Optics Communications 283 (2010) 4346–4349

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Self-focusing in two-color collinear optical Kerr measurements

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ARTICLE INFO

Article history:
Received 18 March 2010
Received in revised form 8 June 2010
Accepted 8 June 2010

ABSTRACT

We performed the femtosecond two-color collinear optical Kerr shutter (OKS) measurements in a thick Kerr medium. The time-resolved OKS signals showed a multi-peak structure and a large broadening with respect to that for non-collinear. By measuring the time-resolved OKS signals in the sample at different powers, we demonstrated that the abnormal profile of the OKS signals was mainly attributed to self-focusing and re-focusing of the pump beam in the Kerr medium and the group velocity difference between the pump and the probe beams.

1. Introduction

The optical Kerr shutter (OKS) measurement is a key means for studying the nonlinear response of materials and has been widely used owing to their precision, easy operating, sensitivity, etc [1–3]. However, when the pump and probe beams with equal wavelength are used in a cross OKS experiments, self-diffraction that resulted from laser-induced transient gratings (LITG) has evident influences on the Kerr signals [4,5]. In particular, when femtosecond pulses with high peak power are used in the OKS experiments for some materials [5,6], Kerr signals result mainly from self-diffraction of the pump beam by the LITG. To avoid the influence of the self-diffraction, femtosecond two-color collinear OKS technique should be introduced. On the other side, many all-optical switching devices, based on fiber or waveguide, have employed the geometry [7–9]. It is essential to study the operation characters of the femtosecond two-color collinear OKS technique, because the propagation of intense ultrashort pulses in a thick Kerr medium can result in plentiful nonlinear effects including self-focusing [10], self-defocusing [11,12], re-focusing [13], self-trapping [14], etc. These nonlinear optical effects will inevitably affect the measurements for nonlinear response of materials and the efficiency of the OKS operation. Although complementary work has been carried out in previous OKS studies [15–21], but all such work has not taken into account the effect of self-focusing. So it is necessary to study the influence of self-focusing on OKS measurement.

In this paper, the femtosecond two-color collinear OKS experiment was performed to study the self-focusing and group velocity difference (GVD) on optical Kerr measurement in a 5-mm thick optical glass. The measured results showed that self-focusing and re-focusing of the pump beam can lead to a two-peak or multi-peak structure in the profiles of the time-resolved OKS signals, while GVD resulted in an asymmetry broadening of OKS signals. The experimental results showed that the dynamic processes including self-focusing, re-focusing, and group velocity difference had evident influences on the time-resolved OKS signals in femtosecond two-color collinear OKS measurements.

2. Experiments

The experimental setup is shown in Fig. 1. A chirped pulse amplification (CPA) Ti:sapphire laser system operating at 800 nm and delivering 30 fs pulses at 1 kHz repetition rate was used. The output beam after the compressor was split into two beams, one beam passed through a time-delay device and a $\lambda/2$ plate to control the path length and polarization of the beam, respectively, served as pump beam. Another beam frequency doubled by a BBO crystal, served as probe beam. A filter was placed behind the BBO crystal to allow only the 400 nm radiation to pass through it. The probe and pump beams were collinearly incident into an achromatic lens ($f = 200$ mm) and focused into a thick optical glass, which was fixed on a stage and can be movable along the light path. The power of the 400 nm radiation was 0.7 mW. A bandpass filter was positioned behind the sample on the optical path of the probe beam to filter out 800 nm light and white-light continuum induced in the sample. The Kerr signals were detected by a photomultiplier tube. An analyzer was placed in front of the photomultiplier to allow only Kerr signals generated through the third-order nonlinearity can pass through it when the pump and probe beams overlap spatially and temporally on the sample. The polarization plane of the pump beam was rotated by $\pi/4$ against the probe beam to optimize the intensity of Kerr signal by adjusting the $\lambda/2$ plate.

3. Results and discussions

In our experiment, the input pulse duration with the full-width at half-maximum (FWHM) at the sample was the same for all

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doi:10.1016/j.optcom.2010.06.036

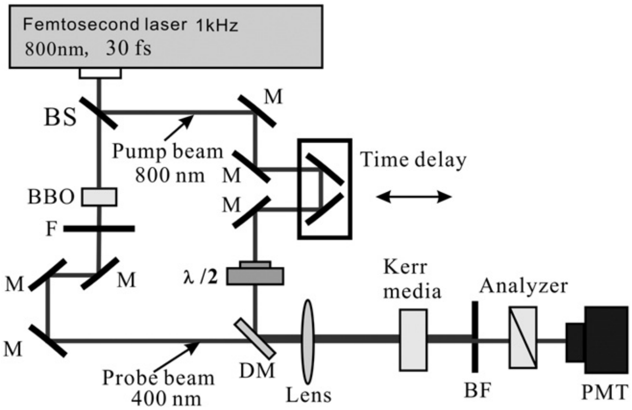

Fig. 1. Schematic diagram of the experimental setup. M: reflector; BS: beam splitter; DM: dielectric mirror; F: 800 nm filter; BF: bandpass filter; PMT: photomultiplier tube.

experiments and equal to 320 fs. Meanwhile, we defined d as the distance between the incident surface of the sample and the geometrical focus of the lens. The d value was negative when the incident surface of sample was inside the focal length. Conversely, the d value was positive.

Fig. 2 shows the temporal profiles of time-resolved OKS signals of a 5-mm thick optical glass sample at different pump powers. The sample was fixed at $d = 1$ mm. From the figure, we notice that the FWHM of time-resolved OKS signals is about 1.3 ps and its temporal profile is asymmetrical at a pump power of 15 mW. This is attributed to the GVD between the pump and probe beams. For the two-color collinear optical Kerr measurements, the GVD between the pump and the probe beams must be taken into account. In addition, along with the increase of the pump power, the width of the time-resolved OKS gets narrow gradually, while a two-peak character at higher powers begin to emerge at the temporal profiles. At a 30 mW pump power, the temporal profile evolves into a distinct two-peak structure. The width and height of two peaks are quite different. This behavior can be explained qualitatively in the light of self-focusing of the pump beam in the optical glass. In the OKS measurements, the efficiency of the Kerr shutter operation is evaluated according to [22]

$$I = I_0 \sin^2(\Delta\phi/2)\sin^2(2\theta) \quad (1)$$

where I is the probe transmission intensity of the Kerr shutter operation, I_0 is the maximum possible transmission intensity, θ is the angle between the polarization of the pump beam and the probe beam, and $\Delta\phi$ is the optically induced phase shift on the probe beam by the pump beam. When the angle θ is set at $\pi/4$ to obtain the maximum I value, the Kerr signal intensity depends only on $\Delta\phi$

$$\Delta\phi = \frac{2\pi n_2 L_{ef} I_{fp}}{\lambda}. \quad (2)$$

Here, n_2 is the nonlinear refractive index of optical glass, L_{eff} is the effective medium length, λ is the probe beam wavelength, and I_p is the pump beam intensity. Probe transmission intensity varies with optically induced phase shift $\Delta\phi$ as $\sin^2(\Delta\phi/2)$, so the probe intensity reaches maximum on condition $\Delta\phi = \pi$. For this measurement, due to self-focusing of the pump beam, I_p will increase rapidly, resulting in the phase shift of the probe beam increasing remarkably through a short distance in the sample. When the phase shift reaches $\Delta\phi = \pi$, the probe transmission is maximum. When the phase shift exceeds π the corresponding transmission decreases from the maximum. At the self-focus the induced phase shift is maximum, the corresponding probe transmission reduces minimum. Along with the increase of pump power, the self-focus moves gradually to the incident surface of the sample. Correspondingly, the valley of the temporal profiles moves to the right side. So the width of the time-resolved OKS signals becomes narrow gradually. However, when the pump intensity at the self-focus is high enough to generate a significant amount of free electrons in the sample, plasma generation will take place at self-focus [23–25]. The laser-induced plasma stopped the self-focusing process and caused decreasing of the pump intensity [26–28]. Naturally, when the probe beam passes through the self-focus, the phase shift on it will decrease, and the transmission will increase again. This process results in the two-peak structure of the time-resolved OKS signals. But owing to the GVD between the pump and probe pulses and restrictions on length of the sample, the probe transmission is much less than the previous one.

We also studied the influence of the re-focusing on OKS measurement. Fig. 3 shows the experimental results, in which the pump beam was focused into a 10 mm sample at a 30 mW pump power. The sample position was located at $d = 2.5$ mm. The inset of Fig. 3 displays the image of re-focusing that was imaged with a digital camera. As shown in the figure, re-focusing of the pump beam induced three peaks in the profile of OKS signals. We noticed that the number of valleys of the temporal profiles was not consistent with those of the focus, which was attributed to the group velocity difference between the pump and the probe beams.

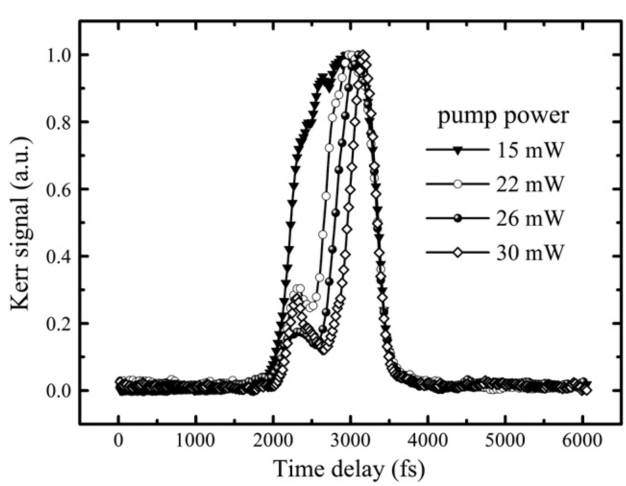

Fig. 2. The temporal profiles of the time-resolved OKS signals of the optical glass sample at different pump powers. (The lines are meant only to guide the eye).

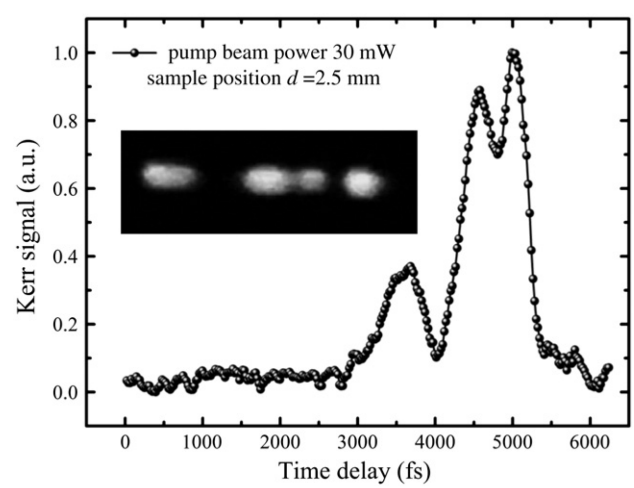

Fig. 3. The temporal profiles of the time-resolved OKS signals of the 10 mm sample at multiple self-focus. The inset image shows the plasma formed at the focus as captured by the digital camera.

To determine the influence of the GVD on the measurements, we investigated the temporal behaviors of the OKS signals for samples of different thicknesses. The pump power and sample position were maintained at moderate values in order to avoid self-focusing effect. Fig. 4 shows the measured results. As shown in Fig. 4, the time-resolved OKS signals for 5-mm and 10-mm samples is broadened greatly compared with that for 1-mm sample. The group refractive indexes of optical glass for 400 nm and 800 nm are measured to be 1.612 and 1.534, respectively, resulting in a non-negligible group refractive index difference of about 0.078. In collinear conditions, the 400 nm probe pulse will be temporally delayed by $\Delta n_G L/c$ after passing through the sample with respect to the simultaneously incident 800 nm pump pulse. Here, Δn_G is the group velocity index difference between the two wavelengths and L is the length of the sample. In other words, if the pump pulse was delayed by $\Delta n_G L/c$ with respect to the probe pulse at the sample entrance, the two pulses will meet at a depth L in the sample. Hence, the width of the time-resolved signals will be broadened by $\Delta n_G L/c$. According to our experimental parameters, the temporal behavior of OKS signals will be broadened by 260 fs for each additional millimeter of the sample thickness. As shown in the figure, the FWHM of the time-resolved OKS signals for 1-mm, 5-mm and 10-mm thick samples are estimated to be about 340 fs, 1.3 ps and 2.8 ps, respectively. The calculated value is in good agreement with the measured value in Fig. 2.

In order to verify our explanation on the two-peak character, the sample was moved to $d = 3.5$ mm, while the pump power was kept at 30 mW. A 4-mm sample was used to reduce the influence of GVD on the experiment. The measured profile of OKS signals in Fig. 5 appears two peaks whose width and intensity are approximately equal, indicating that the self-focusing volume is near the geometric center of the sample. The variation of self-focus in the samples can directly affect the temporal profile of time-resolved OKS signals, demonstrating that the two-peak profile signals originate from self-focusing of the pump beam. Moreover, it revealed that the width and height of each of the two peaks can be controlled by varying the sample position and pump power.

In addition, we also performed two-color collinear time-resolved OKS measurement in a 10-mm thick optical glass sample. The pump power was set to be 19 mW. The position of sample was fixed at $d = 2.1$ mm. As shown in Fig. 6, the temporal evolution of the time-resolved signals exhibits a distinct two-peak structure. In this case, since the optical phase shift on the probe beam reaches 2π, the corresponding probe transmission intensity is zero. As a result, these two peaks separate completely. That is, the optical Kerr modulation over 100% is demonstrated using femtosecond pulse in a 10-mm thick optical glass.

On the basis of our experiments, we reach the conclusion that the self-focusing effect of the pump beam has predominant influences on the profile of the time-resolved OKS signals in two-color collinear femtosecond pump-probe measurements. Moreover, it can be predicted that the time-resolved OKS signals in our experiment may be used to trace the self-focusing of femtosecond pulse in thick medium.

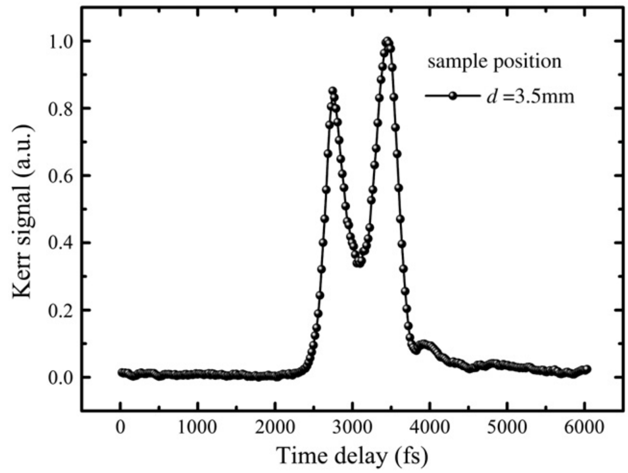

Fig. 5. The temporal profile of the time-resolved OKS signals of a 4-mm thick optical glass sample.

4. Conclusion

In summary, by using femtosecond two-color collinear pump-probe technique, we observed OKS signals with a two-peak character, arising from self-focusing of pump beam in optical glass. Meanwhile, the group velocity difference between the pump and probe beams with different frequencies caused a large broadening of the time-resolved OKS signals.

Acknowledgements

The authors gratefully acknowledge the financial support for this work provided by the National Science Foundation of China under Grant No. 60978015, the National High Technology R&D Program of China under Grant No. 2009AA04Z305, the National Key Scientific Research Foundation of China under Grant No. 2006CB921602, and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 200806980022).

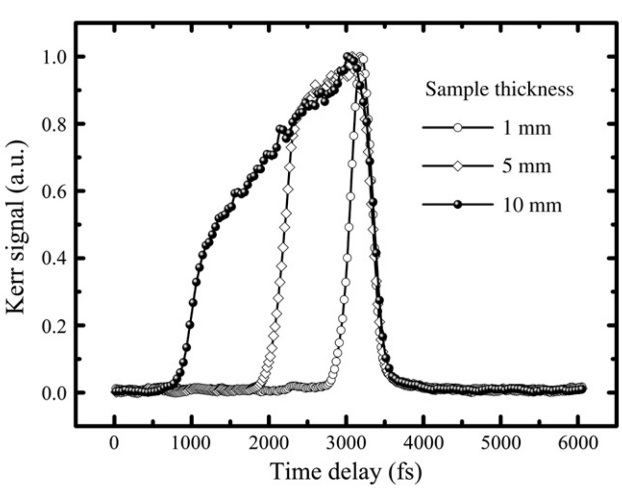

Fig. 4. The influence of GVD between pump and probe beams on the temporal profiles of the time-resolved OKS signals of optical glass samples with different thickness.

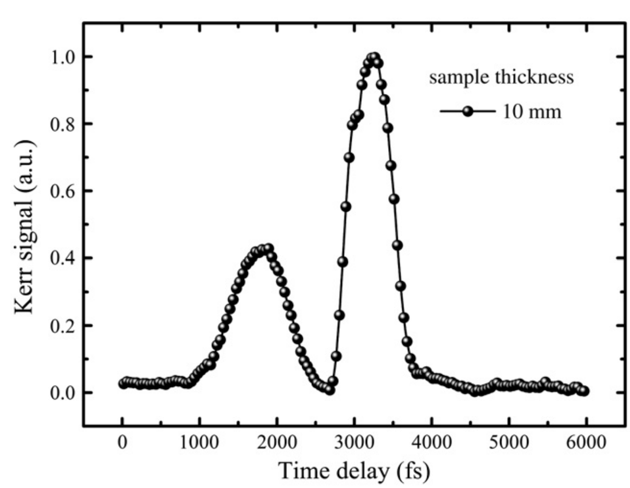

Fig. 6. The temporal profile of the time-resolved OKS signals of a 10-mm long optical glass sample.

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