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Chirp structure measurement of a supercontinuum pulse based on transient lens effect in tellurite glass

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We demonstrated the controllable acquisition of optical gated spectra from a chirped supercontinuum (SC) pulse based on ultrafast transient lens (TrL) effect. Comparing with CS₂, the gated spectra had much narrower spectral bandwidths using tellurite glass (Te glass) as the nonlinear medium due to its ultrafast nonlinear response. Experimental results showed that the chirp structure of the SC pulse measured by TrL method was quite accordant with that measured by femtosecond optical Kerr gate method. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4795587>]

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 various media,^{2,3} and found extensive applications in time-resolved broadband absorption and excitation spectroscopy,^{4,5} optical parametric amplification,⁶ high time-resolved imaging,⁷ and some other applications.^{8,9} Until now, the chirp structure of SC has been studied by sum-frequency generation cross-correlation method,¹⁰ two-photo absorption,¹¹ and optical Kerr gate (OKG) technique.^{12–14}

The ultrafast transient lens (TrL) effect has been discussed a lot for a few decades,^{15,16} and has been utilized in many fields, such as measurement of third-order material response,¹⁷ detecting carrier dynamics in semiconductors.¹⁸ Especially, the propagation feature of femtosecond induced pressure wave inside a glass has been well researched by TrL method in this decade.^{19–23} In these studies, the dynamics of pressure wave are mainly characterized on the time scale from picosecond to nanosecond. When focusing the femtosecond time scale, the gate function of TrL could be explored through detecting the photons diffracted by the TrL effect (TrL signals). Thus, if a SC pulse is served as the probe beam, the chirp structure could be measured. The advantages of TrL method in time-resolving the temporal chirp structure of SC pulse are background free detection, no necessity of phase-match condition and less optical devices. Further, it would be expected that, the temporal resolution of the TrL is mainly depended on the nonlinear optical response of the medium. The chirp structure of the SC probe beam could be measured more precisely if the medium with ultrafast response is used.

In this paper, we proposed a convenient method to measure the chirp structure of a SC probe beam based on transient TrL effect. The wavelength-tunable pulses with narrow

spectral bandwidths can be acquired spatially separated from the incident SC region using TrL method. Using tellurite glass (Te glass) with ultrafast nonlinear response, the chirp structure of the SC probe beam measured by TrL method is quite accordant with that measured by femtosecond OKG method.

II. EXPERIMENTS

The Te glass sample with composition of 80TeO₂-10ZnO-10Na₂O was prepared by conventional melt-quenching method. Reagent chemical powders with purity $\geq 99.9\%$ were precisely weighed up, homogeneously mixed in a glass bottle, melted in a gold crucible at about 800 °C for 1 h, poured onto a brass mold at 220 °C, annealed at 259 °C for 8 h, and then slowly cooled down to room temperature. During the melting process, high melting temperature was chosen to reduce the viscosity of the melted glass. Further, the powders were mixed uniformly by shaking the crucible in the process of melting. The thickness of the Te glass sample was 1 mm. The nonlinear refractive index n_2 of the Te glass was measured to be $\sim 10^{-15}$ cm²/W, and an excellent transmission window was provided from 0.38 μ m to 6.1 μ m.²⁴

Figure 1(a) shows the experimental setup of chirp structure measurement of SC probe beam based on TrL effect. The multi-pass 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 pulses were generated and then collimated after filtering the long-wave components. The other beam which was optically delayed against the probe beam was served as pump beam. A slit with 1.5 mm width was put in the middle of the optical path of pump beam. The collimated probe and pump beams were passed through a lens (L3) with 300 mm focal-length collinearly and focused inside the nonlinear medium. The details of the sample area and collection device were shown in Fig. 1(b). The TrL plane was located at the position of the

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nonlinear refractive index region induced by pump beam in the sample. The distance (d) of the focal point of the SC probe beam from the TrL plane, which was called “focal mismatch.”²¹ In the experiment, the d was adjusted to a negative value of -3 mm by changing the distance between lens L1 and lens L2. For the d of negative value, the center of the irradiated region acted as a lens to defocus the probe beam, and the probe beam was expanded at the detection plane. The TrL signals were detected by an optical multichannel analyzer (OMA) after filtering the pump beam. As the time-delay device moving, the TrL signals from SC probe beam at detection plane could be acquired spatially separated. Figure 1(c) shows the spectrum of the SC probe beam, which covers from 470 to 735 nm.

III. RESULTS AND DISCUSSIONS

In the experiment, the pump power was kept at a low level, and the refractive index change in the nonlinear medium is mainly originated from optical Kerr effect.²⁵ Due to the slit shaped pump beam, the corresponding refractive index change only exists in a thin region. The spatial phase modulation intensity in the direction paralleled to the slit is larger than that in the perpendicular direction. The TrL signal, which is

originated from the defocused SC probe beam, is mainly appeared in the direction paralleled to the slit.

To demonstrate the application of acquiring optical gated spectra from SC pulse using TrL method, we used CS₂ as the nonlinear medium first. The CS₂ was placed in a fused silica cell with 1 mm thickness. Figure 2 shows the gated spectra from SC probe beam using 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 the time delay of 1000 fs. We can see green beam pattern was spatially diffracted outside the incident SC probe beam region, which permitted us to detect the gated spectra signal with no background from the SC probe beam itself. 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 38 nm. By measuring the transmitted differential spectra of the SC probe beam, which was the difference of the transmitted spectra of the SC probe beam with and without the pump beam, a valley at 530 nm was observed. By rotating the slit, the spectra of the TrL signal and the transmitted differential spectra of the SC probe beam had no obvious changes. However, the spectra of TrL signal depended on the relative time delay between the SC probe beam and the pump beam. Figure 2(b) shows

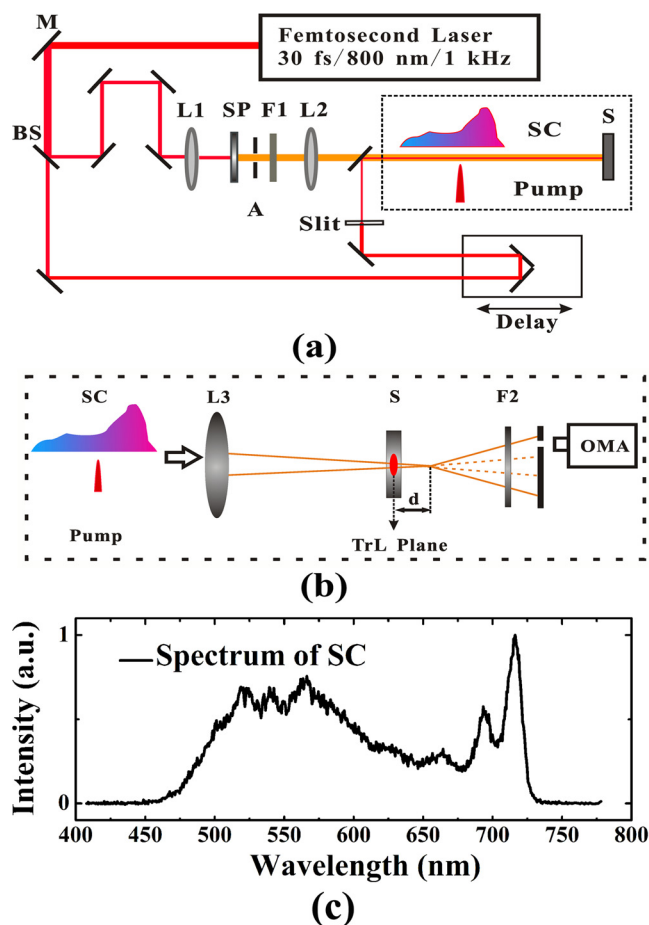


FIG. 1. (a) Schematic illustration of the experimental setup. M: mirror; BS: 1:1 beam splitter; L1, L2, and L3: lens; SP: sapphire plate; A: aperture; S: sample; F1, and F2: low-pass filter. (b) The detail of the TrL method. The solid and broken lines depict the SC probe beam paths with and without pump beam, respectively. (c) Spectrum of SC probe beam.

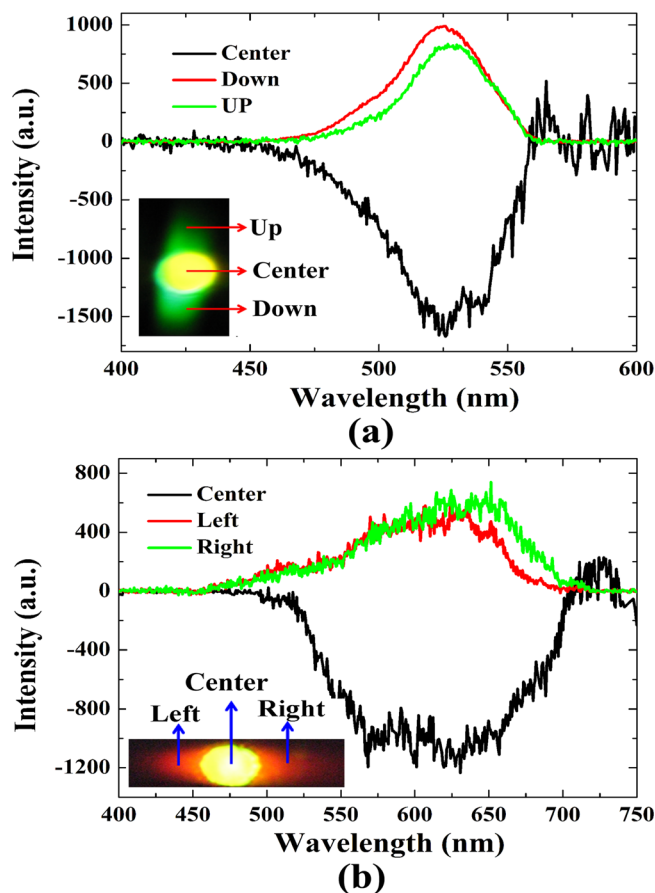


FIG. 2. TrL signals measured at the time delay of (a) 1000 fs and (b) 2100 fs using CS₂. The insets show the photographs of TrL signals. The arrows denote the detected areas. The slit placed in pump beam path was set to (a) vertical and (b) horizontal. Both the spectra measured at the “Center” positions were the differential spectra.

the spectra of TrL signal obtained at the time delay of 2100 fs. In this measurement, the slit placed in the optical path of pump beam was set to horizontal. As expected, the direction of the TrL signal rotated to horizontal, as shown in the inset of Fig. 2(b). The central wavelengths in the TrL signals and the transmitted differential spectra were nearly the same, which were all located about 630 nm. Further, we can see the wavelength onsets of the TrL signals and the differential spectra were nearly the same, indicating the photons of the TrL signals were originated from the SC probe beam.

Then, the spectral characteristics of TrL signals acquired from TrL method have been studied using the CS₂ and Te glass as the nonlinear media, respectively. The results are shown in Fig. 3. A series of gated spectra acquired by TrL method using CS₂ and Te glass at seven different wavelengths are shown in Figs. 3(a) and 3(b), respectively. The time delay intervals of the neighboring gated spectra in Figs. 3(a) and 3(b) are about 410 fs and 350 fs, respectively. The gated spectra from CS₂ exhibit wide bandwidth and obvious band trailing, and the obtained gated spectra using TrL of Te glass have much narrower bandwidth and better symmetry, indicating the use of Te glass could offer better temporal resolution. This is because the nonlinear refractive index induced in Te glass originates mainly from the electronic process, and its response is much faster than that of CS₂. The

corresponding beam patterns obtained by TrL of Te glass are shown in the inset of Fig. 3(b). In these measurements, the slit placed in the pump beam was set to vertical.

Figure 4(a) shows the chirp structure of the SC probe beam measured by TrL method and OKG method using Te glass, respectively. Both the experimental data show the SC probe beam has ~ 2.6 ps in time domain. The central wavelength of TrL signal measured by TrL method at each time delay is close to that measured by OKG, which has been considered to be a powerful technique in the ultrafast measurements. The chirp structure of the SC probe beam measured by TrL method is quite accordant with that measured by OKG method. In principle, the temporal resolution of TrL method is depended on the response of nonlinear refractive index change, which is the same as that of OKG method. In the experiment, the temporal resolution of OKG using Te glass, whose nonlinearity originates from electronic process, is less than 300 fs.²⁶ Therefore, we deduce that the temporal resolution of TrL method using Te glass is less than 300 fs, which is at the same level as that of the OKG of Te glass. Comparing with collinear OKG configuration, the advantages for TrL method to measure the chirp structure of SC probe beam were very clear. Fig. 4(b) shows the gated spectra located at 600 nm acquired by the two methods. The spectral profile gated by TrL method is very clean. However, the

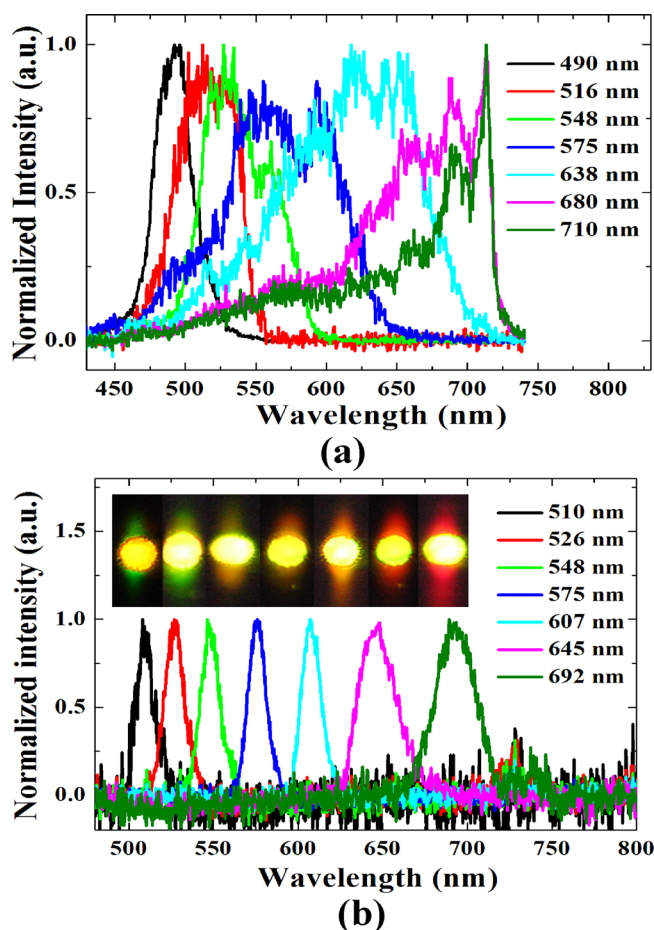


FIG. 3. Normalized intensity of gated spectra obtained by TrL of (a) CS₂ and (b) Te glass. The inset in (b) shows TrL signals at seven measured time delays.

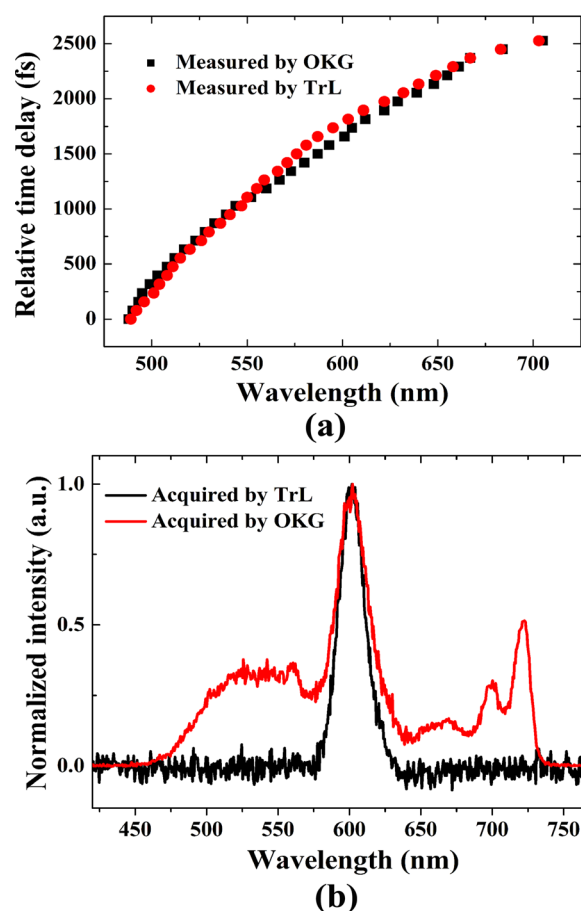


FIG. 4. (a) Chirp structure of SC probe beam measured by TrL and OKG, respectively. (b) Spectral profiles of two gated spectra acquired by the TrL and OKG, respectively.

spectral profile of Kerr signal is disturbed by the SC leakage passed through the polarizer in the OKG configuration. Therefore, the spectral contrast of gated spectra could be highly enhanced using TrL method.

IV. CONCLUSION

In summary, we demonstrate that gated spectra with narrow spectral bandwidths can be acquired spatially separated from the incident SC region using TrL of Te glass. The chirp structure of the SC probe beam measured by TrL method is quite the same as that measured by OKG method. The Te glass has showed ultrafast nonlinear response, indicating its wide application in ultrafast measurement in future. Comparing with OKG, the advantages of TrL method functioned as an ultrafast optical gate are more convenient and sensitive, which promote it in much wider applications, such as transient fluorescence capturing.

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