Superior Method for Measuring Chirp Structure of Femtosecond Supercontinuum Pulse

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***Abstract*— We present a straightforward method to measure the temporal chirp structure of supercontinuum (SC) pulses. Wavelength-tunable laser pulses acquired from the chirped SC are spatially separated from the incident SC region, which can be detected with zero background in the detection plane. Experimental results show that this convenient method, which is based on ultrafast transient lens effect, has many advantages compared with ordinary optical Kerr gate method.**

***Index Terms*—Nonlinear optics, supercontinuum, transient lens effect, ultrafast optics.**

I. Introduction

SUPERCONTINUUM (SC) generation has become a very attractive topic due to its massive spectral components ranging from the UV to the near IR [1]. This well-known phenomenon has been observed in a wide variety of media [2], [3], and found extensive applications [4], [5].

It is generally accepted that the broadband SC pulse generation normally involves a lot of nonlinear processes, such as self-phase modulation, four-wave mixing, and stimulated Raman scattering. Because of positive group velocity dispersion (GVD) of the medium in which the SC is generated, low-frequency components within the SC pulse precede the high-frequency components temporally. The available techniques for measuring the chirp structure of the SC are the sum frequency generation cross-correlation method [6], and two-photon absorption [7]. In addition, the optical Kerr gate (OKG) method also has been demonstrated as a powerful technique for measuring the chirp structure of femtosecond SC [8]–[10]. Wavelength-tunable pulses acquired from SC based on OKG have been applied in simultaneous three-dimensional imaging [11], [12]. However, the detection area of gated pulses is spatially overlapped with the incident SC beam in OKG configuration, therefore, the SC leakage passed through the polarizer, which disturbs the spectra of the gated pulses, restrains the enhancement of signal-to-noise ratio in the SC applications.

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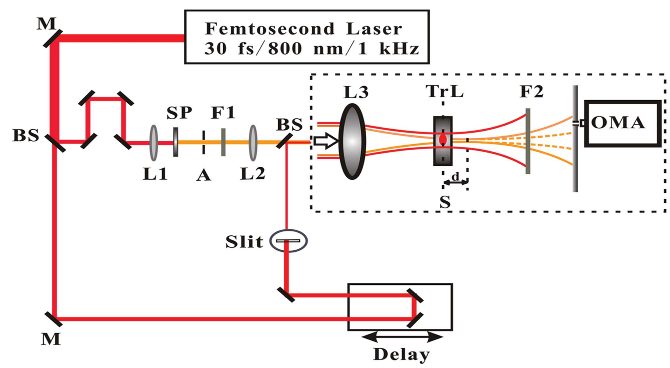
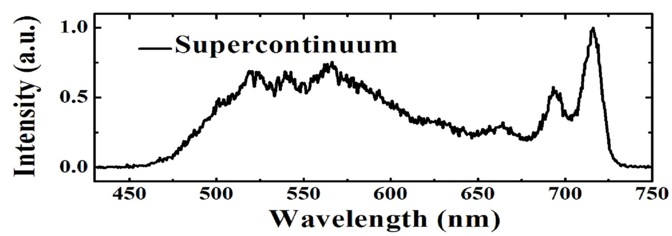


(a)



(b)

Fig. 1. (a) Experimental setup for measuring chirp structure of SC pulse based on TrL effect. The solid and broken lines depict the SC probe beam paths with and without TrL, respectively. M: mirror. BS: 1:1 beam splitter. L1, L2, and L3: lens. SP: sapphire plate. A: aperture. S: Te glass. F1 and F2: low-pass filter. (b) Spectrum of SC pulse.

In this letter, we demonstrated the gate function of ultrafast TrL effect in measuring the chirp structure of SC pulse. This method had many advantages, such as no demand of phase-match condition, and less optical elements. Experimental results showed that, the temporal resolution of the TrL method was comparative to that of OKG method, and the spectral contrast of TrL signal was much larger than that of OKG signal.

II. Experiments

Fig. 1(a) is a schematic illustration of the experimental setup for measuring chirp structure of SC pulse based on ultrafast TrL effect [13]–[15]. The multipass Ti:sapphire laser, which emitted 30 fs, 800 nm laser pulses at a repetition rate of 1 kHz, was split into two beams by a 1:1 beam splitter (BS). One beam was focused into a sapphire plate (SP) with 3 mm thickness by a 100 mm focal-length lens. Stable SC probe pulse was generated and then collimated after filtering the long-wave region by a filter (F1). The other beam which was optically delayed against the probe beam was served as pump beam. A slit with a width of 1.5 mm was put in the middle of the optical path of pump beam. The collimated probe and pump beams were collinearly focused with a lens (L3) of 300 mm focal-length into the tellurite glass (Te glass) sample. The distance (referred as d) of the focal point of the SC probe beam from the TrL plane, which was called "focal mismatch" [16], was adjusted to -3 mm by changing the distance between lens L1 and lens L2. Due to the slit shaped pump beam, the corresponding refractive index change only exists in a thin region in Te glass because of optical Kerr effect [17]. The spatial phase modulation intensity in the direction paralleled to the slit is larger than that in the perpendicular direction. The SC probe beam is mainly defocused in the direction paralleled to the slit. Another low-pass filter placed after the medium was used to filter the pump beam. At the detection plane, an aperture with a diameter of 1 mm was used to select the detected position of the expanded probe beam (TrL signals), and then the TrL signals were analyzed by an optical multichannel analyzer (OMA). Fig. 1(b) shows the spectrum of the incident SC probe beam, which covers from 470 nm to 725 nm. In the experiment, the thickness of the Te glass was 1 mm. The nonlinear refractive index n_2 of the Te glass was measured to be $\sim 10^{-15}$ cm^2/W, and an excellent transmission window was provided from 0.38 up to 6.1 μm [18].

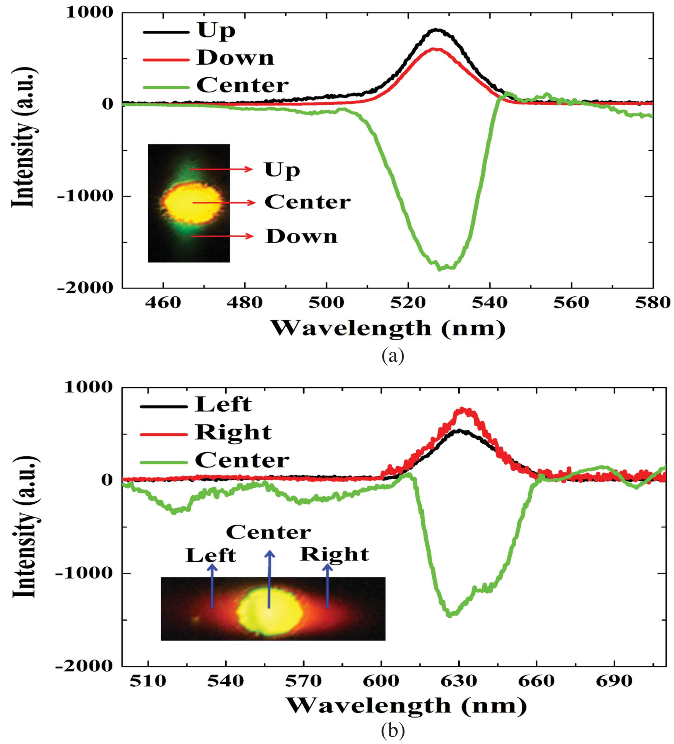


Fig. 2. Spectra of TrL signals measured at the time delay of (a) 800 fs and (b) 2050 fs. The slit placed in pump beam path was set to (a) vertical and (b) horizontal. The insets show the photograph of TrL signals. The arrows denote the detected areas. Both the spectra measured at the center positions were the differential spectra.

III. Results and Discussion

Fig. 2 shows the gated spectra acquired from SC probe beam using ultrafast TrL method. In Fig. 2(a), the slit placed in pump beam path was set to vertical. The inset of Fig. 2(a) shows the photograph of the TrL signal at detection plane at the time delay of 800 fs. Green pattern appeared outside the incident SC probe beam region, which permitted us to detect the back-ground free TrL signal. The direction of the TrL signal was parallel to the slit. The central wavelengths at the positions denoted as "up" and "down" in the pattern were both located at about 530 nm with full width at half maximum (FWHM) of 20 nm. By measuring the transmitted differential spectra of the SC probe beam at the "center" position, which was the difference of the transmitted spectra of the SC probe beam with and without the pump beam, a spectral valley at 530 nm was observed. By rotating the slit, the spectra of the TrL signals and the transmitted differential spectra of the SC probe beam had no obvious changes. However, the central wavelengths of the gated pulses depended on the time delay between the SC probe beam and the pump beam. Fig. 2(b) shows the spectra of gated pulses obtained at the time delay of 2050 fs. At this time delay, the pump pulse overlapped with the SC probe pulse at its longer wavelength range. In this measurement, the slit placed in the optical path of pump beam was set to horizontal. As expected, the TrL signal pattern became horizontal, as shown in the inset of Fig. 2(b). The central wavelengths of TrL signal and the transmitted differential spectra of SC probe beam were nearly the same, which were all located at 630 nm with FWHM of 30 nm. Further, the wavelength onsets of the TrL signals and the differential spectra were nearly the same, indicating that the photons in the TrL signals were originated from the SC probe beam. The efficiencies of original spectral content selection at the two measured wavelengths were both about 10%, which could be further increased by increasing the pump power or the third-order nonlinear refractive index of the medium.

Fig. 3(a) shows seven spectra of gated pulses acquired from SC probe beam using TrL method. The average time delay interval between each spectrum was about 350 fs. Fig. 3(b) shows the chirp characteristic of the SC probe beam measured by TrL method and OKG method, respectively. The SC probe beam was up-chirped due to the positive GVD from the SP itself, and the air. Both the experimental data show the SC probe beam has ~ 2.6 ps in time domain. The central wavelength measured by TrL method at each time delay is close to that measured by OKG, indicating the TrL method has the same capacity in time-resolving spectral measurement of SC chirp pulse. Moreover, the temporal resolution of TrL method using Te glass is at the same level as that of the OKG method using Te glass.

Furthermore, we compared the spectral profiles of gated pulses acquired by TrL method and OKG method, respectively. Fig. 4(a) and 4(b) show the normalized intensities of two gated spectra acquired by the two methods at the central wavelengths of 530 and 630 nm, respectively. The spectral FWHM of the two signals were nearly the same. However, the remained spectrum of SC probe beam is still detected by OKG method,

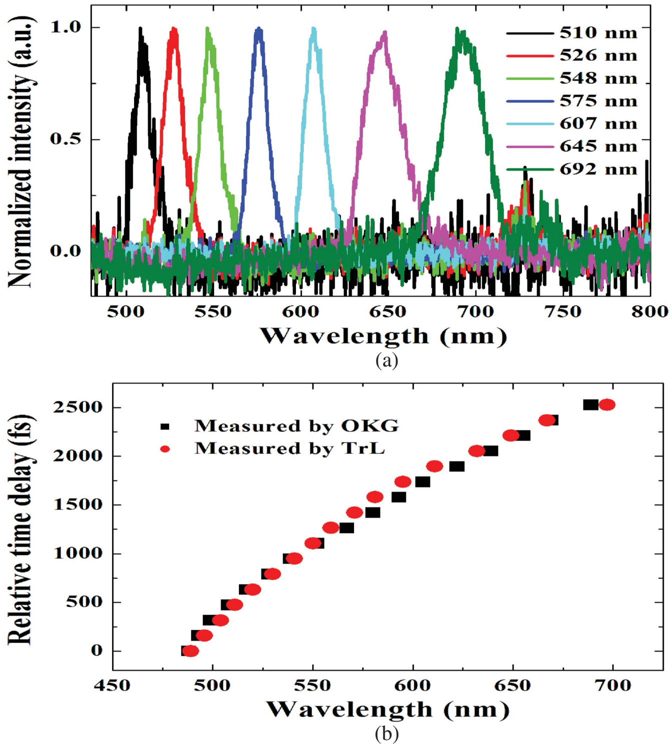


Fig. 3. (a) Normalized spectral intensity of gated pulses obtained by TrL method using Te glass. (b) Chirp structure of SC probe beam measured by TrL method and OKG method, respectively.

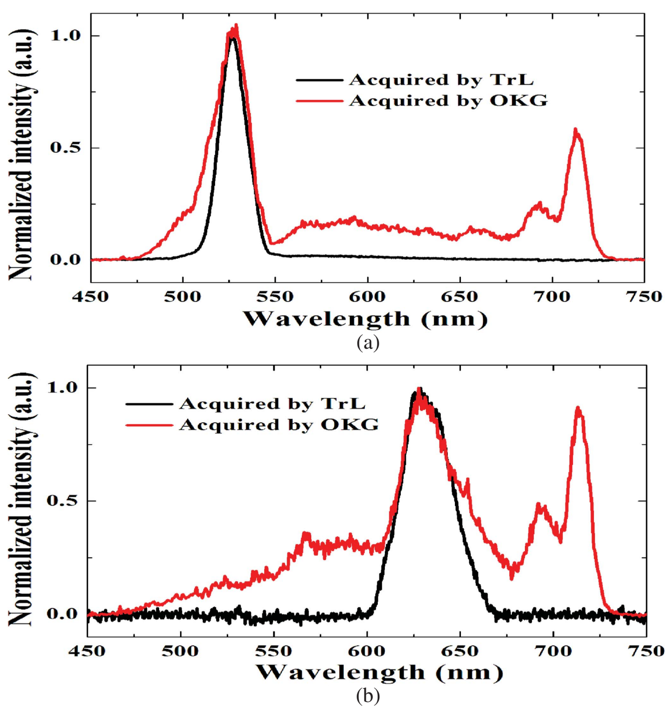


Fig. 4. Comparison of the spectral profiles of TrL signals and OKG signals. Two spectra of gated pulses centered at (a) 530 nm and (b) 630 nm.

and the spectra of TrL signals are much cleaner. The spectral contrasts of TrL signals are much larger than those of OKG signals. The spectral contrast of gated pulses has been largely enhanced by TrL method.

IV. Conclusion

In conclusion, we developed a convenient method of time-resolving spectral measurement of SC chirp pulse. This method was based on ultrafast TrL effect and has many advantages, such as no demand of phase-match condition, and less optical elements. The direction of the TrL signal could be controlled by rotating a slit, which was placed in pump beam path. Experimental results showed that, the temporal resolution of the TrL method is comparative to that of OKG method, and the spectra of TrL signals are much cleaner than those of OKG signals.

References

[1] V. P. Kandidov, *et al.*, "Self-transformation of a powerful femtosecond laser pulse into a white-light laser pulse in bulk optical media (or supercontinuum generation)," *Appl. Phys. B*, vol. 77, pp. 149–165, Sep. 2003.

[2] P. B. Corkum, C. Rolland, and T. Srinivasan-Rao, "Supercontinuum generation in gases," *Phys. Rev. Lett.*, vol. 57, no. 18, pp. 2268–2271, 1986.

[3] A. Brodeur and S. L. Chin, "Band-gap dependence of the ultrafast white-light continuum," *Phys. Rev. Lett.*, vol. 80, no. 20, pp. 4406–4409, 1998.

[4] S. A. Kovalenko, A. L. Dobryakov, J. Ruthmann, and N. P. Ernsting, "Femtosecond spectroscopy of condensed phases with chirped supercontinuum probing," *Phys. Rev. A*, vol. 59, no. 3, pp. 2369–2384, 1999.

[5] M. Balu, J. Hales, D. Hagan, and E. V. Stryland, "Dispersion of nonlinear refraction and two-photon absorption using a white-light continuum Z-scan," *Opt. Express*, vol. 13, no. 10, pp. 3594–3599, 2005.

[6] R. L. Fork, C. V. Shank, C. Hirlimann, R. Yen, and W. J. Tomlinson, "Femtosecond white-light continuum pulses," *Opt. Lett.*, vol. 8, no. 1, pp. 1–3, 1983.

[7] T. F. Albrecht, K. Seibert, and H. Kruz, "Chirp measurement of large-bandwidth femtosecond optical pulses using two-photon absorption," *Opt. Commum.*, vol. 84, nos. 5–6, pp. 223–227, 1991.

[8] S. Yamaguchi and H. O. Hamaguchi, "Convenient method of measuring the chirp structure of femtosecond white-light continuum pulses," *Appl. Spectrosc.*, vol. 49, no. 10, pp. 1513–1515, 1995.

[9] C. Nagura, A. Suda, H. Kawano, M. Obara, and K. Midorikawa, "Generation and characterization of ultrafast white-light continuum in condensed media," *Appl. Opt.*, vol. 41, no. 18, pp. 3735–3742, 2002.

[10] H. Liu, W. Tan, J. Si, X. Liu, and X. Hou, "Acquisition of gated spectra from a supercontinuum using optical Kerr gate of lead phthalocyanine-doped hybrid glasses," *Opt. Express*, vol. 16, no. 17, pp. 13486–13491, 2008.

[11] T. Yasui, K. Minoshima, E. Abraham, and H. Matsumoto, "Microscopic time-resolved two-dimensional imaging with a femtosecond amplifying optical Kerr gate," *Appl. Opt.*, vol. 41, no. 21, pp. 5191–5194, 2002.

[12] W. Tan, J. Tong, J. Si, Y. Yang, W. Yi, F. Chen, and X. Hou, "High time-resolved three-dimensional imaging using ultrafast optical Kerr gate of bismuth glass," *IEEE Photon. Technol. Lett.*, vol. 23, no. 8, pp. 471–473, Apr. 15, 2011.

[13] M. Terazima, "Ultrafast transient Kerr lens in solution detected by the dual-beam thermal-lens method," *Opt. Lett.*, vol. 20, no. 1, pp. 25–27, 1995.

[14] M. Sakakura and M. Terazima, "Oscillation of the refractive index at the focal region of a femtosecond laser pulse inside a glass," *Opt. Lett.*, vol. 29, pp. 1548–1550, Jul. 2004.

[15] M. Sakakura, M. Terazima, Y. Shimotsuma, K. Miura, and K. Hirao, "Observation of pressure wave generated by focusing a femtosecond laser pulse inside a glass," *Opt. Express*, vol. 15, no. 9, pp. 5674–5686, Apr. 2007.

[16] M. Sakakura, M. Terazima, Y. Shimotsuma, K. Miura, and K. Hirao, "Heating and rapid cooling of bulk glass after photoexcitation by a focused femtosecond laser pulse," *Opt. Express*, vol. 15, no. 25, pp. 16800–16807, 2007.

[17] Y. R. Shen, *The Principles of Nonlinear Optics*. New York: Wiley, 1984.

[18] A. Lin, A. Zhang, E. J. Bushong, and J. Toulouse, "Solid-core tellurite glass fiber for infrared and nonlinear applications," *Opt. Express*, vol. 17, no. 19, pp. 16716–16721, 2007.