Lens tilting effect on filamentation and filament-induced fluorescence spectroscopy

Y. Kamali *, Q. Sun, J.-F. Daigle, A. Azarm, J. Bernhardt, S.L. Chin

Department of Physics, Engineering Physics and Optics and Center for Optics, Photonics and Laser (COPL), Laval University, Quebec, Canada G1V 0A6

A R T I C L E   I N F O

Article history:
Received 18 May 2008
Received in revised form 27 October 2008
Accepted 6 November 2008

A B S T R A C T

In filament-induced fluorescence spectroscopy, we experimentally found that if the lens used for the creation and localization of filament is tilted, the signal to noise ratio of spectral measurement increases. Further study shows that with lens tilting, astigmatism occurs and the filament is split into shorter parts. In turn the shortening of filament reduces the generation of white light which is the major 'noise' source of the spectra.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

One of the significant applications of high intensity femtosecond lasers is filament-induced nonlinear fluorescence spectroscopy [1–3]. Filamentation is a result of the dynamic balance between Kerr self focusing and plasma defocusing of femtosecond laser pulses. The plasma formation in air limits and stabilizes the intensity inside the filament to about $5 \times 10^{13}$ W/cm$^2$ [4–6]. This intensity is high enough for dissociation, ionization and excitation of different gas molecules. In the field of filament-induced spectroscopy, the fluorescence signal of dissociated molecules has been studied successfully [7,8], but the improvement of the SNR (signal to noise ratio) of spectral measurement remained a technical challenge. Since filament-induced spectra are used for remote sensing purposes [9,10], increasing the SNR would extend the detection range to longer distances. In this work, we show that, in the backscattered direction, the spectral background noise level is reduced by using a simple experimental technique by tilting the lens which is used to create and localize the filament.

Lens tilting has been used for the suppression of the number of filaments in managing multiple filaments over long distances [11,12]. It has been shown that it is possible to control the number, pattern, and spatial stability of filaments by changing the tilt angle of the lens. Also, the effect of spherical aberration on filamentation has been reported [13], where filament splitting was observed. However, the effect of lens tilting on the filament’s properties and its consequences has not been extensively investigated. In this work, we systematically studied the effects of lens tilting on filamentation and its white light super-continuum. It was observed that this technique can be used to increase the signal to noise ratio of the back scattered fluorescence spectra, which is particularly important for filament-induced fluorescence spectroscopy, as well as remote sensing studies.

2. Experimental setup

Our laser system consists of a Ti:sapphire oscillator (Spectra Physics Tsunami) and a CPA system (Chirped Pulse Amplification) including regenerative amplifier (Spectra Physics Spitfire). A 10 Hz pulse train is extracted from the 1 kHz output of the regenerative amplifier and sent to a two-pass Ti:sapphire amplifier for further amplification. Using a portable compressor, laser pulses are shortened to about 50 fs in duration. The compressed pulse’s spectrum is centered at 800 nm with a 23 nm bandwidth (FWHM). These 9 mJ pulses are guided to a beam expander which enlarges the beam diameter to about 24 mm (1/e$^2$ level of intensity). They are then focused by a 1 m lens ($L_1$) to create a filament inside a 340 cm long vacuum chamber (Fig. 1, top).

Using this setup, we first observed the lens tilting effect on the fluorescence spectra. For the study of the fluorescence signals of the trace gas ethylene inside 1 atm air using filament-induced fluorescence spectroscopy, the vacuum chamber is filled with a commercial gas mixture (1% ethylene + 99% air). All the mirrors have high reflectivity at 800 nm, and high transmission for UV and visible light. The back scattered fluorescence is collected by a 12 cm diameter plano-convex lens ($L_3$) (focal length of 100 cm and diameter of 3.8 mm) and is focused by a 1 m lens ($L_2$) to a fibre bundle connected to a spectrometer (Acton Research Corp., SpectraPro-500i) (Fig. 1, top). The spectral measurements are made by an intensified charged coupled device (ICCD, Princeton instruments PI-Max 512). Before tilting the lens, the white light scattered from the output window is reduced to a minimum by means of gated measurements. Moreover, because of the length of the chamber (340 cm), the white light scattered from the output window is further reduced.

For the systematic study of lens tilting effect on filamentation, another setup is used (Fig. 2a). The laser pulses are guided through a beam expander consisting of two lenses ($L_1$: negative focal length of 25 cm and diameter of 38 mm; $L_2$: positive focal length of 100 cm and diameter of 48 mm). This enlarges the beam diameter to 24 mm (FWHM). The beam is then focused by a tilted plano-convex lens $L_3$ (focal length of 100 cm and diameter of
48 mm) to create a filament in pure air. The lens L3 is put on a rotation stage with a precision of 1/60°. The picture of the filament is taken from the side by a CCD camera. The patterns of the white light generated from the filament in the forward direction are also taken by a CCD camera with a 800 nm reflecting mirror in front and a digital camera (Kodak Z712 IS) (Fig. 2b).

Fig. 1. Experimental setup of back scattered fluorescence spectroscopy of gases. A and B are the spectra of 1% ethylene + 99% air, taken with 9 mJ laser pulses and 10 shots accumulation, without and with lens tilting, respectively.

Fig. 2. (a) Experimental setup (top view) of lens tilting effect on filament. The laser beam is a 7 mJ per pulse, 50 fs and 10 Hz laser pulse train. The focal length of L1, L2 and L3 are –25, 100 and 100 cm, respectively. (b) Experimental setup (top view) for taking the white light pictures using CCD camera and also a normal digital camera. The wavelength of 800 nm is blocked by a 800 mirror.
3. Results and discussion

Fig. 1A and B shows the experimental results of the back scattered fluorescence of the gas mixture (1% ethylene + 99% air). The laser pulse energy was 9 mJ. The fluorescence signal of nitrogen molecules as well as those of the CH and C\textsubscript{2} fragments of ethylene was detected by accumulating 10 shots for each data point. Inside the filament, because of self phase modulation and self steepening, the 800 nm laser pulse self-transforms into a chirped white light laser (super-continuum) with the wavelengths spanning from 230 nm to 4.5 \( \mu \text{m} \) [4,5,9]. This white light could be reflected/scattered from the output window, passed through the 800 nm reflecting mirror and was observed in the gas spectrum in the UV and visible ranges, which, in turn, increased the background of the fluorescence spectrum (Fig. 1, spectrum A). This spectrum is the result of using a long tube and gating the ICCD camera. Even so, the noise level is still relatively high. The SNR of the highest nitrogen peak is approximately 13 which is obtained from the division of the peak value of the fluorescence (5845 ICCD counts) and the mean value of the noise (450 ICCD counts) around the peak (Fig. 1, spectrum A).

We found that when the last 1 m lens (indicated as \( L \) in Fig. 1) was tilted a little (angle not recorded at that time), the spectrum became very clean (Fig. 1, spectrum B) and the SNR increased to approximately 26 (3145/120 ICCD counts); i.e., two times increase of the SNR even though the maximum value of the peaks has decreased from 5845 to 3145 ICCD counts. This observation prompted us to carry out the following systematic study of lens tilting effect experimentally as described in Fig. 2 which shows the top view of the experimental setup using 10 Hz, 7 mJ/50 fs Ti:sapphire laser pulses.

The pictures of the filaments at different lens tilting angles from \(-15^\circ\) to \(15^\circ\) as well as the picture of a ruler for calibration are shown in Fig 3. The lens was located at the zero point of the ruler. For angles different from zero degree, the filament moved towards the lens and decayed into two shorter parts. Larger angles cause longer distances between two parts. The first part (left hand side) was broad as compared to the second part (right hand side). The reason of this effect is astigmatism which is produced by lens tilting (Fig. 4). \( T_1 \) and \( S_1 \) are two focal positions of astigmatism where the focal line of \( T_1 \) is vertical and that of \( S_1 \) is horizontal. The inset of Fig. 4 shows the 3D diagram of \( T_1 \) and \( S_1 \) as well as the position of the camera considering that the laser beam propagates parallel to the x-axis. Filamentation would start before these two higher intensity zones resulting in two filaments. Filamentation near the first focus (\( T_1 \)), when observed from the side (Fig. 2a and inset of Fig. 4), shows the effect of line focusing giving rise to lateral broadening. Because of the same reason, the horizontal dispersion of the second part is observed as a thin and weak line from the side view. The distance between these two focal points is obtained from the following simple formula [14]

\[
X = S_1 - T_1 = f \sin \phi \tan \phi
\]

Table 1

<table>
<thead>
<tr>
<th>Angle</th>
<th>Calculated ( X ) (mm)</th>
<th>Experiment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>14.96</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>24.78</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>37.09</td>
<td>36</td>
</tr>
<tr>
<td>13</td>
<td>51.93</td>
<td>48</td>
</tr>
<tr>
<td>15</td>
<td>69.35</td>
<td>62</td>
</tr>
</tbody>
</table>

\[X = S_1 - T_1 = f \sin \phi \tan \phi\]

Fig. 4. Schematic picture of astigmatism. Inset: 3D diagram of vertical \( T_1 \) and horizontal \( S_1 \) focal lines of astigmatism as well as the position of camera.
where $\varphi$ and $f$ are the angle and focal length of the lens respectively. In Table 1, the calculated $X$ values are compared with the distance between the centers of two filament parts. There is a good agreement between the calculation and the experimental measurement. No filament is formed in between the two line foci at the position of the circle of least confusion. This is due to the weaker intensity at that position. Meanwhile, the patterns of white light at different tilt angles are taken by a CCD camera with an 800 nm reflecting mirror in front and a normal digital camera as described in Fig. 2b. In Fig. 5a, the black-and-white (B&W) pictures taken by the CCD camera are shown where darker points represent higher intensities. The 800 nm reflecting mirror in front of the CCD camera reflects all laser pulse scatterings and only white light passes through the mirror and is detected. The existence of white light implies the existence of filamentation in the focal line regions of $T_1$ and $S_1$. The increase of the lens angle decreases the intensity of white light. Fig. 5b confirms the same decrease of the intensity of different colors which are generated by the conical emission of the white light. White light reduction is caused by filament shortening, because a longer filament produces more white light [4–6]. Thus via lens tilting, the filament is split into shorter parts, which leads to weaker white light. This in turn decreases the noise level and increases the SNR. The shortcoming of this technique could be the decrease of fluorescence signals by filament shortening. But by changing the lens angle, it is possible to find the optimum state for which strong enough peaks together with higher SNR can be obtained.

4. Conclusion

When the lens which is used for filament generation is tilted, reduction of the background level and increase of the signal to noise ratio of the spectra from filaments in air taken in the back scattered direction are accomplished. The reason of this effect is explained by astigmatism through a systematic experimental study; the filament is divided into shorter parts and the shortening of filaments decreases the white light generation. This simple technique could be used in the remote sensing of gases using filament-induced spectroscopy for increasing the SNR.

Acknowledgements

This work was partially supported by the University of Mohaghegh Ardebili, NSERC, Canada Research Chairs, DRDC-Valcartier, FQRNT and CIPI. Technical support and assistance of Mr. M. Martin is highly appreciated.

References