Application of a Spatial Light Modulator for Programmable Optical Pulse Compression to the Sub-6-fs Regime

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***Abstract*—We present a grating-pair-formed pulse shaper with a spatial light modulator (SLM) for programmable chirp compensation by applying voltages on the SLM. When linear and nonlinear chirp are optimally compensated for, corresponding to the quadratic, cubic, and quartic phases of -400 fs^2, 1100 fs^3, and 2000 fs^4 at the center wavelength 780 nm on the SLM, a stronger chirped white light continuum (WLC) pulse with a spectral bandwidth of 570–970 nm is compressed to the sub-6-fs regime.**

***Index Terms*—Chirp compensation, pulse compression, pulse shaping, spatial light modulator, ultrabroad spectrum, ultrashort pulse.**

FEMTOSECOND light pulses are essential tools for time-resolved spectroscopy owing to their ultrashort duration. The shorter the duration of the pulse is, the higher the time resolution achieves. This stimulates the development of optical sources generating shorter and shorter pulses, and optical pulses in the 4–5-fs regime recently have been demonstrated [1]–[4]. In these experiments, prism-pairs or grating-pairs combined with chirped mirrors [5] or double-chirped mirrors [6] have been used for dispersion compensation. However, the drawbacks of these methods, concerning the interdependence of different orders of dispersion compensation and the limited bandwidth of high reflection from chirped (or double-chirped) mirrors, may prevent an optical pulse compression down to the one-cycle regime. Pulse shaping utilizing a spatial light modulator (SLM) or a deformable mirror as a variable phase mask manifests the capability of independent arbitrary phases controlling [7], [8]. Recently, an 11-fs pulse was generated by using an SLM in a pulse shaper [9], and a 15-fs pulse was compressed by using a deformable mirror in a pulse compressor, respectively [8]. The deformable mirror has a feature of the smooth phase modulation. However, the maximum phase shift is limited to be of 20π at 800 nm due to the deflection limits and small pixel number of the deformable mirror, resulting in incompletely compression of a stronger chirped pulse [8]. Its partner, the SLM is able to yield a significantly larger phase shift because of its large pixel number. In this letter, we present a pulse shaper with an SLM for programmable chirp compensation, and experimentally demonstrate a sub-6-fs optical pulse compression when linear and nonlinear chirp are optimally compensated for by the SLM in the pulse shaper.

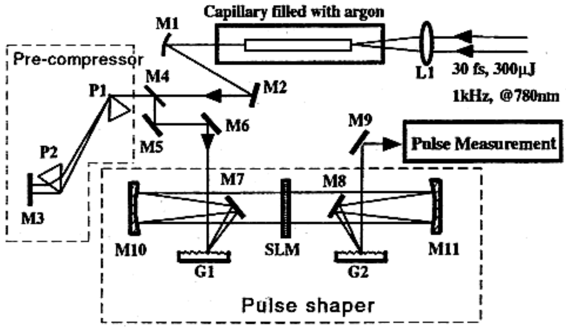

Fig. 1. Layout of experimental setup. M2–M9, silver-coated plane mirrors; M1, M10, and M11, Al-coated spherical mirrors, $R = -400$ mm; L1, $f = 300$ mm; P1 and P2, Brewster-angle cut BK7 prisms; G1 and G2, diffraction gratings with $d = 150$ lines/mm; SLM, a one-dimensional 128-pixel spatial light modulator. The pulse shaper is shown within the dashed frame.

Typically, a pulse shaper consists of a pair of gratings and lenses (or spherical mirrors) configured in a 4-f system with an SLM at the Fourier plane [7], [10]. Our experimental setup is shown in Fig. 1. In our pulse shaper, two plane mirrors, M7 and M8, are used to fold beams, resulting in the smallest folding angles away from two spherical mirrors, M10 and M11. The phase modulator in the pulse shaper is a programmable one-dimensional 128-pixel SLM (Meadowlark Optics, SLM2256) with each pixel width of 97 μm and interpixel gap of 3 μm. The transmittance of the unbiased SLM is about 90%. The gratings, G1 and G2, are Al-coated diffraction gratings with the blaze wavelength at 800 nm and the groove of 1/150 mm (Richardson Grating Laboratory). The measured diffraction efficiencies are over 70% within the 550–900-nm range. We carry out the experiment using a multipass 1-kHz Ti:sapphire amplifier, which can produce pulses having duration of 30 fs centered at 780 nm (FEMTO LASERS). A pulse of energy of 300 μJ is focused by a 300-mm focal lens L1 into an argon-filled glass capillary fiber with an inner diameter of 140 μm and a length of 60 cm. At the gas pressure of 2.0 bar, due to dispersive self-phase modulation (SPM), an almost continuum broadened from 570 to 970 nm is produced. The output mode is circular (fundamental mode)

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TABLE I
DISPERSION OF AN SLM AND A PRISM-PAIR AT 780 nm

	GVD (fs^2)	TOD (fs^3)	FOD (fs^4)
SLM substrate (FS, 2mm)	+75	+54	-22
BK7 glass (24-mm optical path in the BK7 prism-pair)	+1116	+754	-235
BK7 prism-pair (separation length of 50 cm, double passes)	-1546	-2084	-3550
Total dispersion	-355	-1276	-3807

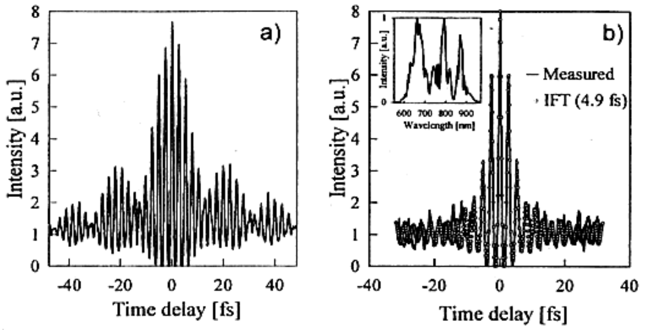

Fig. 2. (a) Measured IAC trace of the precompressed pulse using a pair of BK7 prisms alone. (b) Measured IAC trace of the shortest pulse (solid line). The calculation from direct inverse Fourier-transform (IFT) of the measured pulse spectrum presents 4.9 fs (FWHM) (circles). The measured spectrum of the shortest compressed pulse is shown in the inset.

and the pulse energy is around 38 μJ. The output pulse width is measured to be of longer than 300-fs full width at half-maximum (FWHM) with strong chirp.

We firstly launch the chirped pulse to a precompressor which consists of a pair of BK7 prisms cut at the Brewster angle at 780 nm (see Fig. 1). The reason lies in the fact that the maximum phase shift imparted on the SLM is to be of $\phi_{\max} = \pi \times N$ (N is the pixel number, in our case, $N = 128$) as the phase shift between pixels is limited to π [7]. The stronger chirp the pulse has, the larger phase shift the SLM is required to apply to accomplish complete chirp compensation. Therefore, the precompressor is explored to remove the major linear chirp of the self-phase modulated pulse with a separation length of 50 cm. The dispersion of an SLM and a pair of BK7 prisms at 780 nm is shown in Table I. However, the prism-pair also leads in large negative third-order dispersion (TOD) and fourth-order dispersion (FOD) resulting in observation of big structures on the wings of the measured interferometric autocorrelation (IAC) trace at its output [see Fig. 2(a)]. These unpleasant wing-shapes of the IAC trace can be reduced by launching the nonlinear-chirped pulse into the pulse shaper for its nonlinear chirp compensation, which will be discussed below.

In order to realize programmable phase control on the SLM, we address the frequency on the SLM plane by means of expanding the frequency in a Taylor series with respect to the spatial position, and then the nonlinear phase dispersion applied on the SLM can be written as

$$\phi_{\mathrm{SLM}}(\omega_j) = \frac{1}{2!}\left.\frac{d^2\phi}{d\omega^2}\right|_{\omega_0}(\omega_j-\omega_0)^2 + \frac{1}{3!}\left.\frac{d^3\phi}{d\omega^3}\right|_{\omega_0}(\omega_j-\omega_0)^3 + \frac{1}{4!}\left.\frac{d^4\phi}{d\omega^4}\right|_{\omega_0}(\omega_j-\omega_0)^4 + \cdots \quad (1)$$

where ω_j ($j = 1, 2, \ldots, 128$) represents the frequency spatially distributed on the SLM, and $(d^2\phi/d\omega^2)|_{\omega_0}$, $(d^3\phi/d\omega^3)|_{\omega_0}$, and $(d^4\phi/d\omega^4)|_{\omega_0}$ represent the GVD, TOD, and FOD at the center frequency, respectively. In practice, the center frequency ω_0 (corresponding to $\lambda_0 = 780$ nm) is set to $\omega_0 = \omega_{60}$. The imparted phase shifts are folded back into the range of $-\pi \leq \Delta\Phi \leq \pi$. This is because that chirp compensation by the programmable SLM is carried out in the frequency domain, and the electric field of a short pulse in the frequency domain can be written as

$$E(\omega) = |E(\omega)| \exp(i\phi(\omega)) \equiv |E(\omega)| \exp[i(\Delta\phi(\omega) + m \cdot 2\pi)].$$

Here, $\Delta\phi(\omega)$ is within $[-\pi, \pi]$ and $m = 0, \pm 1, \pm 2, \ldots$. The SLM phase response as a function of the applied voltage is calibrated by using a He–Ne laser, and the maximum phase shift in excess of 6π is obtained. Since our pulse spectrum is very broad, the calibrations for all wavelengths are required. Efimov *et al.* found the uniformity of phase shift in the range of 0–2π for all wavelengths (see [10, Fig. 2]), which has been confirmed by our spatial interferometer. Accordingly, we employ this feature and calibrate our SLM in this range.

The output beam from the pulse shaper has a good circular mode with the pulse energy around 4–5 μJ. This lower output energy is due to the losses from the diffraction gratings and the metal-coated reflective mirrors in the pulse shaper and the losses of other directing mirrors. The output pulse is directed to an interferometric autocorrelator with a 10-μm-thick BBO (Femtometer, FEMTO LASERS) to monitor the pulse duration. First, the negative quadratic phase of -400 fs^2 (corresponding to GVD) at the center frequency is applied to the SLM. Subsequently, the material path of the second BK7 prism is increased to recompensate for this negative GVD in order to own a broad acceptable spectrum (otherwise, the short wavelength will be cut by the second BK7 prism). It is shown in Table I that the precompressor introduces much negative TOD and FOD. So we add the positive cubic phase (corresponding to TOD) and the positive quartic phase (corresponding to FOD) on the SLM. As a result, the better and shorter IAC traces have been observed. While the cubic phase and the quartic phase are set to be of 1100 fs^3 and 2000 fs^4 at the center frequency, respectively, the chirp of the WLC pulse is optimally compensated for, and a short optical pulse is generated. The measured IAC trace is depicted in Fig. 2(b) (solid line), and the measured pulse spectrum is shown in the inset. The direct inverse Fourier-transform (IFT) of the compressed-pulse spectrum results in a pulse of 4.9 fs (FWHM) (circles). The well agreement between the measured IAC trace and the IFT-constructed IAC trace in the main peak of the pulse indicates the small residual phase errors existing in this region. The small oscillatory structures on the wings of

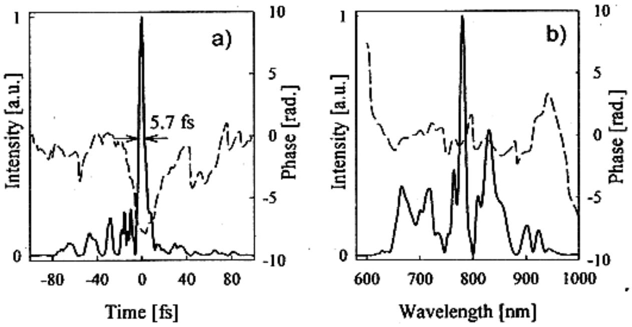

Fig. 3. Retrieved pulse intensities in (a) the time domain and (b) the frequency domain. Dashed curve indicates phases.

IAC traces are due to strong modulation of the spectrum indicating small satellite pulses exist [11]. We verified this prediction by characterizing the pulse using a SHG-FROG (second harmonic generation frequency-resolved optical gating) apparatus [12] with a 10-μm BBO. The retrieved pulse and pulse phase is shown in Fig. 3. The pulse duration is evaluated to be of 5.7 fs (FWHM). Compared with the measured spectrum [the inset of Fig. 2(b)], the retrieved spectrum is little bit narrow. This is due to the reason that the SHG crystal has a limited phase matching bandwidth [13], which results in broadening of the pulse width. With an improved FROG technique, a shorter optical pulse might be characterized in the future [14].

In summary, a strong-chirped ultrabroad spectral pulse has been programmable compressed to sub-6 fs by using a commercially-available 128-pixel SLM for linear and nonlinear chirp compensation. The IFT gives the pulse duration of 4.9 fs, however, SHG-FROG evaluates 5.7 fs. This is, to the best of our knowledge, the shortest optical pulse ever compressed using the SLM pulse shaping technique up to now. It should be noted that the present SLM may limit the pulse compression down to one cycle due to the fact that the SLM is a limited-pixilated system. This effect can be reduced by decreasing gaps and increasing the pixel number of the SLM or replaced by using a nonpixel phase modulator. The losses and the bandwidth limitation from the diffraction gratings in the pulse shaper can be reduced by utilizing the prisms partner [15]. As a result, the improved pulse shaping technique has the unique advantages comparing with the other compensation techniques. First, it has the significantly large bandwidth. Second, it provides the ability of independent and accurate nonlinear-chirp compensation (independent phase compensation among any orders of dispersion) by the *in situ* phase adjustment during pulse measurements. Third, it can be automatically feedback-controlled to realize adaptive pulse compression [9]. Due to these features, we believe that this technique can be used to compress an optical pulse to the one-cycle regime in the near future.

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