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Study on the optical limiting properties of the mixed liquid of carbon black suspensions and green tea solution by multi-pulse laser*

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The optical limiting properties of the mixed liquid of carbon black suspensions (CBS) and green tea solution were studied by using an 8 ns laser pulse at 532 nm. The optical limiting effects of the CBS and mixed liquid have been compared between 5 and 10 Hz repetition frequencies with nanosecond laser pulse. The experimental results indicate that the optical limiting threshold of the sample with the incidence laser at 10 Hz repetition frequency is lower than at 5 Hz repetition frequency. The possible reasons for the influence of the repetition frequency on the samples are discussed. And by observing the optical radiant distributions when the laser pulse passing through different samples, a possible mechanism for the observed effects is suggested. At the same time, the result shows that the optical limiting of CBS is the dominant factor to optical limiting of the mixed liquid.

Keywords: optical limiting, carbon black suspension, radiation protection
PACC: 4265, 4270, 8760P

1. Introduction

The rapid development of laser technology has raised the problem of protecting electro-optic sensors and human eyes. Researchers have been trying their best to find an ideal optical limiting material: high linear transmittance, low limiting threshold, fast switching time and broadband response. Among widely investigated materials for optical limiting were studied such as nematic liquid crystals,[1] porphyrins molecules,[2] metal nanowires,[3] carbon bisulfide,[4] carbon nanotubes[5,6] and so on. But these materials cannot be obtained easily or their preparation procedures are very complex, so they may not be widely used in optical limiting field. While the carbon black suspension (CBS) and green tea solution that we can easily attained also have high optical nonlinearity and had been studied extensively in various laboratories.[7−12] Mansour *et al* studied the optical limiting of CBS at wavelength of 532 and 1064 nm, and found that the limiting depends on the input fluence (J/cm^2) rather than irradiance (W/cm^2).[13] Hernandez *et al* found that CBS with different solvents actually ceases after a few laser firings and a turnover in the limiting curve appears by using 532 nm, 5-ns pulsed laser.[14] In Ref.[15] Zhang *et al* observed the self-focusing and self-trapping in green tea solution, and thought it could be a new type of Kerr media. However, the repetition frequency effects of optical limiting properties of the sample have been reported very little.

Here we use the anhydrous alcohol as solvent, and compare the optical limiting responses of CBS, green tea and their mixed liquid at different repetition frequencies (5 and 10 Hz) by using a 8-ns pulse laser at 532 nm. The possible reasons of the influence of the repetition frequency on the samples' optical limiting are discussed. By observing the optical radiant distributions when laser beam passes through the different samples, the possible optical limiting mechanism for the samples is suggested.

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2. Experimental setup

Figure 1 shows the schematic diagram of the experimental setup for this study. We use a Q-switched Nd:YAG laser operated in the single-shot mode. The infrared fundamental is frequency-doubled to generate the second harmonic at 532 nm, with the maximum of 400mJ/pulse (FWHM ≃8 ns). The attenuation slices (A) are used to reduce the energy of incident laser, and the aperture S1 is used to remove glittering light. The polarizers P1, P2 are used in combination to control the incident energy. Beam splitter BS reflects a portion of the incident laser into detector D1 as an incident energy reference by the lens L1 (f=50 mm), and we focus the transmitted pulse onto the sample by using Lens L2 (f=215 mm). The 5-mm sample cell is placed at the focus where the spot radius of the pulse is 0.1±0.025 mm. Lens L3 (f=150 mm) collects laser beam into detector D2.

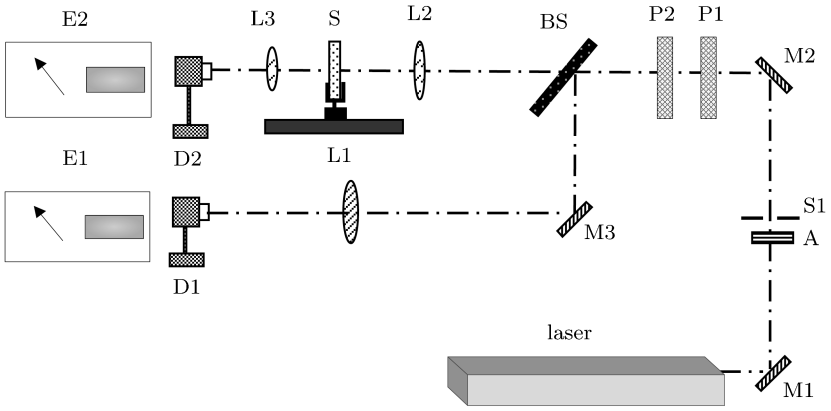


Fig.1. Schematic diagram for the experimental arrangement.

We prepared the green tea solution used in this study by dissolving the green tea in the anhydrous alcohol and letting it deposit for 24 hours, then the tea leaves were removed. We prepared CBS by suspending carbon particles in the anhydrous alcohol, the suspensions are sonicated for approximately half an hour before being filtered with a 0.5 μm nylon filter. The mixed liquid was prepared with CBS and green tea solution with the volume ratio 50:50. The concentrations of the samples are controlled by evaporating the anhydrous alcohol. The concentration of all the samples was specified by the linear transmission at 532 nm.

3. Results and discussions

The linear transmittance was T ≈50% for all the samples. We used two polarizers in combination to make the incident energy increase gradually. All the tested energy was calculated by the average of ten laser pulses. The CBS and mixed liquid were tested to compare the optical limiting response at repetition frequencies of 5 and 10 Hz as shown in Figs.2 and 3.

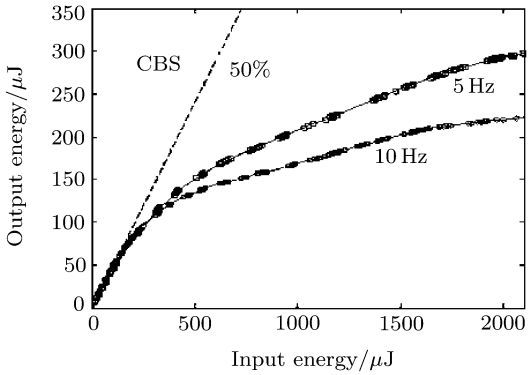


Fig.2. Output energy versus input energy for the CBS at 5 and 10 Hz repetition frequencies. The linear transmittance is ∼50%.

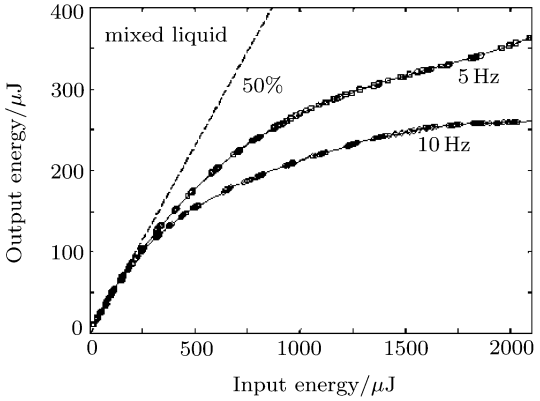


Fig.3. Output energy versus input energy for the mixed liquid at 5 and 10 Hz repetition frequencies. The linear transmittance is ∼50%.

As is seen in these figures, the output energy increases linearly with input energy when incident energy is low enough, namely, the samples have a linear transmission. As the incident energy increases to the limiting threshold, the optical nonlinearities appear. In Ref.[13], Mansour *et al* gave an explanation for the optical limiting characteristic of the CBS, that the microscopic carbon particles are heated by linear absorption to a temperature at which the micro-bubbles and micro-plasma could be created by the optical field; when the incident energy is up to the optical limiting threshold, and these micro-plasmas and micro-bubbles expand rapidly, the output energy will be limited by scattering the incident laser. It is clear from the figures that, for a 10 Hz repetition frequency laser pulse, the optical limiting threshold of the CBS and mixed liquid are much lower than for a 5 Hz repetition frequency laser pulse. We attribute this result to the effect of repetition frequency on the growth of micro-bubbles in CBS. From the Laplace law[16] we have

$$p' = p + \frac{2r}{R},$$

where p' is the pressure of the surrounding fluid, p is the pressure of a micro-bubble, r is the surface tensile between liquid-bubble, and R is the radius of a micro-bubble. At the beginning the micro-bubbles are nucleated, the size of the micro-bubbles is much smaller than the laser wavelength, so the micro-bubbles can scarcely scatter the incidence laser pulse. With their rapid expansion, the micro-bubbles are so large that they could scatter incident laser pulse, thus the output energy is limited by the scattering of the incident laser. On the other hand, the suppression needed to nucleate micro-bubbles in the suspension increases when the micro-bubbles' size decreases. Thus, more laser pulses are involved to nucleate micro-bubbles for a 10 Hz repetition frequency than for a 5 Hz repetition frequency. With a 10 Hz repetition frequency incident laser, the micro-bubbles can expand more rapidly to reach a critical size that can scatter incident laser pulse than with a 5 Hz repetition frequency one. As a result, the optical limiting threshold for a 10 Hz repetition frequency incident laser is much lower than with a 5 Hz repetition frequency laser.

In Fig.4, we compare the results of the optical limiting response of the CBS, green tea solution and mixed liquid, obtained by using 5 and 10 Hz repetition frequencies. The optical limiting threshold of CBS is much lower than green tea solution for both 5 and 10 Hz repetition frequencies. The optical limiting curves of the mixed liquid and CBS are similar. From these results we find that the optical limiting of CBS is the dominant factor to the optical limiting of the mixed liquid. The optical limiting threshold of CBS is only a little lower than that of the mixed liquid.

From this result we may conclude that the optical limiting property of CBS is better than that of the

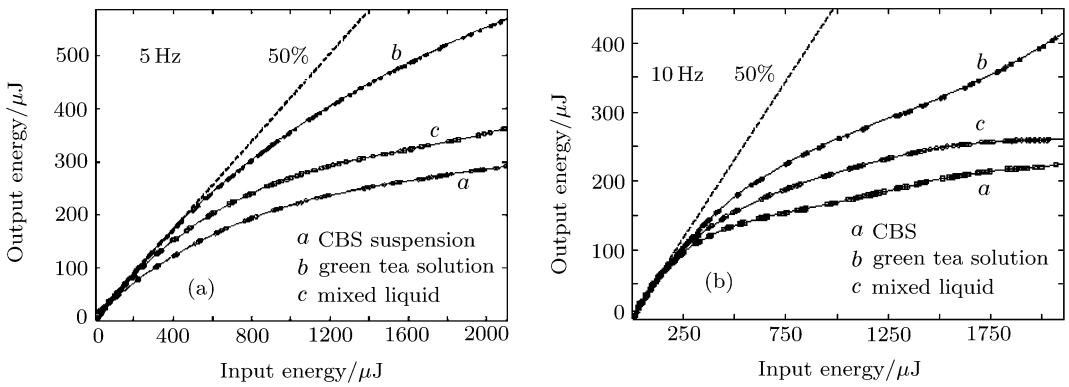


Fig.4. Comparing the optical limiting properties of the CBS, green tea solution and mixed liquid with a 5-Hz repetition frequency(a) and 10-Hz repetition frequency(b).

mixed liquid. But when we observed the optical radiant distributions beyond the sample cell shown in Fig.5, we find that the mixed liquid may have a better optical limiting in the far-field if there is an aperture with a special size. We obtain the figures on the screen placed at a distance of 50 cm behind the samples by using a camera. The samples are placed at the focus of Lens 2 (f=215 mm) in Fig.1, and the input energy is 0.45 mJ with a 5 Hz repetition frequency.

In Fig.5(b), it is clearly seen that the diameter of the beam pattern is 30 mm when the beam passes through CBS, which is much larger than that obtained without sample (the diameter is approximate 20 mm), and the optical radiance distribution does not diminish gradually from centre to edge, thus we attribute this to the laser-heating nonlinear scattering. On the other hand, from Fig.2 we can see clearly that the optical limiting of CBS at 10 Hz repetition frequency is better than that at 5 Hz one, and this is because high repetition frequency may make the micro-plasmas and micro-bubbles expand more quickly, thus CBS exhibits good optical limiting responses.

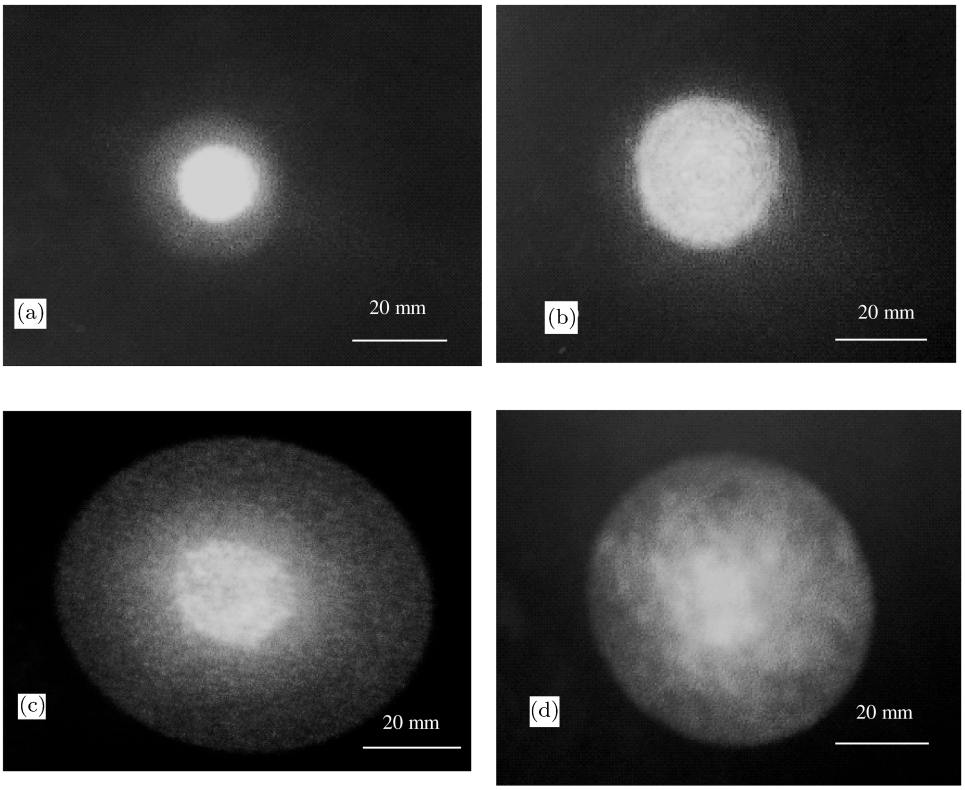


Fig.5. The beam patterns obtained with different samples. (a) The original laser beam without sample. (b) When laser beam passing through the CBS. (c) When laser beam passing through the green tea solution. (d) When laser beam passing through the mixed liquid. All the samples are placed at the focus of Lens 2 (f=215 mm), with input energy being 0.45 mJ at a 5 Hz repetition frequency.

In Fig.5(c), we can observe the optical radiance distributions are gradually diminished from the centre to the edge, and the diameter of beam pattern is 70 mm when beam passes through green tea solution. In Ref.[17], Qing *et al* also observed the same phenomenon, the only difference was that the diameter of the optical pattern was approximately 2 times larger than that obtained without sample in their experiments. From all the results, we could identify that the optical nonlinearity of green tea solution can be attributed to laser-heating-induced nonlinear refraction. These results are also consistent with those obtained with Z-scan method presented in Ref.[18]. Therefore, we may conclude that the nonlinearity of green tea solution can be attributed to a thermal origin.

We have observed the optical radiance distributions when the laser passes through the mixed liquid as shown in Fig.5(d), the diameter of beam pattern is approximately 3 times larger than that of original beam pattern. Due to the laser-heating-induced nonlinear scattering of the CBS and the laser-heating nonlinear refraction of the green tea solution, the optical

radiance distribution of the mixed liquid does not diminish gradually from the centre to the edge but is very decentralized. The diameter of the beam pattern is much larger than that when the laser passes through the simplex CBS. Therefore, if we arrange an appropriate aperture in the practical optical system, the output fluence is much lower, and the mixed liquid has a much better optical limiting in the far-field.

4. Conclusions

In summary, we have compared the optical limiting responses of CBS, green tea solution and their mixed liquid by using an 8 ns 532 nm laser with 5 and 10 Hz repetition frequencies. The results indicate that the optical limiting properties of the mixed liquid when using a 10 Hz repetition frequency, is better than using a 5 Hz, and the CBS is the dominant factor to optical limiting of the mixed liquid. The possible reasons of the influence of the repetition frequency on the samples are discussed. And by observing the optical radiance distributions when laser pulse passes through different samples, the possible mechanism for the observed effects is suggested.

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