Direct measurement of the critical power of femtosecond Ti:sapphire laser pulse in air

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Abstract: We report a simple experiment to directly determine the critical power for self-focusing in air by measuring the focal shift of the focused femtosecond Ti:sapphire laser pulses. The measured critical power is 10 GW for the 42 fs laser pulse; it gradually decreases to 5 GW for (chirped) pulse duration longer than 200 fs.

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References and Links

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Because of its potential applications to pollutant detection [1-4] and lightening control [5-9], the filamentation in air attracted a lot of interests after its early demonstration [10-12]. During
the filamentation process, the ultrashort laser pulse could propagate with almost constant high peak intensity over a distance of many meters [10-13]. Now it is well known that this nonlinear phenomenon is caused by the subtle interplay between self-focusing induced by optical Kerr effect and the defocusing by the self-generated plasma. First, the laser pulse will self-focus if its peak power is higher than the critical power for self-focusing. The intensity at the focus is high enough to ionize the molecules. As a consequence, a plasma is produced. The defocusing effect of the plasma will balance the self-focusing and thus, limits the peak intensity of the laser pulse during the propagation [14-16]. Both the moving focus model [12, 17] and the similar spatial replenishment model [18, 19] describe such a picture very well, resulting in a series of self-foci along the laser propagation axis. After the laser pulse is gone, a long plasma channel is left behind. This plasma channel is normally referred to as a “filament”. At the same time, through self phase modulation and self-steepening [20, 21], the laser pulse self-transforms to a “white light laser pulse” [17, 22] featuring a spectrum from 230 nm to 4 μm (supercontinuum) in air [23-25]. Supercontinuum generation, fluorescence emission from the molecules excited by the high laser intensity and electrical conductivity of the plasma channel provide the physical basis for future applications such as remote sensing and lightening control in the atmosphere.

The whole filamentation phenomenon is initiated by the self-focusing, while the latter is characterized by the critical power, which corresponds to the situation that at this power, the natural diffraction of a parallel laser beam is counteracted by the optical Kerr self-focusing [26, 27]. Therefore, the critical power $P_{cr}$ is one of the key parameters in the filamentation process. Quantitative knowledge of the critical power will provide good guidance for theoretical and experimental research as well as applications. The most direct way to measure the critical power is to record the manner in which the laser beam intensity changes during the propagations [28, 29]. In practice, we have found that to use this approach, the required distance is normally too long to neglect the pulse dispersion effect for an ultrashort (<100 fs) laser pulse with a few millimeters diameter. On the other hand, the critical power could also be inferred for a Gaussian beam by substituting a measured nonlinear refractive index $n_2$ into Eq. (1) [30]:

$$P_{cr} = \frac{3.77 \lambda_0^2}{8 \pi \nu n_0}$$

where $\lambda$ is the laser pulse’s central wavelength, and $n_0$ denotes the linear refractive index. Polarization spectroscopy [31, 32] and spectral analysis [33] of an ultrashort laser pulse after propagation through an optical medium have been demonstrated for the determination of the nonlinear refractive index. However, in order to retrieve the value of $n_2$, considerable theoretical work is still needed to couple with the experimental measurements.

In this paper, we present a simple and compact experimental setup to measure the critical power. Our method is based on the fact that in a focusing geometry, the focus will be shifted toward the focusing lens when the laser power exceeds the critical power [30] while below the critical power, the focal position is practically unchanged.

2. Experimental setup

The experimental configuration is shown in Fig. 1. The laser system used in our experiment has been described in details elsewhere [34, 35]. The output laser pulses are operated at 10Hz with maximum energy of 10 mJ and centered at 800 nm with spectral bandwidth of about 23 nm at FWHM. The beam diameter is 6 mm at FWHM. The laser beam was focused by a 75 cm focal length BK7 lens (diameter: 2.5 cm; center thickness: 3.4 mm) in air. Because of the rather short focal length, the laser pulse could easily ionize the molecules. Recent spectroscopy research has shown that femtosecond laser pulse induced tunnel ionization [36] in air will lead to the clean fluorescence emitted by nitrogen molecule (N$_2$) and ion (N$_2^+$) [37, 38]. Perpendicular to the propagation axis, an intensified CCD camera (ICCD, Princeton Instruments, PI-MAX 512) was used to image the nitrogen fluorescence in the vicinity of the focus. The fluorescence signal was collected and imaged onto the ICCD detector by using a
single plano-convex lens made of fused silica with a focal length of 63 mm and a diameter of 38.1 mm. Furthermore, a band-pass filter was placed in front of the camera (4 mm-thick UG11, Corion) to integrate the light emission over the strongest N$_2$/N$_2$$^+$ bands around 350 nm while rejecting the scattered pump laser light from the environment. There is a good overlap between the band-pass filter transmission curve and the strongest N$_2$/N$_2$$^+$ bands around 350 nm [13]. Using an energymeter (EPM1000), the laser pulse energy was measured and calibrated through measuring the leaked energy from the last mirror before the portable compressor. A representative picture recorded by the ICCD is shown in Fig. 1 as an inset picture. The laser pulse propagates from the right to the left of the picture.

![Experimental setup](image)

Fig. 1. Experimental setup. The inset is a typical picture recorded by the ICCD.

### 3. Results and discussions

![On axis nitrogen fluorescence distribution](image)

Fig. 2. On axis nitrogen fluorescence distribution for three different energy levels: (a) 0.29 mJ; (b) 0.71 mJ; (c) 2.22 mJ. The black lines: experimental results; the red lines: Gaussian fitting.

By analyzing the on axis fluorescence signal, the on axis intensity distribution could be interpreted. Similar technique has been successfully adopted previously in the study of the filamentation phenomena [34, 39, 40]. Fig. 2 gives the plots of the on axis fluorescence distribution as a function of distance for three different energies (black lines), namely (a) 0.29 mJ, (b) 0.71 mJ and (c) 2.22 mJ, as examples. The horizontal axes are indicated in units of ICCD chip pixel. It will be clear later that it is not necessary to calibrate the horizontal axis. Like the inset picture of Fig. 1, in Fig. 2 the laser pulse propagates from the right to the left. That is to say, the larger pixel value is closer to the focusing lens. Since the experimental curves aren’t smooth enough, in order to find the peak position, Gaussian fittings are used (red lines) to fit the experimental measurement. The experimental results in Fig. 2(b) and (c) show some asymmetries compared to the Gaussian fitting curves. The asymmetry could be induced by the pulse deformation during the nonlinear propagation [21]. Since we are interested only in the peak position of the filament fluorescence, the asymmetry would not introduce any difficulty in the determination of the peak position. From the Gaussian fittings, the peak positions were retrieved. It is easy to see that the fluorescence signal’s peak shifts from pixel 80 for 0.29 mJ (Fig. 2(a)), through pixel 100 in the case of 0.71 mJ (Fig. 2(b)), to pixel 206 when the energy is increased to 2.22 mJ (Fig. 2(c)). The measured peak positions are illustrated in Fig. 3 (solid squares) as a function of the pulse energy in a log-log scale.
note that the solid squares in Fig. 3 exhibit two behaviors. First, the peak position of the on axis fluorescence keeps constant from the lowest energies to a certain level. From this point further, the peak position is quickly shifted toward the focusing lens. Two red straight lines are drawn in Fig. 3 helping to emphasize this tendency. Another red arrow in Fig. 3 highlights the deviation position, where the energy is equal to 0.42 mJ.

![Fig. 3. Fluorescence signal peak position as function of the pulse energy. Solid squares: experimental results; red lines: straight lines used to determine the critical power.](image)

It is known that in the case of external focusing, the focal position will be shifted due to self-focusing if laser pulse’s peak power is higher than the critical power. The shift obeys the lens transformation formula, which is written as [41, 42]:

\[
f' = \frac{f \cdot z_{sf}}{f + z_{sf}}.
\]  

(2)

\(f'\) is the focal position under the circumstance with both geometrical focusing and self-focusing; \(f\) denotes the focal length of the external focusing lens and \(z_{sf}\) represents the self-focusing distance of the parallel Gaussian beam given by Eq. (3) [30]:

\[
z_{sf} = 0.367k\alpha^2 \left\{ \left( \frac{P}{P_{cr}} \right)^{1/2} - 0.852 \right\}^{1/2}.
\]  

(3)

Here \(k\alpha^2\) indicate the diffraction length, where \(k\) is the wave number and \(\alpha\) is the radius at 1/e level of the beam profile. However it is important to point out, if the pulse peak power is lower than the critical power, the focal position would be unaltered; i.e. it should be constant. Consequently, the deviation point, which is indicated by the red arrow in Fig. 3, represents the position where the pulse’s peak power is equal to the critical power in air. By single shot autocorrelation measurement (Positive Light, SSA), we measured that right after passing through the lens, the pulse duration is 42 fs at FWHM. Finally we could tell that the critical power for a 42 fs pulse in air is:

\[
P_{cr} = \frac{0.42 \text{ mJ}}{42 \text{ fs}} = 10 \text{ GW}.
\]  

(4)

This value is in good agreement with a recent theoretical assumption, which was used to well fit the experimentally recorded third harmonic patterns during the filamentation process with numerical simulations [43]. Here, we have used the self-focal distance of a Gaussian beam as an example (Eqs. (2) and (3)). Our method is also valid in the case of a beam profile different from that of a Gaussian because near the critical power, the self-focusing is a ‘whole beam self-focusing’ process. Multiple filamentation, which is mainly due to the inhomogeneity across the beam profile, will occur only at higher laser power.
Next, we investigate the critical power dependence on the pulse duration. In the experiments, the pulse length was varied by changing the distance between the grating pair inside the portable compressor. The critical powers were obtained in the same way. The final result is shown in Fig. 4. The solid black squares correspond to the positively chirped pulses and the solid red circles indicate the negatively chirped pulses. All the pulse durations were measured right after the lens. We have estimated that 75 cm propagation distance in air will lengthen or shorten the pulse width by maximum 1.5% for the chirped pulses we have used in the experiments. Thus it is reasonable that Fig. 4 shows mainly the effect of pulse durations. It is interesting to see that with the increase of the pulse duration, the critical power quickly drops from 10 GW at 42 fs to around 5 GW at 200 fs. For pulse duration longer than 200 fs, the change of the critical power isn’t significant, keeping at a constant value of about 5 GW. This result is close to the earlier value estimated by the filamentation threshold in air with 250 fs laser pulses (6 GW) [35].

![Image](image_url)

**Fig. 4.** The critical power changes in terms of the pulse duration. Black solid squares: positively chirped pulse; red solid circle: negatively chirped pulse.

The reason for the decrease of the critical power when the pulse duration is lengthened/chirped has been elucidated by Ripoche et al. [33, 44]. It is because the nonlinearity in air consists of two parts: the instantaneous electronic response and the delayed nuclear response. For shorter pulses, the nonlinearity contribution from nuclear response is less. It leads to a lower effective nonlinear refractive index $n_2$, and hence a higher critical power (see Eq. (1)).

4. Summary
A simple way to directly determine the critical power of femtosecond Ti:sapphire laser pulse in air was presented. Our method is applicable to normal transparent optical media. The method is based on the principle that under geometrical focusing condition, the focal position will shift towards the focusing lens if the laser power is higher than the critical power. The movement of the focus is studied by observing the nitrogen fluorescence distribution in air. We report that the critical power in air changes from 10 GW to 5 GW when the pulse duration increases from 42 fs to 200 fs (chirped). In the case of pulse duration longer than 200 fs, the critical power is almost a constant of 5 GW. The physical reason is that with shorter pulse length, only instantaneous electronic response of the media is responsible for self-focusing while with longer pulse length, delayed nuclear response also contributes to the nonlinearity.

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