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# Instantaneous three-dimensional imaging using supercontinuum and ultrafast optical Kerr gate of tellurite glass

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**Abstract.** An instantaneous three-dimensional imaging technique using a chirped supercontinuum and an ultrafast optical Kerr gate, in which a sapphire plate and a $TeO_2$-ZnO-$Na_2O$ oxide glass were used to generate the chirped supercontinuum and the ultrafast optical Kerr gate, respectively, is demonstrated. This technique is applicable to ultrafast shape measurement, such as shape imaging of moving objects, or imaging of laser-induced refractive index changes in transparent media. [DOI: 10.1117/1.OE.53.4.043108]

Keywords: femtosecond; optical Kerr gate; tellurite glass; instantaneous three-dimensional imaging; supercontinuum.

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## 1 Introduction

Time-resolved imaging based on optical Kerr gate (OKG) was an effective method to diagnose various ultrafast phenomena,[1–5] such as ultrafast fluorescence, laser-produced plasmas, propagation dynamics of laser pulses in a medium, and so on. By combining the chirped supercontinuum and the OKG, an instantaneous three-dimensional (3-D) imaging technique was proposed.[6] This method has both an ultrahigh time resolution and a better longitudinal resolution and has successfully been used to several types of shapes for shape measurement,[7–9] such as a completely diffusing surface, stepped and spherical surfaces. It is applicable for shape imaging of moving objects, or imaging of laser-induced refractive index changes in transparent media,[10,11] which provides interesting tools for scientific and potential practical applications.

For this instantaneous 3-D imaging technique, the fast respond time and the large optical nonlinearity of the optical Kerr material could improve the time resolution, longitudinal resolution, and the signal intensity.[6] However, in the femtosecond time domain, a trade-off between high sensitivity and fast response mostly limits the gate performance in the time-resolved imaging. To overcome this issue, an amplifying OKG has been proposed,[7] in which the stimulated radiation effect in dyes was used to gain the incident laser pulses. Although the amplifying OKG improved the gate performance, the imaging system became more complex. In addition, the response time of the amplifying OKG is limited to ~460 fs by the complex photochemistry reaction of the dye molecules.[9]

Recently, it has been reported that bismuth glasses were suitable for such application due to their large optical nonlinearity and ultrafast response time.[12] However, bismuth glasses have a limited transmission bandwidth in the visible region, the absorption edges of which are ~500 nm. It somewhat restricts the dynamic range. Apart from the large optical nonlinearity and the ultrafast response time,[13–15] tellurite glasses have a wider transparency window compared with bismuth glasses,[16,17] which are transparent in the visible to mid-infrared region. Therefore, these glasses could offer a larger dynamic range for this instantaneous 3-D imaging based on the OKG.

In this study, we used a $TeO_2$-ZnO-$Na_2O$ oxide glass (here denoted by Te glass) as the Kerr medium to demonstrate the instantaneous 3-D imaging in detail. One Kerr-gated true two-dimensional color image and its corresponding Kerr-gated spectrum were simultaneously obtained using the ultrafast OKG and a supercontinuum, which clearly showed the surface structure of the illuminating area of the object. Furthermore, we discussed and corrected the thickness deviation and reconstructed the 3-D shape in the end.

## 2 Experimental Details

The 3-D imaging system we used is shown in Fig. 1. A Ti:sapphire laser system (FEMTOPOWER compact Pro) with a repetition rate of 1 kHz, pulse duration of 30 fs, and an average power of 1 W at 800 nm was used in our experiments. The emitting fundamental laser beam was split into two beams by a beam splitter with a split ratio of 1∶4. Passing through an optical delay translation stage, the intense one was finally focused onto the Kerr material as a gating beam. A half-wave plate was used to rotate its polarization by $\pi/4$. The weak one was focused into a 3-mm sapphire plate, which was nearly on the geometrical focal plane. Before the sapphire, an iris diaphragm was introduced to adjust the self-focusing condition in the sapphire plate and an adjustable neutral optical attenuator was used to adjust

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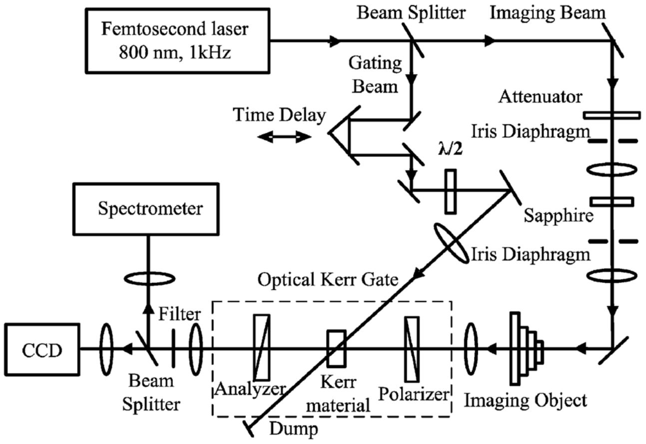

**Fig. 1** Schematic setup for a high time-resolved three-dimensional (3-D) imaging technique.

laser power to obtain a stable supercontinuum as the imaging beam.[18] Another iris diaphragm was introduced to eliminate the accompanying conical emission. The imaging beam was collimated and expanded to illuminate a transparent object, that is, a glass sheet composed of three flat steps as shown in Fig. 2. The diameter of the illuminated area of the object was ∼4 mm. The step thicknesses were, respectively, measured to be 165, 330, and 495 $\mu$m by a step profiler. The OKG consisted of a pair of calcite crossed polarizers and a Kerr material between them. The gating beam and the imaging beam were focused into the Kerr sample at a crossing angle of 15 deg.

When the OKG was opened by the gating beam, a time-sliced supercontinuum passed through the analyzer and was synchronously detected with a color CCD and a microspectrometer. The numerical aperture of the imaging system in object space is ∼0.0014. Care has been taken to collect the entire Kerr-gated spectra with minimized residual fundamental by cutting off most of the incident fundamental laser frequency with the help of an 800-nm reflective cutoff filter.

Figure 2 shows the schematic of the instantaneous 3-D imaging technique. A collimated and expanded supercontinuum was introduced to the imaging object. After passing through the object, the imaging beam had different optical paths for different regions of the imaging object. For example, in our experiments, the illuminated areas of the imaging object had three regions. By adjusting the time delay between the gating pulse and the supercontinuum, the OKG could transmit a time-sliced supercontinuum with three wavelengths, which was detected by a color CCD. The transmitted imaging beam shows a color distribution corresponding to the surface structure, so we could obtain a real-time spectrally resolved and colored 3-D map of the object.

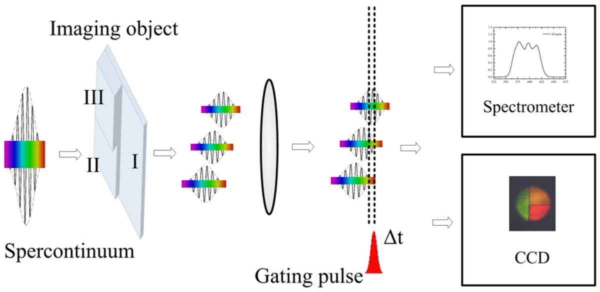

**Fig. 2** Schematic of the instantaneous 3-D imaging technique using supercontinuum and ultrafast optical Kerr gate.

In the instantaneous 3-D imaging technique, the longitudinal resolution is dependent on the optical path difference corresponding to the different regions on the object surface. For the reflection-type imaging, the optical path difference is twice the step height on the object surface, while for the transmission-type imaging, the optical path difference is equal to the product of the step height and the refractive index difference between air and the object. In order to avoid the uncertainty to evaluate longitudinal shape information with the color 3-D map, we further proposed to measure the spectrum and image of the transmitted time-sliced imaging beam by the color CCD and a microspectrometer synchronously. So using the chirp character of the supercontinuum calibrated beforehand, the longitudinal shape information of the imaging object can be precisely calculated.

## 3 Results and Discussion

The Te glass used in our experiments was prepared by melting $TeO_2$, ZnO, and $Na_2O$ according to a certain proportion. The details about the preparation of the Te glass were given in Ref. 15. The linear transmission spectrum from 300 to 900 nm of the Te glass was first measured, as shown in Fig. 3. We can see that the Te glass is excellently transparent in the visible region. Its absorption edge is <400 nm, which means that the Te glass could offer a large dynamic range for the instantaneous and simultaneous 3-D imaging.

Measurement of the ultrafast response of the Te glass was performed by using the OKG measurement,[19] and the results are shown in the inset of Fig. 3. The hollow circle and the solid circle refer to the Te glass and the $CS_2$, respectively. From the inset of Fig. 3, we can see that the time-resolved optical Kerr effect signal of the Te glass was symmetrical and the full width at half-maximum of the signal was ∼250 fs, which suggests that the Te glass could also offer better temporal and longitudinal spatial resolution for the simultaneous 3-D imaging compared with $CS_2$.

In addition, we measured the chirp character of the supercontinuum using the OKG method. A series of Kerr-gated

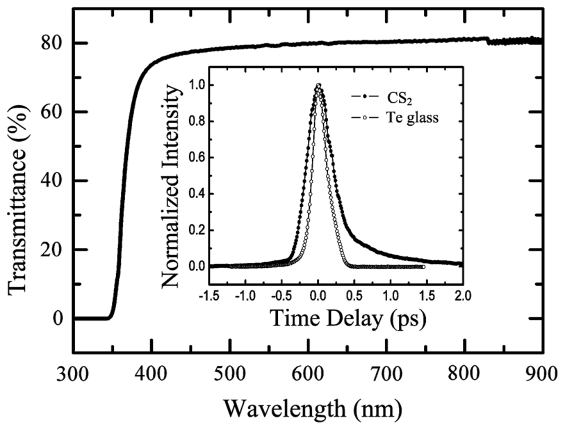

**Fig. 3** Transmission spectra from 300 to 900 nm of the Te glass. Inset: femtosecond time-resolved optical Kerr gate signals of the Te glass (hollow square) and $CS_2$ (solid square).

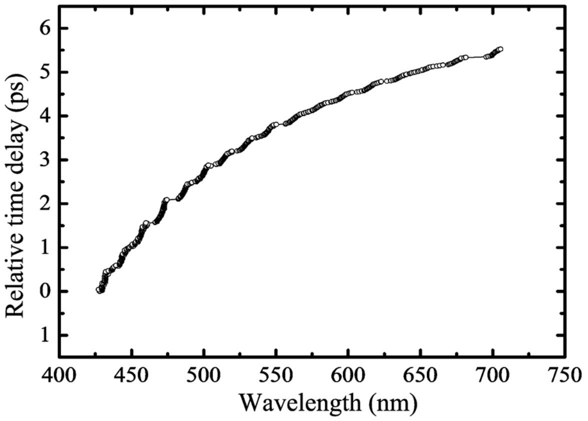

**Fig. 4** The relative time delays against the various peak wavelengths of the overall Kerr-gated spectra without the imaging object.

spectra from the supercontinuum were acquired using the setup shown in Fig. 3, in which the object was removed. Figure 4 presents the relative time delays versus the various peak wavelengths of the overall Kerr-gated spectra. From Fig. 4, we can see that the supercontinuum used in our experiment, with a spectrum ranging from 450 to 750 nm, expands nonlinearly to 4.6 ps in time domain and has low chirp in the short-wave region.

Moreover, we demonstrated the simultaneous 3-D imaging using the chirped supercontinuum and the Te glass. The exposure time of the CCD in this experiment was set to be 1 ms. Figure 5 shows the Kerr-gated image and its spectrum of the circular illuminated area of the imaging object obtained at one fixed delay time simultaneously. In Fig. 5, there are three colored regions in the circular illuminated area of the imaging object, i.e., green, orange, and red, corresponding to regions I, II, and III of the object, respectively. There are also three distinguishable peaks in the Kerr-gated spectrum, which are 578, 597, and 614 nm, respectively. From Fig. 4, we got the intervals of the relative delay times for photons propagated through the regions I, II, and III of the object to be ~0.1976 and 0.2808 ps, respectively. And the imaging object used in our experiments was quartz, the linear refractive index of which at the wavelengths of 578, 597, and 614 nm were all ~1.54. Then, we calculated the step heights to be ~110 and 157 $\mu$m, respectively. However, the results deviate from the values measured by the step profiler. We attributed the deviation to the nonuniform intensity distributions for different wavelength components in the supercontinuum, which could distort the judgment of the peak wavelength of the Kerr-gated spectrum for a fixed step region.

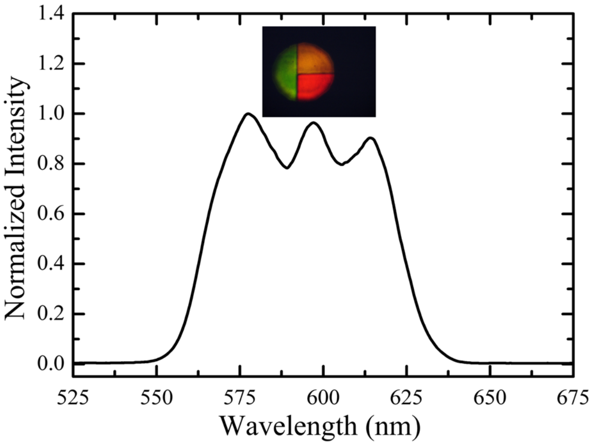

**Fig. 5** Kerr-gated spectra of the circular illuminated area of the imaging object. The inset shows the corresponding Kerr-gated true two-dimensional color image.

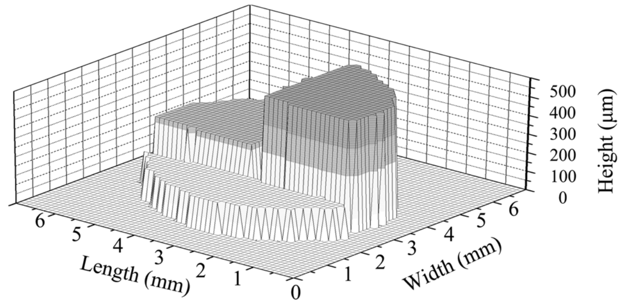

**Fig. 6** 3-D reconstruction of the circular illuminated area of the imaging object.

To further verify our inference, an aperture was introduced after the OKG to select a fraction of Kerr-gated spectrum. When only single color Kerr-gated spectrum was selected to be imaged on the CCD, the Kerr-gated spectrum from one single step region was measured by the microspectrometer synchronously. Then the single Kerr-gated spectrum of every step region was measured sequentially. The peak wavelengths of the spectra for the regions I, II, and III were remeasured to be 571, 593, and 616 nm, respectively, and the modified intervals of the relative time delays were ~0.2912 and 0.2964 ps. The step heights were recalculated to be ~162 and 165 $\mu$m, respectively. The modified results agree well with those measured by the step profiler and indicate that a flat supercontinuum and a high-resolution spectrometer must be necessary for high longitudinal resolution of the instantaneous 3-D imaging technique. It should also be noted that the lateral resolution of the instantaneous 3-D imaging technique depends on the combined numerical apertures of the imaging system.[8] Finally, using the lateral distributions obtained from the color map in Fig. 5 and the step heights recalculated, the 3-D surface of the illuminated areas of the imaging object were reconstructed as shown in Fig. 6.

## 4 Conclusions

In conclusion, we demonstrated the time-resolved 3-D imaging using one excellent Te glass as the Kerr material. One Kerr-gated true two-dimensional color image and its corresponding Kerr-gated spectrum were simultaneously obtained using the ultrafast OKG and the supercontinuum, which clearly showed the surface structure of the illuminating area of the object. The measurement deviation was also discussed and corrected. In the end, the 3-D stepped surface of the illuminated areas of the imaging object was reconstructed.

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Biographies of the other authors are not available.