Shape measurement of objects using an ultrafast optical Kerr gate of bismuth glass

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An ultrafast optical Kerr gate of $Bi_2O_3-B_2O_3-SiO_2$ oxide glass (BI glass) was used in an ultrafast time-resolved imaging system for shape measurement of objects. The experimental results showed that the longitudinal resolution of the imaging system using the ultrafast optical Kerr gate was less than 20 μm and the measurements of object shape using the ultrafast optical Kerr gate of BI glass had more advantages compared with that using CS_2. © *2010 American Institute of Physics*. [doi:10.1063/1.3310492]

I. INTRODUCTION

Optical shape measurement is an attractive subject for scientific interest and practical applications, such as automatic online inspection, intelligent robots, accurate stress, and vibration measurement.[1–3] Lots of methods have been developed for the shape measurement of objects. Among them, an ultrafast time-resolved two-dimensional imaging system has been proposed by Minoshima *et al.*,[4–7] in which supercontinnum pulses and an optical Kerr gate (OKG) are used for the three-dimensional (3D) shape measurement. This technique combines some advantages of the time-of-flight method[8,9] and the time-resolved imaging method,[10–12] such as direct shape measurement without complex mathematics calculation, high time resolution to inspect objects embedded in turbid media, and dynamic measurement for the shape of moving objects.

However, in the femtosecond time domain, a trade-off between high sensitivity and fast response mostly limits the gate performance in time-resolved imaging. To overcome this issue, an amplifying OKG has been proposed,[5–7,13] in which the stimulated radiation effect in dyes was used to gain the incident laser pulses. Meanwhile, two perpendicularly polarized pump pulses were used to reduce the gate time. Although the amplifying OKG improved the gate performance, the imaging system became more complex.

In this study, we suggest to use fundamental pulses as the imaging pulses and $Bi_2O_3-B_2O_3-SiO_2$ oxide glass (BI glass) as the Kerr material. The nonlinear response time of BI glass has been measured to be less than 90 fs.[14] The ultrafast OKG of BI glass could provide a high longitudinal resolution in 3D shape measurements. Moreover, the BI glass presents an optical nonlinearity as large as that of the chalcogenide glass,[14–17] insuring high signal noise ratio of the imaging system. A stepped surface composed of two glass plates coated with aluminum was measured to verify the feasibility of the time-resolved imaging system for 3D shape measurement of objects. As a comparison, results measured using the OKG of CS_2 were also presented.

II. EXPERIMENTS

Figure 1 shows a typical time-resolved imaging system for shape measurement of objects using the OKG. In our experiment, a Ti:sapphire laser system based on multipass amplification was employed, which emitted linearly polarized 30 fs pulses at a repetition rate of 1 kHz. The center wavelength was 800 nm, and the bandwidth was about 40 nm. The incident fundamental beam was divided into two beams by a beam splitter. One beam passed through an optical delay translation as a gating pulse. A half-wave plate was used to control its polarization for the maximum gate efficiency.[14] The other beam was expanded by two lenses as an imaging pulse before it was introduced onto an object perpendicularly. Two neutral attenuators were used to adjust their intensity. Both of the imaging pulse reflected from the object and the gating pulse were focused onto the Kerr material and carefully overlapped inside. A pair of crossed Nicol prisms was used as the polarizer and the analyzer. By

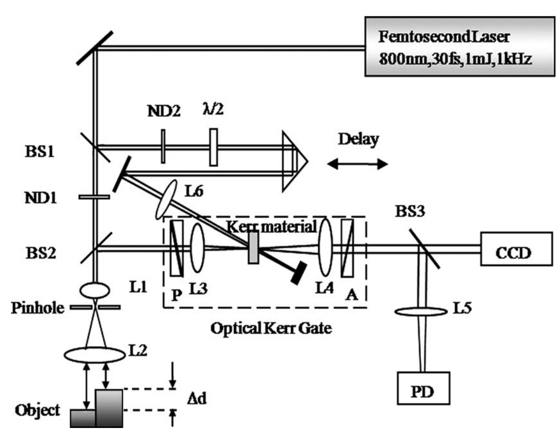

FIG. 1. Experimental setup for the time-resolved imaging system using ultrafast OKG: BS_{1-3}, beam splitter; ND_{1-2}, neutral attenuation; P, polarizer; A, attenuator; Δd, step height; L_{1-6}, lenses with focal lengths of 60, 120, 100, 150, 100, and 180 mm, respectively.

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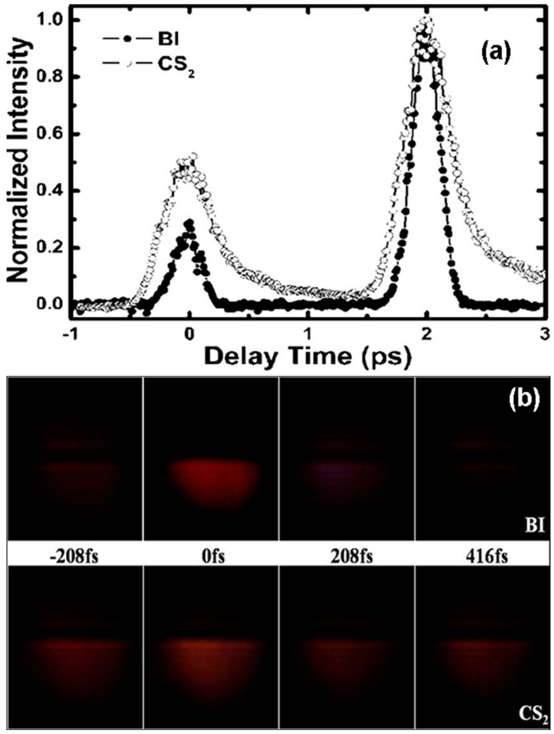

FIG. 2. (Color online) (a) Temporal behavior of OKG signals for the BI glass and CS_2. (b) Time-resolved images measured at different delay times.

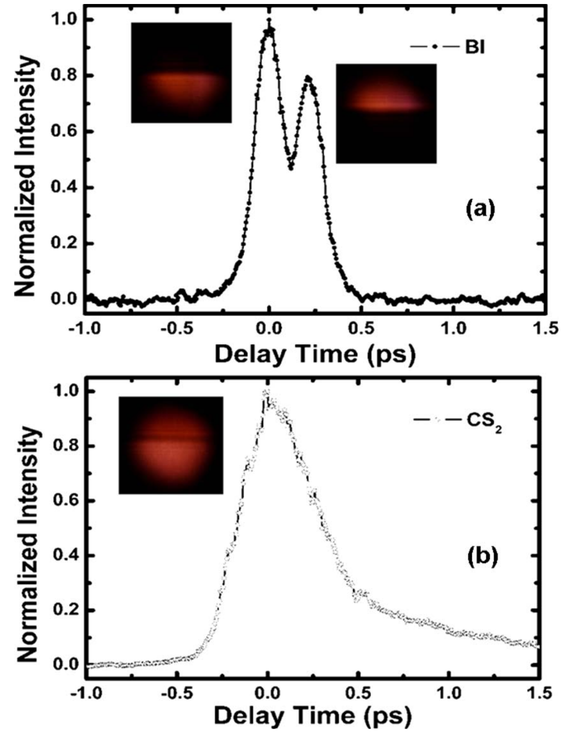

FIG. 3. (Color online) Temporal behavior of OKG signals. (a) BI glass as Kerr material. (b) CS_2 as Kerr material. Inset: time-resolved images measured at the peaks of OKG signals.

adjusting the delay time between the gating pulse and the imaging pulse, time-resolved OKG images and signals were imaged with a charge coupled device camera and detected with a photodiode, respectively.

A stepped surface composed of two glass plates coated with aluminum was measured using this setup. The step height was adjustable by shifting the left glass plate accurately as shown in Fig. 1. As a comparison, we used the BI glass and the referential CS_2 as the Kerr materials, respectively. The CS_2 solution was filled in a glass cuvette with a path length of 1 mm. The details about the preparation of the BI glass have been given in the Ref. 14.

III. RESULTS AND DISCUSSION

Figure 2(a) shows two time-resolved OKG signals from the whole surface of the object for the BI glass and CS_2 at $\Delta d = 300$ μm, where Δd is taken as the adjustable step height. The first peak and the second peak correspond to the left part of the stepped surface and the right one, respectively. The delay time between the two peaks depends on the step height. The first peak for both cases of the BI glass and CS_2 is lower than the second one, which is due to the smaller illuminated area of the left surface of the object. Figure 2(b) shows some OKG gating images at different delay times around the first peak when the BI glass and CS_2 was used, respectively. From Fig. 2(b), we can see the imaging using the BI glass has a higher longitudinal resolution than that using CS_2. The image using the BI glass almost disappears at the 208 fs delay time, but the image using CS_2 is still clear at the 416 fs delay time. It is because the width of OKG for the BI glass, which was measured to be about 162 fs (full width at half maximum) due to the positive group velocity dispersion in our experiments, is much narrower than that using CS_2 as shown in Fig. 2(a).

To compare further the different performance of the time-resolved imaging system using the BI glass and CS_2, a similar experiment was made at $\Delta d = 30$ μm. The results are shown in Fig. 3. There are two distinguishable peaks of the time-resolved OKG signals using the BI glass in Fig. 3(a). From Fig. 3(a), we can see that the first peak is higher than the second one due to the bigger illuminated area of the left surface of the object, which is different from that in Fig. 2(a). Two clear OKG gating images are shown in the inset of Fig. 3(a), which were measured at the two peaks. The delay time between the two peaks in Fig. 3(a) is 208 fs, which is equivalent to 31.2 μm in height. It agrees well with the actual step height considering the pulse intensity fluctuation. Figure 3(b) shows the time-resolved OKG signals for CS_2. An OKG gating image composed of the whole surface of the object measured at the signal peak is shown in the inset of Fig. 3(b), which illustrates that the time-resolved imaging system using CS_2 cannot distinguish this small step height. These results show that the time-resolved imaging system using the BI glass has a high longitudinal resolution.

Moreover, we experimentally investigated the longitudinal resolution of the time-resolved imaging system using the BI glass. The time-resolved OKG signals measured at $\Delta d = 0$, 15, 20, 25, and 30 μm were shown in Fig. 4, illustrating that the longitudinal resolution is 20 μm in our experiments. If the fundamental pulse is compressed further, the longitudinal resolution of the time-resolved imaging system using the BI glass could be further improved. At last, we converted the images in the inset of Fig. 3(a) into the binary images and

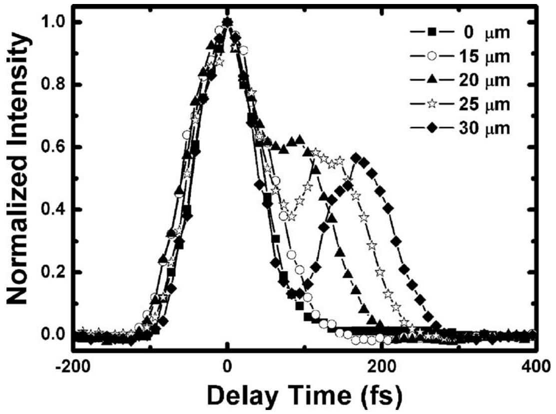

FIG. 4. Temporal behavior of OKG signals for the BI glass measured at $\Delta d=0$, 15, 20, 25, and 30 μm, respectively.

reconstructed the 3D stepped surface of the illuminated areas of the object according to the time difference between them. The result is shown in Fig. 5. It demonstrates the time-resolved imaging system using the BI glass is an effective tool for 3D shape measurement of objects. In addition, this method will be useful to inspect objects embedded in turbid media and dynamic measurement for the shape of moving objects.

IV. CONCLUSIONS

In summary, we proposed a time-resolved imaging system for shape measurement of objects, in which the BI glass was used as the Kerr material of femtosecond OKG. A stepped surface with adjustable step height was measured. The experimental results showed that the time-resolved imaging system using the ultrafast OKG of BI glass had more advantages compared with that using CS_2 and the longitudinal resolution using the BI glass was less than 20 μm. The 3D stepped surface of the object with 30 μm in height was reconstructed by a simple processing.

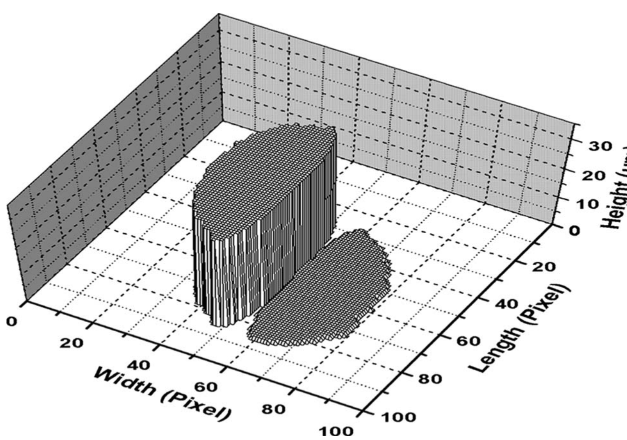

FIG. 5. 3D reconstruction of the object according to the images in the inset of Fig. 3(a).

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