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Efficient optical Kerr gate of Bi_2O_3–B_2O_3–SiO_2 glass for acquiring high contrast ballistic imaging in turbid medium

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Abstract
We investigated the ballistic imaging of a 1.41 line pair mm^{-1} section of a resolution test chart hidden behind a solution of polystyrene spheres with a femtosecond optical Kerr gate (OKG). A better transillumination image contrast could be acquired with an OKG of Bi_2O_3–B_2O_3–SiO_2 (BI) glass than that with an OKG of fused silica in a highly scattering media, which indicated that the BI glass was a better OKG medium due to its large nonlinear refractive index.

Keywords: femtosecond, optical Kerr gate, ballistic imaging, bismuth glass

(Some figures may appear in colour only in the online journal)

1. Introduction

There is considerable interest in the use of optical imaging through highly scattering medium because of its potential applications in medical diagnosis [1], fluid dynamics measurements [2], combustion detection [3] and materials science [4]. It is well known that an optical pulse traveling through a scattering medium consists of ballistic, snake, and diffusive photons [5], and only the ballistic photons carry the information on objects behind or inside the scattering medium. So, it is difficult to observe a target hidden in a turbid medium because of the strongly scattered photons, which will degrade the image contrast. Generally, using the method of ballistic imaging [6, 7], transillumination images can clearly be improved by limiting the scattered photons. In order to preferentially select photons based on their propagation direction [8, 9], a direct method introduces a spatial filter. Also, a temporal limit is a useful tool for ballistic imaging. However, significant improvements with time gating generally require short gate times. In practice, most systems that make use of time gating to reject scattered light depend on the use of the optical Kerr gate (OKG) technique [10–13]. Imaging of a target in a highly scattering medium using an OKG could enhance the imaging quality. Recently, the OKG technique has been applied to investigate the dynamics of spray breakup and vaporization to overcome the strong scattering in the near-field of liquid-fuel combustion in a high-speed rocket spray [14–16].

The OKG consists of a pair of crossed polarizers with a Kerr medium between them. The good quality of an OKG is mainly dependent on a Kerr medium with an ultrafast response and a large nonlinear optical refractive index. Nonlinear optical materials with fast response times and transparency have attracted much attention in many optical

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fields [17, 18]. Specifically, for ballistic imaging, the third-order optical nonlinearity of such highly nonlinear materials is the most significant property. The Bi_2O_3–B_2O_3–SiO_2 glass (BI) is an optical material with a large nonlinear optical refractive index and an ultrafast response time. The nonlinear refractive index of BI glass has been estimated to be about 2.93×10^{-15} cm^2 W^{-1} and the response time of the ultrafast nonlinear process has been measured to be less than 85 fs [19].

In this paper, we investigated ballistic imaging based on OKGs of BI glass and fused silica, respectively. Fused silica is a typical Kerr medium that has a high transmittance over a wide spectral range, but its nonlinear refractive index is low compared with the BI glass. We studied the dependence of image contrast on different optical densities (ODs). The maximum OD for a recognizable image was 11.5 using the OKG of BI glass, while it was only 8.7 for the OKG of fused silica. A better image contrast could be obtained by the OKG of BI glass than for the OKG of fused silica at the same OD, because the nonlinear refractive index of BI glass was one order of magnitude larger than that of fused silica.

2. Experiments

A schematic of the ballistic imaging system in our experiments is shown in figure 1. A Ti:sapphire laser system with a repetition rate of 1 kHz and a pulse duration of 50 fs at 800 nm was used in our experiments. The output beam was split into two beams in the power ratio of 1:28 by a short pass filter (SPF). The long wavelength portion, whose central wavelength was about 800 nm, was used as a probe beam, and the short wavelength part, centered at about 780 nm, was used as a gating beam. The high-power beam was used as the imaging beam, and was modulated by a 1.41 line pair mm^{-1} section of a resolution test pattern (a United States Air Force contrast target), which was placed on the conjugate imaging plane of a color charged-coupled device (CCD) camera (NIKON DXM 1200F). The transmitted light from the sample was collected by a lens (L2) and then passed through the ultrafast OKG. The distance between the resolution test pattern and L2 was equal to the focal length of lens L2. The OKG consisted of a pair of calcite-crossed polarizers with a Kerr medium between them. The gating beam was focused into the Kerr medium by lens L1, and this beam was time delayed by a delay line and rotated in polarization by 45° using a half-waveplate for maximum gate efficiency. The Kerr signal was subsequently collected by two lenses (L3, L4) and directed to a CCD camera. A long pass filter (LPF) was placed between L4 and the camera in order to reduce the intensity of the noise generated by the pump scattering in the Kerr medium. Using this system, the ballistic light, which traveled a shorter path compared with the scattered light, reached the Kerr medium first, and could be effectively selected temporally by the OKG. When the incident pulse passed through a long turbid medium, the duration of ballistic light is broadened due to the temporal chirp effect, so the intensities of the ballistic light and the image will be reduced when the gate width of the OKG is kept constant.

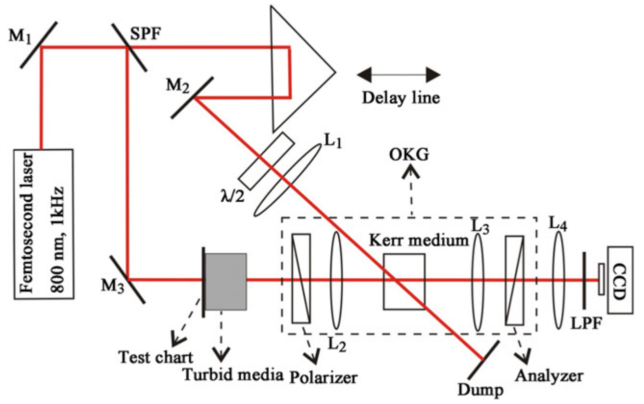

Figure 1. Schematic of the ballistic imaging system. L: lens; M: mirrors; λ/2: half-waveplate; SPF: short pass filter; LPF: long pass filter.

In our experiments, we used BI glass and fused silica as the Kerr media, respectively. For the BI glass, the nonlinear refractive index n_2 was estimated to be about 2.93×10^{-15} cm^2 W^{-1} in comparison with that of fused silica of 2.7×10^{-16} cm^2 W^{-1} [20]. The nonlinear refractive index of BI glass was one order of magnitude larger than that of fused silica. The thickness of the BI glass and the fused silica were both 1 mm. The turbid medium consisted of dilute polystyrene sphere solutions with a mean diameter of 0.4 μm in a 10-mm-thick optical cell.

3. Results and discussions

3.1. Acquiring a better image contrast with the OKG

An essential aspect of an optical system is its ability to transmit spatial information. The relevant parameter to evaluate performance is the visibility, or image contrast. To investigate the dependence of image contrast with and without an OKG, we measured the image contrast of the bar chart with the OKG of BI glass and direct shadowgraph imaging at different ODs. Contrast is defined as

$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{min} is the average light intensity corresponding to the shadowed region and I_{max} is the average light intensity corresponding to the unshadowed region of the imaged resolution test chart.

We placed the test chart before a 10-mm-thick sample cuvette. First, we investigated the image of the resolution test chart without an OKG when the sample cuvette was filled with distilled water, as shown in figure 2(a), and the corresponding normalized intensity variation of the image is also shown in figure 2(a). We regarded this image as the original image of the resolution test chart, and the image contrast calculated was 85% using equation (1). Then, we acquired the image when the sample cuvette was filled with the polystyrene sphere solution. As shown in figure 2(b), we acquired this image at OD 10.2 without an OKG, and the contrast of this image

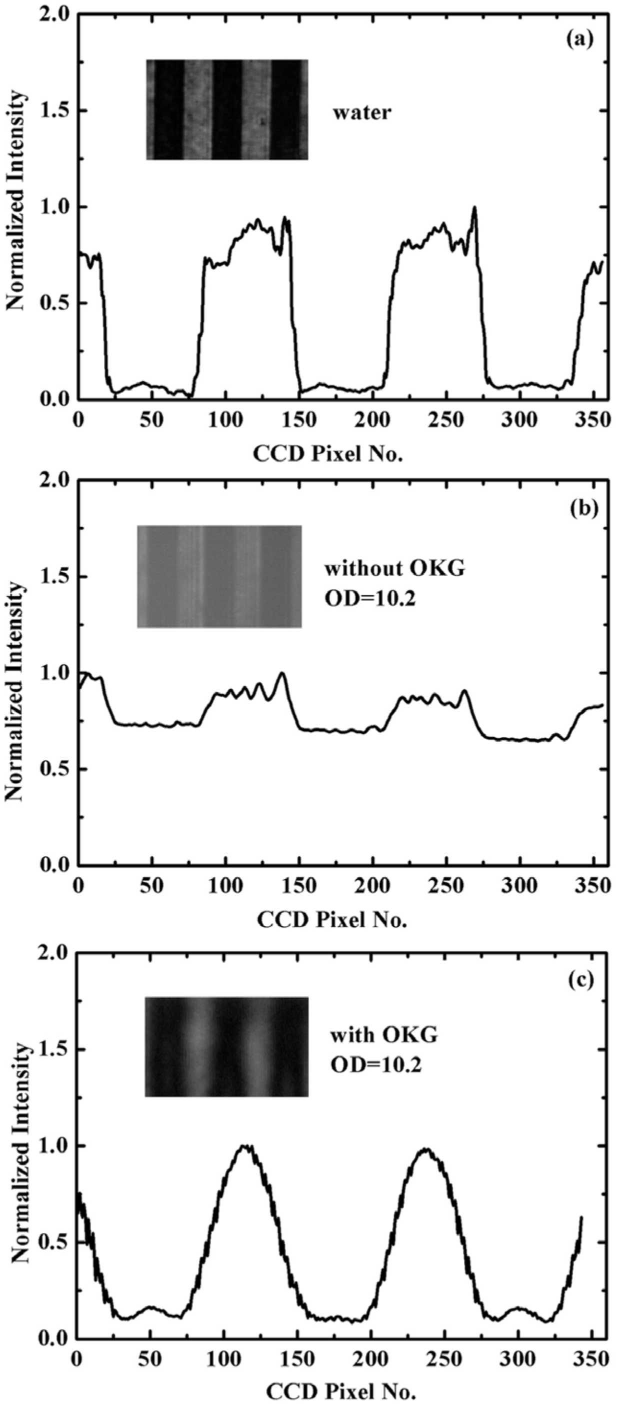

Figure 2. Comparison of the images of the bar chart hidden behind a solution of polystyrene spheres with and without an OKG, and the corresponding normalized intensity distributions. (a) Through water and without an OKG. (b) Through the scattering sample and without an OKG. (c) Through scattering sample and with the OKG of BI glass.

was calculated as 5.7%. Finally, using the OKG of BI glass, the image was acquired when the sample cuvette was filled with the polystyrene sphere solution. As shown in figure 2(c), the contrast of this image is 76.6% at the same OD 10.2. From figures 2(a) and (b), we found that the image contrast was greatly improved by the OKG of BI glass, mainly due to the OKG eliminating diffuse scattering noise and obtaining a better signal-to-noise ratio (S/N) in the image. It should be noted that the 'Kerr–Fourier' imaging setup in our ballistic imaging system configuration was originally adapted [21] so that the gating beam induced a transient spatial gate in the Kerr material in this imaging system, which filtered some high-frequency components of spatial frequency spectrum of the object. The boundary sharpness of the ballistic images decreased. Therefore, the curve in figure 2(c) shows a convex line shape near the maxima, while the original chart shows a rectangular line shape in figure 2(b).

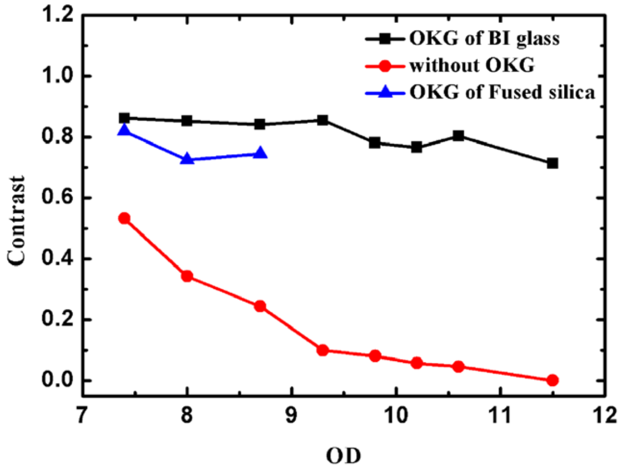

Figure 3. The image contrast measured in different ODs with OKGs of BI glass and fused silica, and without an OKG, respectively.

3.2. Image contrast enhancement using the OKG of BI glass

Furthermore, we acquired a series of images with OKGs of BI glass and fused silica in different ODs of turbid medium. The ODs of the turbid media were 7.4, 8.0, 8.7, 9.3, 9.8, 10.2, 10.6 and 11.5, respectively, obtained by varying the concentration of the polystyrene sphere solution. We also obtained images without an OKG at different ODs. The contrasts of all the images acquired for different ODs were also calculated by equation (1), and the curves of the corresponding image contrast variations under the same situation are showed in figure 3. The salient feature of figure 3 is that the image contrasts acquired with the OKG of BI glass in different ODs have no obvious change. The range of image contrast with the OKG of BI glass varies from 0.71 to 0.86. The image contrast is 84.16% with the OKG of BI glass at OD 8.7, but the image contrast is only 24.41% without an OKG. The image contrast using the OKG of fused silica also changes slightly while varying the OD, as shown in figure 3. The contrasts of these images acquired with the OKG of fused silica are nearly 75%. In addition, the maximum OD for the recognizable image is about 8.7 when using the OKG of fused silica. From figure 3, when an OKG is not used, the image contrast decreases quickly from 0.53 to 0.05 with increasing concentration of the turbid medium. For the same OD, the image contrast obtained by the OKG is higher than

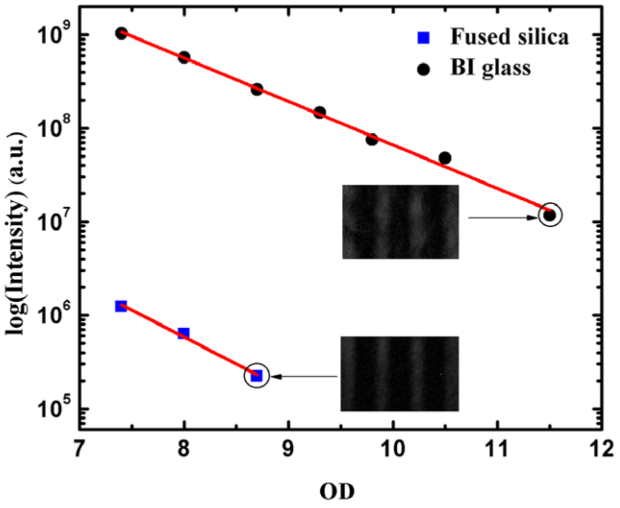

Figure 4. The transmitted intensities of images acquired with the OKGs of BI glass and fused silica at different ODs. The symbols represent experimental results while the lines represent exponential fitting results.

that without an OKG because the OKG effectively eliminates the scattered light. The image contrast acquired with the OKG of BI glass is better than that acquired with the OKG of fused silica at the same OD, because of better signal-to-noise ratio with the OKG of BI glass.

We evaluated the transmitted intensities of images acquired with the OKG of BI glass and the OKG of fused silica at different ODs. Figure 4 shows the exponential relationship between the intensity and the OD. The points represent the experimental results, which were fitted by a linear function. This linear relationship conforms well to Beer's law and demonstrates that the intensities of the images acquired with the OKG decrease exponentially with the OD, indicating that scattered light was isolated efficiently by the OKG and the remaining transmitted light was almost all ballistic light.

Additionally, as shown in figure 4, when using the OKG of BI glass the images could be recognized even at an OD of 11.5, but the maximum OD for the recognizable image is 8.7 when using the OKG of fused silica. The corresponding images for the maximum ODs are also shown in figure 4. In our experiments, using the BI glass as a Kerr medium, the transmittance of the optical Kerr gate was 22.5%, whereas the transmittance of the optical Kerr gate was only 0.13% for the fused silica. The image intensity acquired with the OKG of BI glass is stronger than that with the OKG of fused silica at the same OD because of the higher transmittance of the OKG of BI glass. These results indicate that the OKG of BI glass is superior to the OKG of fused silica in ballistic imaging.

4. Conclusions

In summary, we investigated ballistic imaging of a test chart behind a turbid medium using OKGs of BI glass and fused silica at the same OD, respectively. The image contrast acquired with OKGs was better than without an OKG at the same OD. The contrast and intensity of the images acquired with the OKG of BI glass were higher than those acquired with the OKG of fused silica at the same OD because of the higher transmittance of the OKG of BI glass. The results show that the BI glass is a good candidate for an OKG medium due to its ultrafast response and large nonlinear refractive index.

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