assumed temperature distribution. (b) Calculated group delay spectrum (pale tone line) and measured spectrum (deep tone line). (c) Local group delay spectrum and spectra of two pulses. (d) Variation in group velocities of two pulses in LSPCW. (e) Relative delay, $\Delta t_{cc}$, of signal pulse components with 1-ps interval. $\Delta t_0 = -4\text{ ps}$ and $\Delta t_t = 12\text{ ps}$ are assumed. The positive value of $\Delta t_{cc}$ shows that the signal pulse is delayed from the control pulse. The change of line color beyond $\Delta t_{cc} = 0$ schematically expresses the blueshift due to the dynamic tuning.

the length of the signal pulse does not change between the input and output. On the other hand, when the signal pulse is blueshifted by the dynamic tuning, the behavior changes, as shown in Fig. 6(f). Here, we simplified the situation such that each temporal component of the signal pulse is blueshifted when it overlaps with the control pulse peak ($\Delta t_{cc} = 0$). Since the control pulse is attenuated mainly due to the TPA and the free-carrier absorption, we consider that the amount of the blueshift $\Delta \lambda_0 + \Delta \lambda_{\text{cc}}$ at the input end decreases in inverse proportion to $z^2$ and vanishes at $z > z_0$, i.e.,

$$\Delta \lambda_0(z) = \Delta \lambda_{\text{cc}}(1 - z/z_0)^2.$$  \hspace{1cm} (3)

**TABLE I.** (Color online) Three functions produced by dynamic tuning in copropagating slow-light system.

<table>
<thead>
<tr>
<th>Function</th>
<th>Signal spectrum</th>
<th>Pulse length relation</th>
<th>Signal dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse compression</td>
<td>Expanded</td>
<td>Signal</td>
<td>Control</td>
</tr>
</tbody>
</table>
the main differences are in the setting of pulse length and wavelength, as summarized in Table I. As pure spectral shift without broadening is desired in the adiabatic wavelength shift, the dynamic index change should be applied uniformly to all the signal components. For this purpose, a low-dispersion signal pulse and a long control pulse are effective. The fast delay tuning also uses similar wavelength shifts but needs the dispersion in the signal pulse for changing the output timing. Moreover, the control pulse used as a timing clock needs to be short enough for the fast response. Therefore, the optimum length of the control pulse is the same as that of the signal pulse. In contrast, the pulse compression is obtained in the spectral broadening process, whereby the short control pulse sweeps the signal pulse, and the dispersion compensation. Such a variety in pulse length, group velocity and dispersion, as well as the enhanced nonlinearities, are achieved by the LSPCW and the large flexibility of slow light. The dynamic tuning in the copropagating slow-light system of the LSPCW is expected to additionally produce other functions.

This study was partly supported by the New Energy and Industrial Technology Development Organization.