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Abstract. An ultrafast optical Kerr gate (OKG) in femtosecond time scale was used to determine the scattering coefficients of intralipids, in which the BI_2O_3-B_2O_3-SiO_2 oxide glass was employed as the Kerr medium. Because of the joint action of the time gate and a transient spatial gate that was induced in the Kerr materials by the gating beam, more precise scattering coefficients could be obtained. Our experimental results show that, for low turbid media, the scattering coefficients measured using the OKG method are similar to those measured using the collimated transmittance (CT) approach, while for highly turbid media, the results obtained using the OKG method are bigger than those using the CT approach. © *2011 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.3567069]

Subject terms: bismuth glass; optical Kerr gate; intralipid; scattering coefficients.

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1 Introduction

Intralipid is a type of excellent turbid media for providing the scattering content of a phantom applied in the modeling of light propagation through tissues,[1–3] because it has a low absorption, an easy adjustable scattering coefficient, and an accessible clinical environment. Precise experimental determination of the scattering coefficients of intralipid solutions is fundamentally important in optical-biomedical research.

In the previous studies, scattering coefficients of intralipid solutions have been evaluated by direct[1,3–5] and indirect methods.[6–8] Indirect methods depend on the theoretical prediction used for the comparison with the experimental data and on how the comparison is done, which limits its accuracy. The most widely used direct method is the collimated transmittance (CT) approach.[1,4] It evaluates the scattering coefficients by measuring the transmitted intensity with a small aperture, which is a spatial gate, before the detector. However, this kind of gate could not separate the collimated photons from the diffusive ones emerged at small angles. Alfano et al. presented a picosecond optical Kerr gate (OKG) method for determining the scattering coefficients of Intralipid-10% at 1054 nm and their experimental results were closer to the true scattering coefficients.[5] Recently femtosecond Ti:sapphire lasers working at 800 nm have more and more applications in biomedical researches,[9–12] because they could afford the capability to penetrate further into most biological tissue. However, there are few reports on determining the scattering coefficients using femtosecond OKG. We expect that the method based on femtosecond OKG has an advantage in dealing with the strong scattering media, in which photons are scattered mainly in the forward direction.

Photons issued from a short laser pulse emerging from a turbid medium are separated into ballistic and diffusive portions.[13,14] The ballistic portion keeps their coherence passing through in a straight line without being disturbed, which is the first part to exit the turbid media. Compared with the ballistic portion, the corresponding diffusive portion expands temporally and spatially.[15,16]

In this study, an ultrafast OKG in femtosecond time scale was used to determine the scattering coefficients of intralipid solutions, in which the BI_2O_3-B_2O_3-SiO_2 oxide (BI) glass was employed as the Kerr material. The nonresonant-type BI glass presents both large nonlinearity and ultrafast response time. Because of the joint action of the time gate and a transient spatial gate that was induced in the Kerr material by the gating beam, a more precise scattering coefficient could be obtained by eliminating the most unwanted diffusive photons from the ballistic photons. The true scattering coefficients of turbid matter should be determined by ballistic photons according to Beer's law. Our experimental results show that the values of the scattering coefficients measured using a femtosecond OKG are closer to the true scattering coefficients than those using the CT approach.

2 Experiments and Methods

Measurements of the scattering coefficients μ_s were performed by use of the OKG method setup in Fig. 1(a). A Ti:sapphire laser system with a repetition rate of 1 kHz, a pulse duration of 30 fs, and an average power of 1 W at 800 nm, was used in our experiments. In the OKG method measurement system, the 800-nm laser beam was split into two beams by using a short pass filter. The long wavelength portion, whose centered wavelength was about 800 nm, was used as probe beam, and the short wavelength part at about 780 nm was used as gating beam. A delay line was used to control the time delay between gating pulse and probe pulse. The gating beam, the polarization of which was rotated 45° by a $\lambda/2$ wave plate, was focused into the Kerr medium by lens L1. The linear polarized probe beam was introduced into the scattering sample, but the average probe power is limited to about 30 mW in our experiment. The optical depth is up to 12 (transmission factor of $\sim 10^{-10}$). The disturbed probe beam emerging from the turbid media was focused into the Kerr material together with the gating beam. The OKG consisted of a pair of calcite crossed polarizers and a Kerr material between them. When the gate was opened, the

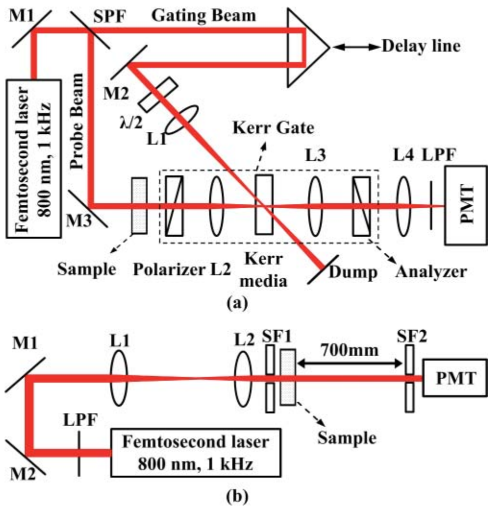

Fig. 1 Schematic setup used to determine the scatter coefficient of intralipid solutions: (a) the OKG method; (b) the CT approach. L: lenses; M: mirrors; λ/2: half wave plate; SPF: short pass filter; LPF: long pass filter; PMT: photomultiplier; SF: spatial filter.

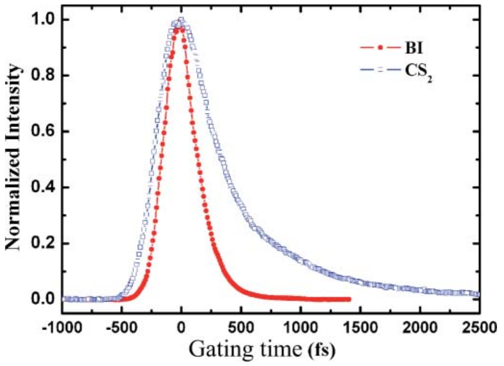

Fig. 2 The femtosecond time-resolved optical Kerr gate signals of CS_2 and BI glass. Solid: BI; Hollow: CS_2.

Kerr material rotated the probe beam and allowed it to pass through the analyzer. A long pass filter (LPF) was set before the photomultiplier to block the scattered gating beam to improve the signal-to-noise ratio. The turbid media consisted of diluted Intralipid-20% solutions in an optical cell with the dimension $2 \times 2 \times 2$ cm^3.

The setup for the CT approach is shown in Fig. 1(b). In order to determine the scattering coefficients at the same wavelength as used in the OKG method system, we added the same LPF in the CT approach setup. A pair of lenses was used to decrease the diameter of the beam. The sample was illuminated with collimated light, the diameter of which was 4 mm. A pair of diaphragms was used as the spatial gate whose apertures were 4 mm. The distance between the sample and SF2 was 700 mm, which was large enough to exclude off-axis photons with a cone of 0.16 deg.

The BI glass used in our experiments presents large nonlinearity and ultrafast response time, and nonlinear refractive index n_2 and the response time were estimated to be 1.6×10^{-14} cm^2/W and less than 90 fs, respectively.[17] The BI glass was prepared by melting $BiO_{1.5}$, SiO_2, B_2O_3, and GeO_2 according to a certain proportion. There is no evident absorption above the absorption edge of 450 nm. More details about the preparation of the sample were given in Ref. 18. The thickness of the glass sample was about 1.5 mm. The CS_2 solution was filled in a glass cuvette with a path length of 1 mm. In our experiments, the duration of the laser pulses was expanded because of the dispersion of the optical elements. Figure 2 shows the time-resolved measurements of Kerr signals of BI glass (solid) and CS_2 (hollow), in which the sample holder was filled with deionized water. The opening time of the OKG for BI and CS_2 are estimated to be 300 fs (FWHM) and 2 ps, respectively. These results were in accord with previous reports and indicated the reliability of our experiment.

The calculation scheme providing an approach for calculating the scattering coefficients by using the OKG method is shown in Fig. 3. The calculation method using the CT approach can be found in Refs. 1–4. Migrating through a turbid medium, the incident pulse expands temporally and spatially. In the OKG method configuration, the transmittances for the ballistic portion and the scattered portion are different, described as T_B and T_S, respectively, because the OKG temporally excludes many diffusive photons, which travel over a much larger distance in turbid media and arrive at the detector later than the ballistic photons. Moreover, the gating beam induces a transient spatial gate in the Kerr material and filtering many diffusive photons. So T_S is much smaller than T_B. Similarly, because of the randomization of the polarization of the diffusive photons, the polarizer acts as a filter, and the transmittance is T_P. So the final detected signal intensity I_I is described as follows:

$$I_I = I_{in}^I \times \exp(-\alpha L - \mu_s L) \times T_B + I_S \times T_P \times T_S. \tag{1}$$

Here, I_{in}^I is the intensity of the incident pulse, α is the absorption coefficient, μ_s is the scattering coefficients, and L is the geometrical path length in the sample cell. The absorption coefficient of intralipid is 10^{-3} smaller than scattering coefficients and can be neglected at 800 nm.[19] When the sample is changed to deionized water, the detected signal intensity I_W is described as:

$$I_W = I_{in}^W \times \exp(-\alpha L) \times T_B. \tag{2}$$

So the scattering coefficients of the turbid media can be modified as:

$$\mu_s = -\frac{1}{L} \ln\left(\frac{I_I/I_{in}^I}{I_W/I_{in}^W} - \frac{I_S T_P T_S}{\exp(-\alpha L) T_B I_{in}^I}\right). \tag{3}$$

The first part in the bracket is simplified as $(I_I/I_{in}^I)/(I_W/I_{in}^W)$ (here it is called relative intensity ratio) which describes the ballistic portion of the detected signals according to Beer's law. The second part describes the scattered portion of the detected signals. When the OKG is

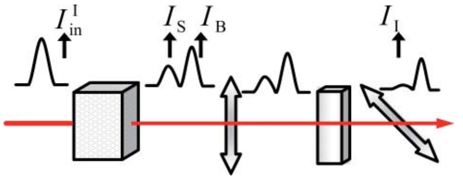

Fig. 3 Calculation scheme of scattering coefficients based on the OKG method.

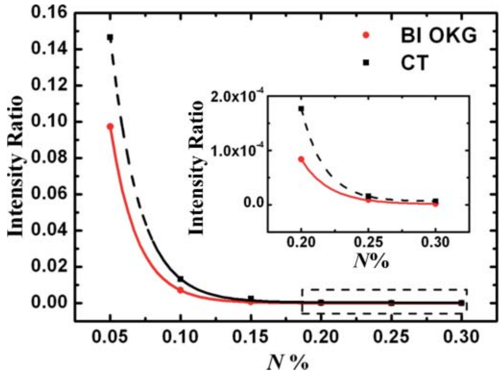

Fig. 4 The relative intensity ratio versus diluted volume concentration *N*% of Intralipid-20% solutions: The symbols represent experimental results while the lines represent exponential fitting results: BI OKG: circle and solid line; CT: square and dashed line. Inset: the enlarged plots of the data in the dashed rectangular frames.

opened at zero time delay, the transmittances for the diffusive photons (i.e., T_P and T_S) are very small, so the second part could be ignored, and Eq. (3) is abridged as:

$$\mu_s = -\frac{1}{L}\ln\left(\frac{I_I/I_{in}^{I}}{I_W/I_{in}^{W}}\right). \tag{4}$$

3 Results and discussion

Figure 4 shows the relative intensity ratio for the diluted Intralipid-20% (Intralipid®, Sino-Swed Pharmaceutical Corp., Ltd.) solutions. For the OKG measurements, the relative intensity ratios were measured when the OKG was opened at the zero time delay. To compare the results measured using OKG with those using CT, the measurements using CT were also performed, and the results are shown in Fig. 4. The enlarged plots of the data in the dashed rectangular frames are also given in the inset in Fig. 4. We can see that the relative intensity ratios decrease with increasing the volume concentrations. The data for both of the methods are fitted to an exponential curve, which agree well with the experimental results. It is shown that the relative intensity ratios using the CT approach are always bigger than those using the OKG method, because the latter arrived forward scattered diffusive photons (i.e., the I_S part in Fig. 3) in the CT measurements leaked into the detector.

Furthermore, the scattering coefficients are calculated based on Eq. (5), and the results of the Intralipid-20% are shown in Fig. 5. It is observed that the scattering coefficients using the OKG method are bigger than those using the CT approach. The reason is that OKG can eliminate the diffusive photons emerging at both small and large angles, but the spatial filtering action of the CT setup cannot exclude the diffusive photons in the acceptance angle.

Additionally, the scattering coefficients measured using the OKG of the BI glass and CT were fitted by a linear function and shown in the insets in Fig. 5. The linear function is described as $\mu_s = kN$, where k is the fitting parameter, and N is the concentration of the intralipid solutions varying from 0 to 20% for Intralipid-20%. The fitted scattering coefficients for the undiluted turbid media at 800 nm are $\mu_s = 463\ \text{cm}^{-1}$ for BI OKG and 418 cm^{-1} for CT and the corresponding result from Ref. 4 is 440 cm^{-1}. Values suggest a good agreement between our experiments and the investigation in the reference. Finally, we confirm that the measurement using the OKG method is more precise than that using the CT approach, and the scattering coefficient measured using femtosecond OKG of BI glass is the bigger one because the least forward diffusive photons leak into the detector.

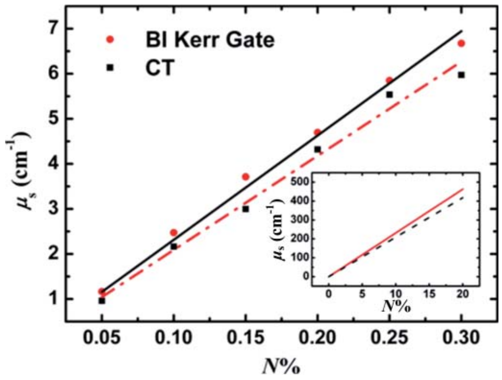

Fig. 5 The calculated scattering coefficients μ_s versus diluted volume concentration *N*% of the Intralipid-20% solutions: The symbols represent experimental results while the lines represent exponential fitting results: BI OKG: circle and solid line; CT: square and dashed line.

4 Conclusions

In summary, measurements of the scattering coefficients of Intralipid-20% at 800 nm were performed using the OKG method and the CT approach. Our experimental results have confirmed that the femtosecond OKG of BI glass has an advantage in determining the scattering coefficients of the turbid media. Compared with the OKG method, the CT approach fails in filtering the diffusive photons in the detection acceptance angle, and its results deviate from the true scattering coefficients more for highly turbid media.

Acknowledgments

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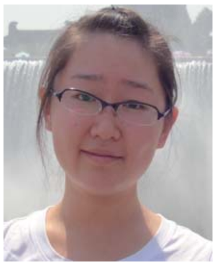

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Biographies and photographs of the other authors are not available.