Pulse Compression Using Direct Feedback of the Spectral Phase From Photonic Crystal Fiber Output Without the Need for the Taylor Expansion Method

Muneyuki Adachi, Keisaku Yamane, Ryuji Morita, and Mikio Yamashita

***Abstract*—Characterization and compensation of the complex spectral phase and the temporal profile of output pulses from a photonic crystal fiber (620–945-nm spectral broadening) were performed using a computer-controlled feedback system that combines a modified spectral-phase interferometry for direct electric-field reconstruction apparatus and only a 4-f chirp compensator having a spatial light modulator. These pulses were adaptively compressed from 12-fs input pulses to 6.8-fs. In addition, the compressed pulse profile showed excellent agreement with results measured independently with fringe-resolved autocorrelation.**

***Index Terms*—Chirp compensation, optical pulse compression, photonic crystal fiber (PCF).**

THE PHOTONIC crystal silica fiber (PCF) has attracted much attention because of its unusual dispersion profile and hence the efficient generation of ultrabroad-band pulses [1]–[2]. Since the first experimental demonstration of the efficient spectral broadening using the fiber [1], [2], a variety of applications such as pulse compression, ultrabroad-band and frequency-conversion optical sources for spectroscopy and biomedicine, optical frequency metrology, and telecommunication technologies have been pointed out. Among them, it is expected that further pulse compression of ultrashort laser pulses without any amplification opens the way for monocycle fiber optics.

Very recently (2003), pulse compression using the PCF was attempted by a passive chirp compensator consisting of the combination of a prism pair and a chirped mirror [3]. The experiment was done using the conventional measurement of only the group-delay dispersion (GDD) of the fiber output (700–810-nm spectral broadening) by a spectral gating method with sum frequency generation. The compressed pulse duration was estimated to be 25 fs by fringe-resolved autocorrelation (FRAC) which contained relatively large wings under the assumption of a pulse shape. This imperfect pulse compression far from the 18-fs transform limited pulse was the result of the following problems: 1) the bandwidth limitation and the inter-relation between the GDD and third-order phase dispersion of the employed chirp compensator; 2) insufficient information on the complicated spectral phase $\phi(\omega)$ of the output from PCF where several nonlinear phenomena occur simultaneously, such as self-phase modulation, parametric four-wave mixing, stimulated Raman scattering, soliton formation and self-steepening, as well as unusual dispersion profile [4]; 3) nonexact measurement of the temporal intensity profile of the compressed pulse; and 4) the relatively low peak power of the output pulse from the PCF, which is due to the ultrabroadening of its spectrum and the limitation of the fiber-input power available directly from a Ti : sapphire laser.

The purpose of this letter is to experimentally demonstrate that a technique based on direct feedback of the spectral phase without Taylor expansion enables us to perfectly compress the much broader band pulses from the PCF and to overcome the above-mentioned problems.

The main experimental setup consists of a 12-fs Ti : sapphire laser, a 3-mm-long PCF, a computer-controlled feedback system that combines only a 4-f chirp compensator having a spatial light modulator (SLM) (see [5, Fig. 1]) and a modified spectral-phase interferometer for direct electric-field reconstruction (M-SPIDER) apparatus with a high sensitivity [6]–[8], and a fringe-resolved autocorrelator. The employed feedback system is based on a previously reported apparatus [5]. The pulse beam from a mode-locked Ti : sapphire laser (12-fs pulse duration, 600-mW average power, 75-MHz repetition rate, and 790-nm center wavelength with a spectrum from 680 to 920 nm) was split with a 1 : 3 beam splitter. The lower intensity pulse (150 mW) was passed through a focusing lens (100-cm focal length) for collimation and then directed into the M-SPIDER apparatus as an intensified chirped reference pulse. The higher intensity pulse (450 mW) was coupled into the PCF (2.6-μm core diameter, 3-mm length, 900-nm zero dispersion wavelength) by a reflective objective lens ($\times$36, Au coated), and the output pulse was recollimated by another reflective objective lens ($\times$36, Al coated) to avoid the dispersion and astigmatism effects of the conventional glass lenses. The effective coupling and transmission efficiency was 20%. The PCF output spectrum was measured by a 50-cm spectrometer. The self-phase modulated output pulse (60 mW) with a large and complicated nonlinear chirp was directed into the 4-f chirp compensator. This 4-f system consisted of a pair of gold-coating gratings (300 lines/mm groove density), a pair of sliver-coating mirrors, a pair of silver-coating concave mirrors (200-mm focal length), and an SLM (648 pixels, 97-μm pixel width, 5-μm pixel gap, 66.1-mm total length, 85% transmission at 800 nm).

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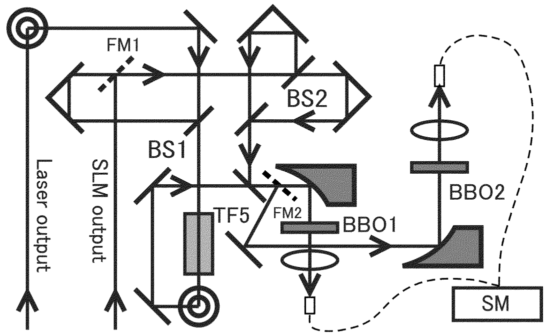

Fig. 1. Optical configuration for highly sensitive and reproducible M-SPIDER. When flipped mirror FM1 is OFF and FM2 is ON, the SH interferogram is measured using a 25-μm-thick BBO2 crystal (type I). BS1, BS2: ultrabroad-band beam splitters. TF5: highly dispersive glass. BBO1: 50-μm-thick BBO crystal (type II). SM: multimode-fiber attached spectrometer.

The output (15 mW) from the 4-f chirp compensator was directed into the M-SPIDER apparatus for characterization (Fig. 1). Upon entering the M-SPIDER apparatus, the input pulse was split into two beams (1 : 4), and upon recombining the two beams, a delay τ was inserted through a Michelson interferometer arm. The reference pulse (the weaker of the two beams split directly from the laser oscillator output) was used to provide a strongly chirp pulse by transmission through TF5 glass (10-cm length). The duration of the chirped reference pulse was 20 ps. The reference pulse and the aforementioned pulses from the M-SPIDER input were combined and focused onto a β-barium borate (BBO) crystal (type II, 50-μm thickness: BBO 1) by an aluminum parabolic mirror (50-mm focal length) to produce the interferogram of two sum-frequency waves. The SPIDER signal was detected by a 50-cm spectrometer (1200-lines/mm groove density, 800-nm blaze wavelength) with an intensified charged coupled device camera of 1024×256 channels. The total wavelength resolution was better than 0.05 nm at 400 nm. Because the limited bandwidth at any given angle of the grating was 37.5 nm at 400 nm, the grating was automatically rotated three times (center wavelengths of 380, 410, and 440 nm) in order to detect the SPIDER signal with the ultrabroad-band spectrum (370–445 nm). Consequently, it took 3×10 s $= 30$ s to get one signal.

The delay time was evaluated from the measurement of the second-harmonic (SH) interferogram [Fig. 2(e)] of the intensified pulses split directly from the oscillator (Fig. 1) because of the better signal-to-noise ratio compared with the usual SH replica interferogram. Moreover, spectral range (370–455 nm) is almost the same as that (370–445 nm) of the SPIDER signal. In addition, through the use of flipped mirrors, a parabolic mirror, a 25-μm-thick BBO (type I: BBO 2), a filter, and a fused-silica lens, another SH arm for the independent adjustable measurement of the SH interferogram was made. To accurately reconstruct the spectral phase over the whole spectral range, we employed a previous subtraction method [5], [9]. This method permitted us to avoid the nonlinear wavelength error appearing in measurements in the greatly broadened spectral range with high wavelength resolution, but not employed the delay time of the constant value (approximately $\tau \cong 850$ fs). The phase difference $\theta_{\rm SPI}(\omega)$ obtained from the SPIDER

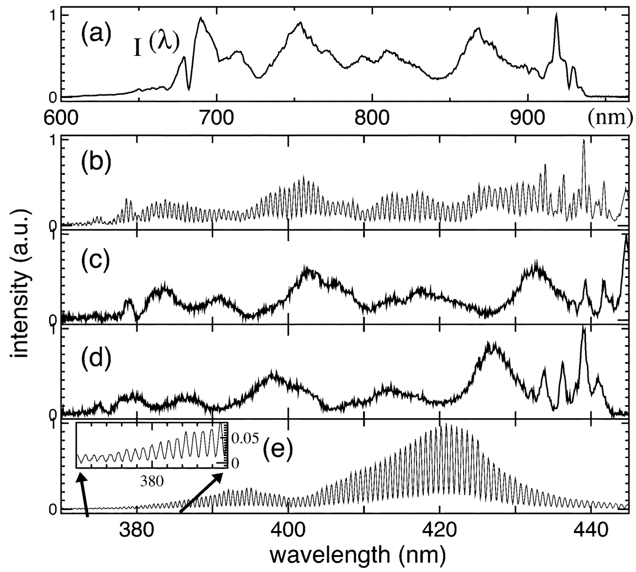

Fig. 2. In the SLM-OFF case (before chirp compensation), (a) PCF output spectrum, (b) SPIDER signal, (c) and (d) replica spectra, and (e) SH interferogram.

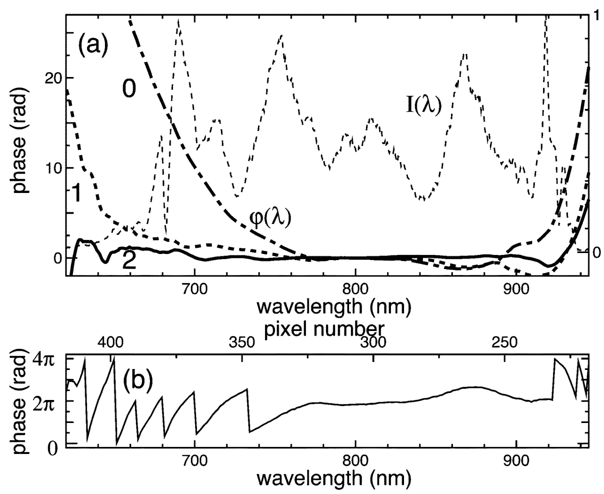

Fig. 3. (a) Dashed–dotted, dotted, and solid lines are reconstructed spectral phases before compensation and after first and second feedback compensations, respectively. A thin dashed line is SLM-output spectrum after second feedback. (b) Wrapped spectral phase applied by SLM at the second feedback time.

signal [9] contains a delay-dependent linear term $\tau\omega$ (which must be removed for spectral phase reconstruction) according to $\theta_{\rm SPI}(\omega) = \phi(\omega) - \phi(\omega - \Omega) + \tau\omega$. On the other hand, the corresponding phase difference $\theta_{\rm SH}(\omega)$ obtained from the SH interferogram contains only the delay term $\tau\omega$ according to $\theta_{\rm SH}(\omega) = \tau\omega$. Therefore, if there is system error involved in the determination of the delay time, this method is the best way to subtract $\theta_{\rm SH}(\omega)$ from $\theta_{\rm SPI}(\omega)$ over the whole spectral range as a background to correctly remove the term $\tau\omega$ [5], [9].

The procedure of the feedback chirp compensation is as follows: 1) Measure the SH interferogram. 2) Measure the SPIDER signal and the replica pair spectra in the SLM-OFF case. 3) Reconstruct the spectral phase in the SLM-OFF case. 4) Apply the corresponding negative spectral phase by the SLM to compensate for the chirp. 5) Return to Step 2 in the SLM-ON case. After

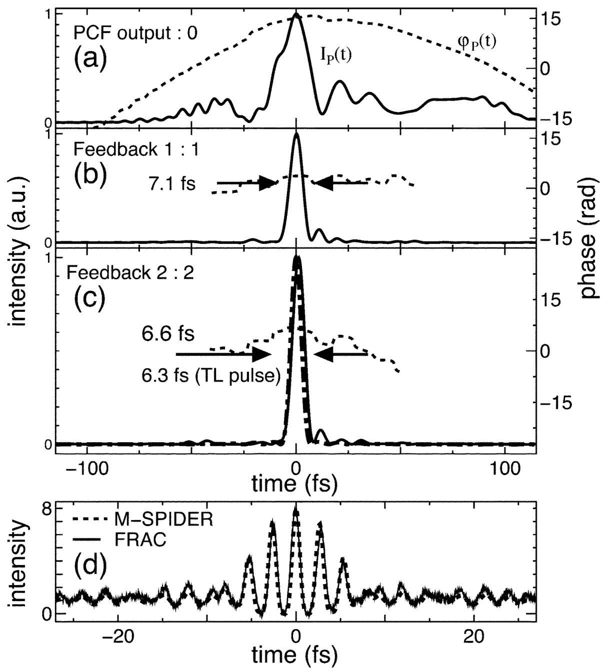

Fig. 4. Reconctructed temporal intensity profiles (solid lines) and phases (dotted lines) for (a) before compensation and after (b) first and (c) second feedback compensations. A dashed–dotted line in (c) is 6.3-fs transform limited pulse. (d) FRAC traces of direct measurement (solid line) and retrieved from M-SPIDER data (dotted line).

one more iteration in the SLM-ON case, $(2) \rightarrow (3) \rightarrow (4) \rightarrow (2)$, the pulse compression is accomplished.

The PCF output spectrum with 60-mW average power broadened from 620 to 945 nm, as shown in Fig. 2(a). The SPIDER signal and replica spectra of the PCF output before feedback compensation (SLM-OFF case) are shown in Fig. 2(b), (c), and (d). The replica spectral structures are similar to the PCF output one, implying that the thickness of the BBO crystal does not affect the SPIDER signal. Moreover, the intensity of the SPIDER interferogram is strong enough to characterize the spectral phase of the PCF output pulse over the entire spectral region. The minimum detectable average power is about 5 mW (60 pJ/pulse) [6]–[8]. The value of the spectral shear $\Omega/2\pi$ was measured to be 8.24 THz. The reconstructed spectral phase of the PCF output pulse is shown by a dashed–dotted line in Fig. 3(a). It indicates the complicated behavior in the 710–930-nm wavelength region and the variation over 30 rads. A dotted line and a solid line in Fig. 3(a) show the spectral phases after the first and second iterative compensations, respectively. The compensated spectral phase after second feedback was converged within 1.3 rad throughout the pulse spectral region. This result was confirmed to be stable at least for 1 h by remeasurements of its spectral phase. The spectral phase applied by SLM at the second feedback time is shown in Fig. 3(b). In actuality, the applied phase change was wrapped between 0 to 4π due to limitations of the modulation depth of SLM.

The corresponding reconstructed temporal intensity and phase profiles are shown in Fig. 4. The temporal intensity profile of the PCF output broadens asymmetrically over 150 fs and the phase varies complicatedly over 30 rads. After first and second iterative compensations, its pulsewidth was reduced to 7.1 [Fig. 4(b)] and 6.6 fs [Fig. 4(c)], respectively. This compressed pulse almost corresponds to the 6.3 fs transform-limited one. To the best of our knowledge, this is the first complete pulse compression of the PCF output in the two-cycle region.

The compressed pulse after second iteration was also measured independently by the FRAC method, as shown by a solid line in Fig. 4(d). The employed fringe-resolved autocorrelator has a flipped mirror, a thin polarizer to select the p-polarization, a 25-μm-thick BBO (type I), and a filter to cut the fundamental pulse. The FRAC trace retrieved from the reconstructed spectral phase and measured spectral intensity is shown by a dotted line in Fig. 4(d). The agreement between the measured and retrieved FRAC traces is excellent. This result suggests that the spectral-phase feedback technique without using the Taylor expansion method at all for $\phi(\omega)$ is significantly reliable and powerful even for complicated nonlinear-chirp compensation. Moreover, this simple technique can be applied for chirp compensation of any unknown or fluctuated spectral phase $\phi(\omega)$ in the quasi-real time mode. Furthermore, this technique has the potential of an extremely useful tool in generating extremely short pulses, even for ones who are not familiar with ultrafast optical technologies.

In conclusion, we have demonstrated that a computer-controlled spectral-phase feedback system combining only a programmable chirp compensator with a liquid crystal SLM and an M-SPIDER apparatus enables us to compress the PCF output pulse to 6.6 fs in the two cycle region for the first time. The generated pulse profile with a nearly transform limitation has also been confirmed by an excellent agreement with the independently measured FRAC trace.

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