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# Pulse compression of white-light continuum generated by induced phase modulation in a conventional glass fiber

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The 530–880-nm continuum pulse with a greatly asymmetric temporal profile over 500 fs and a spectral phase variation over 150 rad, which was generated by induced phase modulation (IPM) as well as self-phase modulation in a conventional fused-silica fiber, was compressed to 7.8 fs by a feedback technique. Fundamental (a center wavelength of 800 nm, a duration of 80 fs, a pulse energy of 64 nJ) and signal pulses (a center wavelength of 670 nm, a duration of 80 fs, a pulse energy of 65 nJ) produced by one common femtosecond source with an optical parametric amplifier were copropagated in the fiber under an optimum delay time between the two pulses. The computer-controlled feedback system that combines a 4-*f* phase compensator with a spatial light modulator and a modified spectral phase interferometry for a direct electric-field reconstruction, automatically compensated for not only the conventional nonlinear chirp (group-delay dispersion and its higher-order dispersion) but also the frequency-independent group-delay (first-order phase dispersion), both of which are essential for pulse compression by use of the IPM effect. © 2004 Optical Society of America

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## 1. INTRODUCTION

For the generation of monocyclelike optical pulses, over-one-octave spectral broadening of pulses and compensation of complicated phase dispersion over the whole frequency range are required. One of the approaches to realize these key technologies is to utilize not only self-phase modulation (SPM) but also induced phase modulation (IPM) based on nonlinear copropagation of two or more different-color femtosecond pulses with a carrier phase locking in a single-mode fiber and to utilize a 4-*f* phase compensator with a spatial light modulator (SLM).<sup>1–4</sup> Recently, white-light continuum generation with the IPM effect in a conventional glass fiber (480–900 and 690–1230 nm) and that in a gas-filled hollow fiber (300–1000 nm) were experimentally demonstrated.<sup>5–7</sup> Moreover, it has been experimentally indicated that the adjustment of frequency-independent group delay (first-order phase dispersion) as well as conventional chirp compensation (compensation of group-delay dispersion and its higher-order dispersion) is needed, for which only an active phase compensator with a SLM is applicable.<sup>8</sup> In addition, the SLM phase compensator has been experimentally demonstrated to have a capability of phase compensation of ultrabroadband pulses and hence the generation of sub-4-fs pulses.<sup>9–13</sup>

The spectral phase of the white-light continuum generated by the dispersive IPM effect in a glass fiber, however, is complicated (owing to the combined effect of the two-

pulse interaction and high dispersion) and the peak power is low. Therefore, it is difficult to characterize its spectral phase precisely over the whole frequency range. In this paper, we demonstrate that a feedback technique that combines programmable SLM phase compensation and modified spectral phase interferometry for direct electric-field reconstruction (M-SPIDER) with a high sensitivity<sup>14–16</sup> enables us to overcome the above-mentioned problems and to compress induced phase-modulated pulses in a conventional glass fiber to sub-8 fs for the first time to our knowledge.

The continuum generation technique with the IPM effect in a conventional glass fiber has advantages over that when the SPM effect is used in a photonic crystal fiber or in a tapered fiber, as follows: the capability of generation of the continuum with an arbitrary central wavelength regardless of fiber dispersion characteristics (by selective combinations of different wavelength signal and idler pulses from an optical parametric amplifier, the fundamental pulses, their second-harmonic pulses, and their third-harmonic pulses as different-color fiber-input pulses) and the potential for widespread availability of conventional glass fiber. In addition, the IPM technique has the following advantages compared with the SPM technique for a conventional glass fiber and a gas-filled hollow fiber: the practical efficiency in phase modulation is twice that shown by a coefficient of the cross-modulation term in nonlinear pulse propagation

equations,<sup>1-3,5-7</sup> and the fiber-output electric fields with different central wavelengths are constructively synthesized in the spectral region to broaden the bandwidth significantly (exceeding one octave<sup>7</sup>). That is, these effects enable us to significantly broaden the spectral width under the relatively low input power and hence to avoid optical damages of the glass fiber or the gas-filled fiber unlike in the SPM case.

## 2. EXPERIMENTAL

The experimental setup is shown in Fig. 1. A single-mode fused-silica fiber (Model F-SPV, Newport) with a 4-mm length and a 2.7- $\mu\text{m}$  core diameter was used for continuum generation by dispersive IPM and SPM effects.<sup>5,6,8</sup> Two-color pulses (800 nm, 80 fs, 64 nJ and 670 nm, 80 fs, 65 nJ for a center wavelength, a pulse duration, and a pulse energy, respectively) originated from a

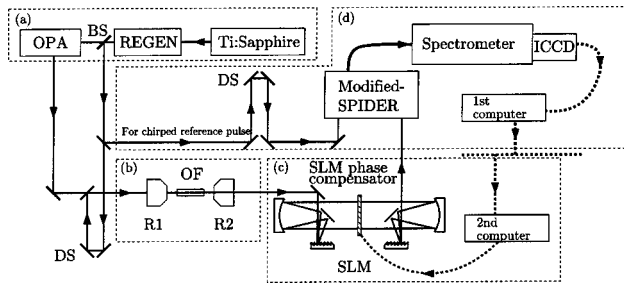


Fig. 1. Experimental setup for adaptive compression of induced phase-modulated pulses. (a) Optical source for fiber input of 80-fs fundamental and signal pulses. (b) A fused-silica fiber (OF) for continuum generation by use of IPM (DS, delay stage; R1, R2, reflective objectives). (c) 4- $f$  phase compensator with a feedback-controlled SLM. (d) Real-time operation, modified SPIDER apparatus.<sup>14</sup>

common optical source consisting of a femtosecond pulse oscillator, a regenerative amplifier, and an optical parametric amplifier at a 1-kHz repetition rate (Alpha-1000S, B.M. Industries). To focus these two input pulses into the fiber and collimate its output, a pair of nondispersive reflective objectives ( $\times 36$ ) coated with gold and silver, respectively, was employed. The delay time of the 800-nm fundamental pulse with respect to the 640-nm signal pulse was adjusted to overlap in the middle of the fiber and hence to yield the most efficient IPM effect. The typical fiber-output efficiency was 20%. The output pulse was spectrally broadened from 530 to 880 nm [Fig. 2(a)] and was directed to a programmable SLM phase compensator.<sup>8-13,15</sup> The 4- $f$  phase compensator with a 648-pixel SLM (97- $\mu\text{m}$  pixel width, 5- $\mu\text{m}$  pixel gap, 1/150-mm grating constant, 350-mm focal length) and the procedure to apply the phase shift was almost the same as those previously reported.<sup>8-13,15</sup> The throughput of the compensator including several guiding aluminum mirrors was 25%.

## 3. FEEDBACK PHASE COMPENSATION

To characterize the pulse before (SLM off) and after (SLM on) compensation, a highly sensitive M-SPIDER apparatus was employed, which is described in detail in Refs. 14 and 15. The powerful reference pulse  $E_c$  with strong chirp was directly generated by letting the fundamental pulse (1.2- $\mu\text{J}$  energy, 800-nm center wavelength, 80-fs duration) from the regenerative amplifier pass through a highly dispersive glass (10-cm length TF5 glass with a round-trip path) instead of use of the pulse to characterize itself. Combined reference  $E_c$  and two replica pulses

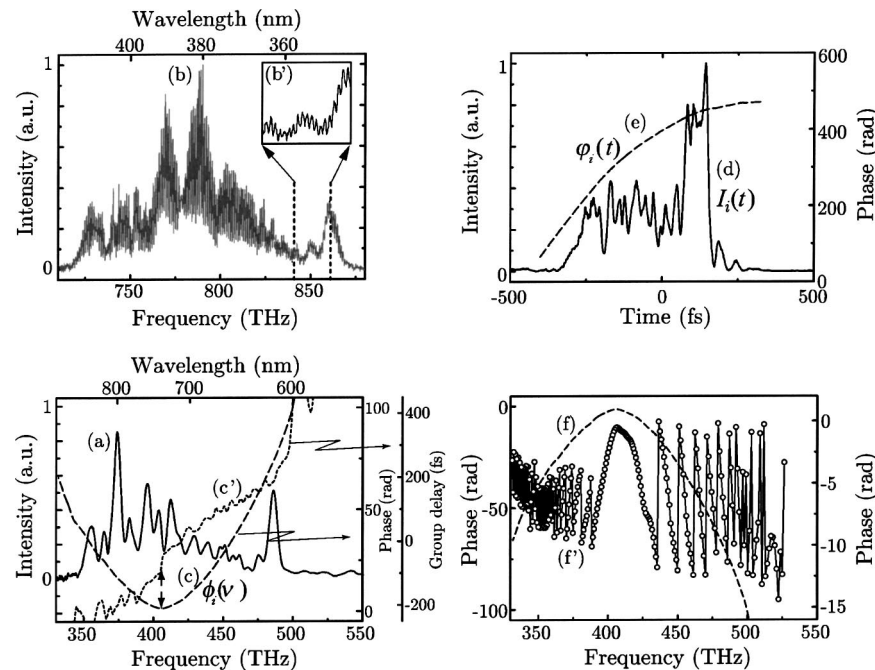


Fig. 2. M-SPIDER measurement in the SLM off case and applied spectral phase: (a) pulse spectrum; (b), (b') SPIDER signal; (c), (c'), (d), (e) reconstructed spectral phase (dashed curve), spectral group delay (dotted curve), temporal intensity (solid curve), and temporal phase (dashed curve), respectively; (f), (f') spectral phase applied by SLM after feedback operation (dashed curve) and its folded phase (solid curve), respectively.

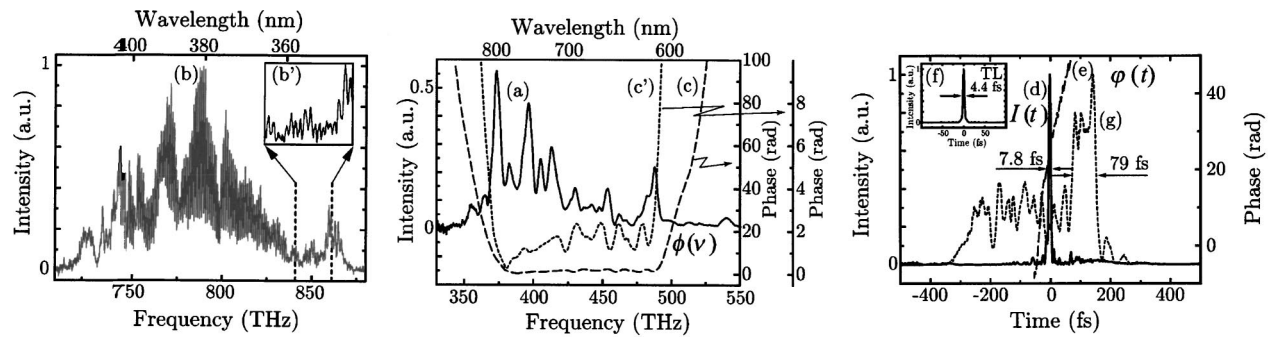


Fig. 3. M-SPIDER measurement in the SLM on case: (a) pulse spectrum; (b), (b') SPIDER signal; (c), (c'), (d), (e) reconstructed spectral phase (dashed curve); enlarged spectral phase (dotted curve), temporal intensity (solid curve), and temporal phase (dashed curve), respectively; (f) calculated transform-limited pulse profile (solid curve); (g) fiber-output pulse before compensation (dotted curve).

$E_1$ ,  $E_2$  were focused on a type II 50- $\mu\text{m}$  thick  $\beta\text{-BaB}_2\text{O}_4$  crystal to produce a SPIDER signal  $E_1E_c + E_2E_c$ . The signal was detected by a 50-cm spectrometer having an intensified CCD camera with a total wavelength resolution of 0.05 nm at 400 nm. Since a 1200-lines/mm grating resulted in a limited bandwidth of 37.5 nm at 400 nm, the full bandwidth of the SPIDER or second-harmonic wave signal was recorded automatically by the synthesis of three spectral parts of different center wavelengths at updated times of  $3 \times 100 = 300$  s. The procedure of the feedback phase compensation is as follows: (1) We measured the interference signal of second-harmonic waves  $(E_1 + E_2)^2$  of replicas  $E_1$ ,  $E_2$  by blocking reference beam  $E_c$  and by a 45-deg rotation of the  $\beta\text{-BaB}_2\text{O}_4$  crystal so that we obtained a delay time  $\tau_d$  of 960 fs. This value was fixed for measurements of SPIDER signals in the cases of SLM off and SLM on. (2) We then measured the SPIDER signal in the SLM off case [Fig. 2(b)]. (3) We then measured the two sum-frequency signals between the replica and the reference,  $E_1E_c$  and  $E_2E_c$ , to obtain the spectral shear  $\Omega/2\pi = 5.68$  THz. (4) After the spectral phase was applied [Fig. 2(c)] with the first computer by use of those results and was used as feedback to the second computer, (5) the corresponding negative spectral phase was transmitted by the SLM controlled by means of the second computer. The closed loop of (5)  $\rightarrow$  (2) in the SLM on case  $\rightarrow$  (4)  $\rightarrow$  (5) was repeatedly performed three times for better phase compensation. Finally, the two sum-frequency signals,  $E_1E_c$  and  $E_2E_c$ , corresponding to process (3), were again measured for confirmation of the above-obtained spectral shear. The SPIDER signal measured after the operation of three feedbacks is shown in Fig. 3(b). The corresponding applied phase in wrapped form and the reconstructed results in the spectral and temporal regions are shown in Figs. 2(f') and 3(c)–3(e), respectively. In addition, the temporal profile of the transform-limited pulse is shown in Fig. 3(f).

#### 4. RESULTS AND DISCUSSION

Figure 2(c) shows that the fiber-output pulse has a significantly large and complicated phase variation over 150 rad as a function of frequency. In addition, its group delay [Fig. 2(c')] as a function of frequency varies over 600 fs

and indicates an effective discontinuity around 740 nm at which point the two input pulses spectrally overlap at the fiber output. This finding corresponds to the result found through the spectrally resolved autocorrelation study for near-infrared continuum generation (730–1250 nm) by use of the IPM effect.<sup>8</sup> In general, such novel behavior of the spectral phase is not compensated for by conventional passive optics such as combinations of chirped mirrors, prism pairs, and grating pairs. As for the reconstructed temporal behavior [Figs. 2(d) and 2(e)], the pulse broadens over 500 fs and the phase varies over 300 rad, in both asymmetrical and complicated ways.

However, the result of our feedback technique suggests, as shown in Fig. 3(c), that even such novel phase behavior is successfully compensated for over the nearly whole frequency range of  $\Delta\nu \cong 110$  THz. That is, the multistructured, asymmetric output pulse with a duration of approximately 500 fs from the fiber was compressed to 7.8 fs, which is close to the 4.4-fs transform-limited pulse. To our knowledge, this is the first demonstration of optical pulse compression for the white continuum generated by the IPM effect. It seems that the small variation of approximately 1 rad in the spectral phase after compensation [Fig. 3(c')] is caused by the intensity fluctuations of the fundamental and signal fiber-input pulses. The difference between the compressed and the transform-limited pulses could be due mainly to the imperfect compensation of a rapidly varying spectral phase at the low- and high-frequency edges [Fig. 2(c)]. This occurs because the applied phase shift per one pixel at the edges exceeds  $\pi$  rad [Fig. 2(f')]. This problem will be solved by a suitable selection of components of a SLM phase compensator such as longer focal-length concave mirrors and larger  $1/d$  gratings.

Here we discuss the influence of the pulse intensity fluctuation and the group-delay time change  $\Delta t_g$  of the input signal pulse (with respect to the input fundamental pulse) on the compressed pulse during one feedback loop. For this purpose we carried out two experiments. We measured the long-term stability of the averaged pulse intensity using a photodiode with an oscilloscope. The result showed that the pulse intensity fluctuation of the fiber output was  $\pm 2.5\%$ . The other measurement (faster than 1 s) was for the difference between the fiber-output intensity spectrum under the 100-Hz oscillatory change



in group-delay time ( $\Delta t_g = \pm 3.5$  fs) of the input signal pulse (its central angular frequency  $\omega_{s,0}$ ) with a piezoelectric transducer attached to a mirror and its corresponding spectrum under no change in group-delay time. The result showed that only the spectral structure around 740 nm that appeared in the latter case was relatively smooth in the former case and changed in intensity by several percent its spectral region. This central region corresponds to the overlapping region of the spectrally broadened signal and fundamental pulses. This suggests that even the group-delay change that exceeds  $2\pi(\Delta t_g \times \omega_{s,0})$  causes only a several percent intensity change in the central region of the spectrum.

On the basis of these results, we carried out a computer simulation to clarify the practical influence of the fluctuations of the pulse intensity and the group delay on the compressed pulse. That is, we calculated the spectral phase and intensity of the fiber output and the phase-compensated pulse using two equations that describe IPM and SPM effects during nonlinear pulse propagation (Refs. 1 and 2) with experimental parameters. The calculation is based on the model that the spectral phases obtained after intensity fluctuation  $\Delta I/I$  and/or group-delay change  $\Delta t_g$  are compensated for by the use of spectral phases obtained before these fluctuations. As a result, the group-delay change yielded the small change in only the fine structure in the central overlap region of the output intensity spectrum that corresponds to the experimental result. Moreover, the simultaneous fluctuations of the intensity ( $\Delta I/I = \pm 2.5\%$ ) and the group delay ( $\Delta t_g = \pm 3.5$  fs) caused only a slight increase of the sub-pulse intensity and a less than 1% broadening of the main pulse duration for the compressed pulse. These fluctuations also indicated that the ratio increase of the subpulse energy to the whole pulse energy was at most less than 4%.

We also investigated numerically the influence of the carrier envelope phase fluctuation, which was much less than that of the intensity and group-delay fluctuations. The reasons are as follows: First, nonlinear phenomena of the IPM and SPM occur because of the pulse intensity but not the phase-sensitive electric field of the pulse. Second, since the durations (80 fs) of the input signal pulse and the input fundamental pulse both have huge optical cycles and are remarkably long compared with the time shift that is due to the carrier envelope phase fluctuation, the ultrabroad spectra of intensity  $I(\omega)$  and group delay  $t_g(\omega)$  at the fiber output are significantly insensitive unlike the case of a few optical cycle pulses.

Finally, we consider the influence of the independent group-delay change  $\Delta t_{g,r}$  in the reference chirped pulse on the M-SPIDER signal. When the reference pulse has a group-delay change of  $\Delta t_{g,r}$ , the response function  $N_I^P(t; \Omega)$  of the temporally linear phase modulation in Ref. 16 becomes  $\exp[-i\Omega(t + \Delta t_{g,r})]$ . This yields only a constant shift for the spectral phase predifference  $\theta_{\text{SP1}}(\omega)$  (Ref. 16) according to  $\theta_{\text{SP1}}(\omega) = \varphi(\omega) - \varphi(\omega - \Omega) + \tau\omega + \Omega \times \Delta t_{g,r}$ . That is, the group-delay change does not affect the reconstructed spectral phase except for a small constant shift of  $\Omega \times \Delta t_{g,r}$  ( $\approx 10^{-3}$  rad) and hence the reconstructed profile of the temporal intensity. This issue was also confirmed by the excellent agreement between

the M-SPIDER measurement (for a few hundred seconds) and the independent autocorrelation measurement for sub-7-fs pulses in another recent experiment.<sup>17</sup>

## 5. CONCLUSION

We have demonstrated what we believe to be the first compression of white-light continuum (530–880 nm) generated by IPM as well as SPM in a conventional fused-silica fiber. The 500-fs fiber-output pulse with an asymmetrical profile and an effective group-delay discontinuity has been compressed to 7.8 fs of near-Fourier-transform limitation by utilization of a feedback electric-field phase manipulator that combines SLM phase compensation and the M-SPIDER. The present technique can be extended to an automatic generator of high-power monocycle pulses by use of a gas-filled hollow fiber<sup>7</sup> and an arbitrary time-sequential, automatic manipulator of optical electric-field wave packets.

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