Ultrashort Pulse Compression for Mode-Locked Ti:Sapphire Laser by Using a Tapered Fiber and Grating Pair

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Ultrashort Pulse Compression for Mode-Locked Ti:Sapphire Laser by Using a Tapered Fiber and Grating Pair

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Extracavity pulse compression for pulses from an 82 MHz mode-locked Ti:sapphire laser is demonstrated by utilizing a tapered fiber of 1 μm in diameter and 10 mm in length. Group velocity dispersion of the tapered fiber is calculated, which shows two zero dispersion wavelengths locating at 545 and 1250 nm, respectively. The nonlinear coefficient γ of the tapered fiber is estimated to be 733 (W^{-1} km^{-1}) at 880 nm wavelength. With 80 fs input pulses at 880 nm center wavelength, the optical bandwidth is broadened beyond 22 THz by the tapered fiber. After dispersion compensation by a grating pair with 1.45 cm separation, 26 fs output pulses are obtained. One-third pulse compression ratio has been experimentally demonstrated in this work for center wavelengths ranging from 720 to 880 nm.

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1. Introduction

Over the last four decades, various methods have been proposed and developed for generating ultra-short optical pulses. Among them, the extraordinary broad gain bandwidth of the Ti:sapphire crystal makes it one of the most widely used gain media for ultrafast lasers around the 800-nm wavelength. Many mode-locking related techniques, such as Kerr-lens mode-locking[1] with chirped-mirrors[2] or double chirped-mirrors,[3] have been utilized to generate ultra-short pulses from Ti:sapphire lasers. Although ultrafast lasers with 80–150 fs output pulsewidth can be readily obtained from commercial laser systems, some advanced applications such as ultrashort time-resolved measurement will require much shorter pulsewidths (10 to 30 fs) to enhance the performance of the system. To further reduce the pulsewidth, fiber-based extracavity compression technique is generally utilized. Nakatsuka *et al.* have experimentally demonstrated that the laser output pulses can be compressed during the propagation inside a single-mode fiber through the wide bandwidth generation resulting from self-phase modulation (SPM).[4]

Another fiber-based component, nonlinear photonic crystal fiber (PCF), has also been utilized to achieve octave-spanning supercontinuum generation (SCG).[5] The spectral broadening is due to various nonlinear effects including four-wave mixing, stimulated Raman scattering, cross-phase modulation and self-phase modulation.[6] In combination with the spatial light modulation, grating pairs, or prism pairs to provide group velocity dispersion compensation, the Ti:sapphire pulses exiting from a PCF can be successfully compressed to generate relative short pulses.[7–9] However, nonlinear PCFs may not be suitable for ultrafast pulse generation in some applications. The relative high pulse energy launched into nonlinear PCFs can induce unexpected high nonlinearity and complicate the output pulse-shape. Alternatively, hollow fibers filled with the noble gases and photonic bandgap fibers filling with Xe have been used to generate high-energy ultrashort pulses through soliton pulse compression.[10–12] Moreover, theoretical and experimental demonstrations of SCG by using tapered microstructure fibers have also shown great enhancement of the nonlinearity.[13–17]

Typically, few cycle optical pulses are generated with the central wavelength close to the gain maximum of Ti:sapphire lasers (about 790 nm). However, in many nonlinear optical experiments, it is desirable to obtain ultrafast pulses at the edge of the gain spectrum. For these cases, using PCFs to attain pulse compression[7] may suffer from the fact that the center wavelength of input pulses has to be restricted to the suitable dispersion regime in order to avoid unwanted nonlinear effects. Luckily, dispersion management can be easily achieved by simply tapering a standard single-mode fiber.[18–20] By utilizing tapered fibers of centimeters in length to manage the fiber dispersion, one can operate the pulses in the anomalous dispersion region for SCG.

In this work, we have successfully demonstrated extracavity pulse compression for mode-locked Ti:sapphire laser pulses by simply using a tapered fiber and a grating pair. By launching 82-MHz femtosecond pulses into the tapered fiber with about 40% coupling efficiency, broad spectral bandwidth can be obtained. After propagating through the grating pair, about one-third pulse compression ratio can be readily obtained with a Kerr-lens mode-locked Ti:sapphire laser. The pulse compression can be produced in wide wavelength range (720 to 880 nm), even at wavelengths far from the gain maximum of the Ti:sapphire crystal.

2. Experimental Methods

Figure 1 shows the schematic setup of the pulse compression experiment. A commercial tunable femtosecond Ti:sapphire oscillator (Spectra-Physics Tsunami) is used to generate s-polarized pulse trains at 82 MHz repetition rate. An isolator is located outside the laser cavity to prevent the back reflection from entering the oscillator. To reduce the loss caused by prism pair, a half-wave plate is used to rotate the polarization of optical field from s- to p-polarization. Then the pulses pass twice through the prism pair with 30-cm separation. In this experiment, a standard single-mode fiber (SMF-28) is tapered down to about 1 μm in diameter and the

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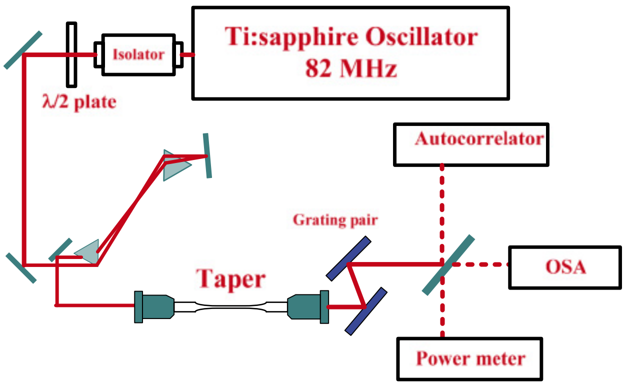

Fig. 1. (Color online) Schematic setup of the pulse compression by using a tapered fiber and grating pair.

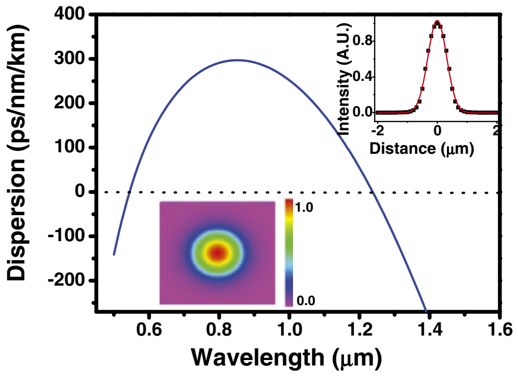

Fig. 2. (Color online) The group velocity dispersion of the tapered fiber versus the wavelength. The one dimensional and two dimensional plots of the mode field distribution are shown in the inset.

uniform region of the waist is approximately 10 mm in length. The first 10× microscope objective is utilized to focus the light into the tapered fiber, and the second microscope objective is used to collimate the light before incident on the grating pair (600 lines/mm). To achieve maximum coupling efficiency, the input side of the tapered fiber is mounted on a three-axis high-resolution translation stage. The spectral response and pulsewidth of the re-compressed pulses are measured by a optical spectrum analyzer (Ando AQ6315A) and a two-photon-absorption autocorrelator with a GaAsP photodiode.

3. Results and Discussion

To study the relation between pulse compression and the dispersion effect induced by the tapered fiber, group velocity dispersion of the tapered fiber is calculated and plotted in Fig. 2. For given refractive indices of core ($n_{\rm core}$) and cladding ($n_{\rm clad}$), the propagation constant β can be obtained by solving the eigenvalue equation of the tapered fiber. The dispersion parameter D of the tapered fiber with 1 μm diameter can be obtained from second derivative of the propagation constant β. As shown in Fig. 2, there are two zero dispersion wavelengths locating at 545 and 1250 nm, respectively. Thus, a wide range of anomalous dispersion will be encountered when Ti:sapphire laser pulses propagate through the tapered fiber. The insets of Fig. 2 show the two dimensional contour plot of the optical field and the corresponding one dimensional mode field distribution for 800 nm wavelength. By fitting with the sech^2 function, the radius of the mode field is estimated to be about 0.305 μm, indicating that the optical fields are strongly confined in the waist of the tapered fiber. To determine the dominating factor as pulse propagation in tapered fiber, it is important to calculate the ratio of dispersion length $L_{\rm D} = \tau_0^2/|\beta_2|$ to the nonlinear length $L_{\rm NL} = 1/(\gamma P_0)$. Here, τ_0 and P_0 are pulsewidth and peak power of the incident pulse and β_2 is the group velocity dispersion (GVD) parameter. At center wavelength $\lambda_0 = 880$ nm, $|\beta_2|$ is about 121 ps^2/km [derived by the relation $D = -(2\pi c/\lambda_0^2)\beta_2$ from Fig. 2] and the nonlinear coefficient γ of the tapered fiber is estimated to be 733 W^{-1} km^{-1}.[21] Using the parameters $\tau_0 = 80$ fs and $P_0 = 30$ kW, we obtain that the value of $L_{\rm D}$ is about 5.27 cm but $L_{\rm NL}$ is only about 45.5 μm. Therefore, the nonlinear effect will give apparent influence but the dispersion effect can be ignored as the pulses pass through the 10-mm long tapered fiber.

The measured optical spectrum (bandwidth $\Delta\lambda = 14$ nm) and autocorrelation trace of the pulses exiting from the Ti:sapphire laser are shown in Fig. 3(a), with a center wavelength of 800 nm. Using the sech$^2(-1.76\,t/\tau_0)$ function to fit the envelope of the autocorrelation trace, the measured pulsewidth τ_0 is 80 fs. At 460 mW of launched power (4.87 nJ per pulse), 46 nm bandwidth (21.6 THz) can be obtained when the pulses propagating through the tapered fiber, as shown in Fig. 3(b). The spectral width of the pulses gets broadened through the SPM effects. Since the time delay provided by the speaker in our fringe resolved autocorrelator is not sufficient for measuring these temporally broadened pulses, we put the grating pair right after the tapered fiber to compensate the pulse chirp induced by the tapered fiber. By tuning the separation d_0 of the two gratings to be 2.35 cm, the fringe resolved autocorrelation (FRAC) shows a symmetrical shape with a peak to background ratio of 8 : 1. In comparison with the previous sech^2 autocorrelation signal in Fig. 3(a), there are now some structures in the wings due to the existence of the pulse side lobes [Fig. 3(b)]. By calculating the interference fringe in Fig. 3(b), the pulsewidth is found to be 26 fs. It reveals that about one-third pulse compression ratio can be obtained by the tapered fiber and the grating pair.

Tuning the center wavelength of the launched Ti:sapphire laser pulses not only affects the broadened spectra range after the pulses propagate through the tapered fiber, but also changes the pulsewidth after compression. At longer center wavelengths, the grating separation d_0 needs to be shortened because of the increasing negative β_2 of the grating pair and the decreasing normal dispersion of the single mode fiber (SMF28) before the pulses enter the tapered fiber. For the case of 880 nm input center wavelength with the separation of grating pair $d_0 = 1.45$ cm and the pump power P_0 of 460 mW, the measured FRAC traces and the optical spectra right from the Ti:sapphire laser and after the grating pair are shown in Figs. 4(a) and 4(b), respectively. The spectrum bandwidth from the Ti:sapphire laser at 880 nm is broaden to 18 nm [inset of Fig. 4(a)], which is larger than that of 800 nm [$\Delta\lambda = 14$ nm, inset of Fig. 3(a)]. However, the measured autocrrelation trace for $\lambda_0 = 880$ nm in Fig. 4(a) (by fitting sech^2 function) shows the same pulsewidth (about

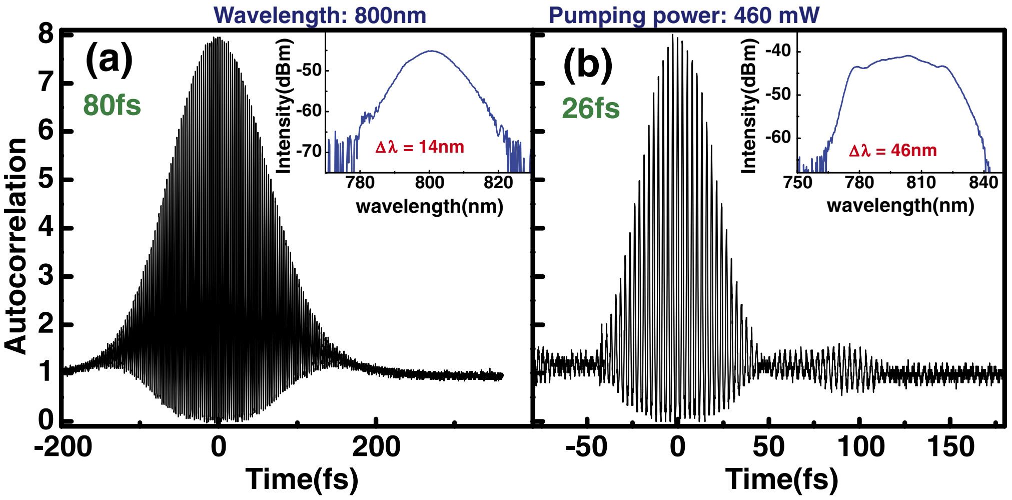

Fig. 3. (Color online) The measured autocorrelation traces and spectra (a) exiting from the Ti:sapphire laser, and (b) after the grating pair at center wavelength of 800 nm.

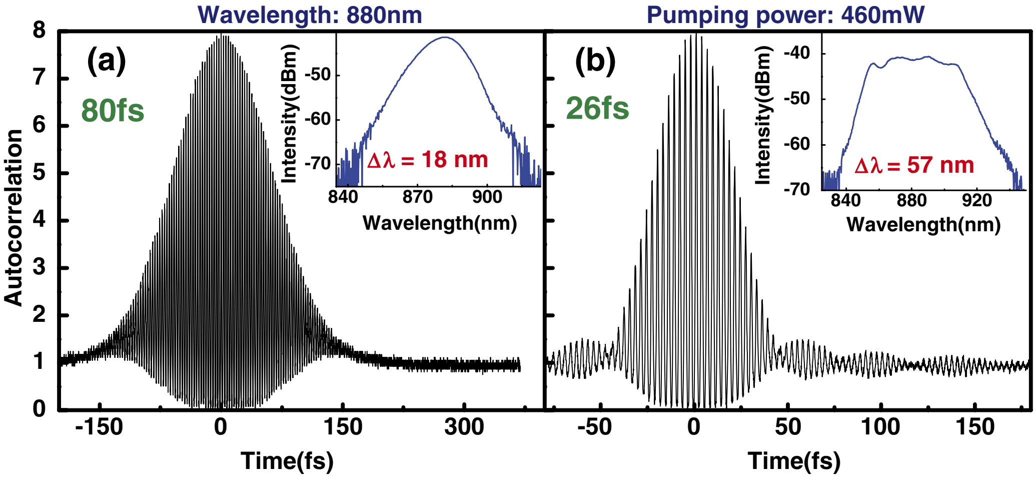

Fig. 4. (Color online) The measured autocorrelation traces and optical spectra (a) exiting from the Ti:sapphire laser, and (b) after the grating pair at 880 nm center wavelength.

80 fs) with that of $\lambda_0 = 800$ nm from the laser output. This might be due to the existence of the residual chirp of Ti:sapphir laser at 880 nm. The broadened and flattened spectrum with $\Delta\lambda = 57$ nm can be achieved after the tapered fiber at the pump power P_0 of 460 mW [inset of Fig. 4(b)]. After compression by the grating pair, the shortest pulsewidth of about 26 fs can be obtained, whose FRAC in Fig. 4(b) reveal more side lobes in comparison with Fig. 3(b).

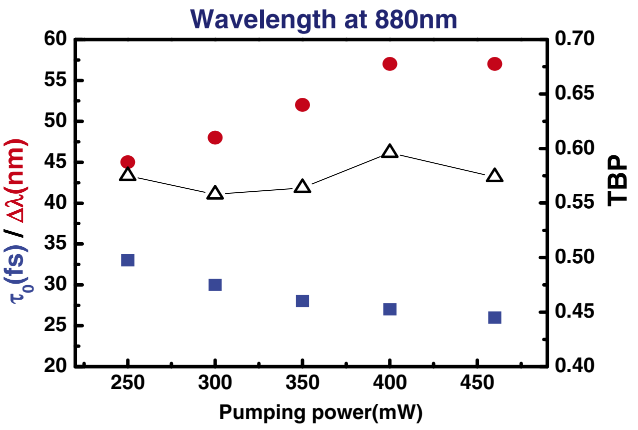

Fig. 5. (Color online) Measured pulsewidth, spectral bandwidth and time bandwidth product versus the input pumping power at 880 nm center wavelength.

For $d_0 = 1.45$ cm and $\lambda_0 = 880$ nm, the measured pulsewidth (blue squares), the spectral bandwidth $\Delta\lambda$ (red circles) and the time bandwidth product $\tau_0\Delta\nu$ (open triangles) versus the incident powers are shown in Fig. 5. Due to the large third-order nonlinearity, such as SPM induced by the tapered fiber, $\Delta\lambda$ broadens linearly from 45 to 57 nm as P_0 increases from 250 to 460 mW. Besides, the measured pulsewidth τ_0 after the grating pair shortens from 33 fs to about 26 fs as shown in Fig. 5. The calculated time-bandwidth products (TBP) for different pumping powers are also shown in Fig. 5 (open triangles). Due to un-compensation of the higher-order chirps of the pulses, the calculated TBP values (about 0.57 in Fig. 5) are larger than the transform limited value (0.32) for a sech^2 pulse. In this experiment, pulse compression is mainly implemented using a tapered fiber exhibiting SPM via the optical kerr effect and chirp filter using GVD introduced by the grating pair. However, several optical components will cause additional chirp, such as the isolator, prism pair outside Ti:sapphire laser and the two objective lens used to collimate the optical beam from the free space to the tapered fiber and re-collimate it to the free space. The isolator and objective lens will induce the normal dispersion, and it functions as an up-chirp, i.e., frequency is an increasing function of time. Normal dispersion (and up-chirp) from the isolator and objective lens can be compensated by using the prism pair that induce anomalous dispersion and down-chirp. However, the prism pair can only induce limited down-chirp and can not compensate the up-chirp from the kerr effect of tapered fiber and normal dispersion from single mode fiber. Besides, only the linear part of the chirp can be balanced by grating pair, and the higher order chirp from all the optical components mentioned above can not be effectively compensated. Therefore, the measured pulseswidth of Fig. 4(b) deviates from the shortest value about 14 fs predicted from the Fourier transform.

Besides, the intensity and phase of compressed pulse after the tapered fiber and grating pair can also be retrieved by the one- and two-photon autocorrelations with the genetic algorithm (GA).[22] According to the results by Naganuma *et al.*,[23] the fundamental spectrum $E(\omega)$ can be obtained from the one-photon absorption (OPA) FRAC by the Fourier transforms of electric field autocorrelation $G_1(\tau)$, i.e., $|E(\omega)|^2 = F[G_1(\tau)]$. Besides, from the two-photon absorption (TPA) FRAC, the Fourier transform of the intensity $I(\omega)$ and second-harmonic field $u(\omega)$ can be obtained from the intensity autocorrelation $G_2(\tau)$ and second-harmonic field autocorrelation $F_2(\tau)$, i.e., $|I(\omega)|^2 = F[G_2(\tau)]$, $|u(\omega)|^2 = F[F_2(\tau)]$. Using the GA, the retrieved results of the compressed pulses for the pumping power of 400 mW are shown in Fig. 6. It reveals that the compressed pulses have a relative flat phase distribution (blue curve in Fig. 6) inside the pulse (black curve in Fig. 6).

By tuning the center wavelength from 720 to 880 nm at the fixed pump power of $P_0 = 350$ mW (4.26 nJ per pulse), the measured pulsewidth (red circles), the spectrum bandwidth (blue squares) and the TBP (open triangles) are shown in Fig. 7. The value of $\Delta\lambda$ shows the tendency of increase when the operation wavelength of Ti:sapphire laser increases. It may be due to increase of the anomalous dispersion resulted from the tapered fiber as shown in Fig. 2 and decrease of the normal dispersion of the single mode fiber at longer operation wavelength. Before the pulse enters the tapered fiber, the normal dispersion induced by single mode fiber will result in broadening of the pulsewidth and lowering of the intensity before the pulse enter the tapered fiber. Nevertheless, the anomalous dispersion, or negative β_2, from tapered fiber will compensate the positive chirp induce by the kerr effect and shorten the pulsewidth. Therefore, the measured pulsewidth for compressed pulses will become shorter for longer center wavelengths. For 720 nm center wavelength, spectral bandwidth of only 24 nm can be obtained after compressed by the tapered fiber, which results in 38 fs pulsewidth after compressed by the grating pairs. When the center of pumping wavelength is at 880 nm, the widest spectrum bandwidth for the pulses of about 52 nm (about 20 THz) can be obtained to result in the shortest pulsewidth of about 28 fs. In this figure, it suggests that ultrashort pulse compression can be easily obtained far from the gain maximum of the Ti:sapphire laser by the tapered fiber and grating pair. In addition, the calculated TBP will change between 0.47 and 0.59 for our operating wavelengths.

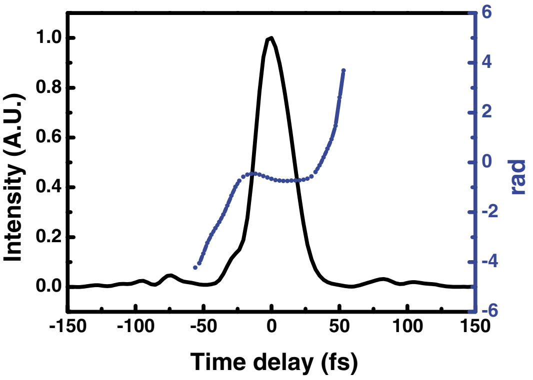

Fig. 6. (Color online) Retrieved results for the compressed pulses at pumping power of 400 mW.

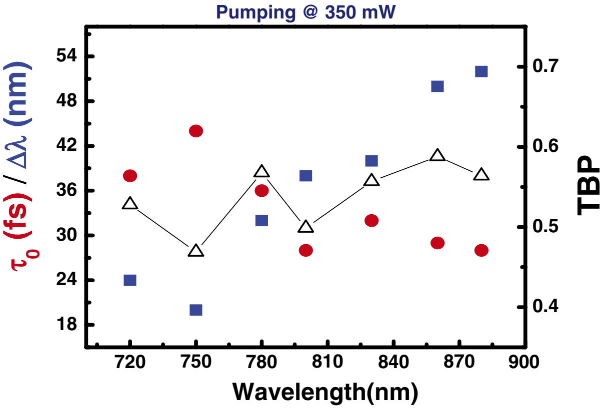

Fig. 7. (Color online) Measured pulsewidth, spectral bandwidth and time bandwidth product versus the center wavelength at 350 mW pump power.

4. Conclusions

Ultra-short pulse compression for mode-locked Ti:sapphire oscillators has been successfully demonstrated by using a tapered fiber and grating pair outside the laser cavity. The spectral bandwidth of the mode-locked pulses get broadened when passing through a 10-mm-long and 1-µm-diameter tapered single mode fiber. By tuning the center wavelength from 720 nm to 880 nm and choosing the optimal separation of grating pair to yield suitable GVD compensation, shortest pulsewidth of less than 26 fs has been obtained. The present work of utilizing tapered fibers to attain ultrashort compression could provide a easy way of wide flexibility to generate ultrashort pulses. In particular, this work demonstrates ultra-short pulse compression operating far away from the maximum gain wavelength of Ti:sapphire. This will be very advantageous for many applications including the high precision ultrafast spectroscopy of semiconductor nanostructures.

Acknowledgment

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