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Prolongation of the fluorescence lifetime of plasma channels in air induced by femtosecond laser pulses

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ABSTRACT The lifetime of plasma channels induced by femtosecond laser pulses is investigated by detecting the decay time of the fluorescence signals from ions. It is found that the lifetime of the plasma can be prolonged to the order of microseconds when an additional sub-nanosecond laser pulse is injected into the channel. This prolongation is due to the heating and further ionization through the inverse bremsstrahlung absorption of the post-pulse.

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1 Introduction

In recent years there has been great interest in the formation of long plasma channels in air induced by femtosecond (fs) laser pulses [1–10]. Many experimental and theoretical researches have demonstrated that the fundamental mechanism is the dynamic balance between the nonlinear Kerr self-focusing due to the nonlinear intensity-dependent refractive index and plasma defocusing due to high-order multiphoton ionization (MPI) of air and the normal diffraction of the laser beam. The nonlinear refractive index in air acts as a positive lens to focus the beam. The Kerr lens overcomes diffraction and leads to a beam collapse when the beam power exceeds the critical power $P_{\rm crit} = \lambda^2/2\pi n_0 n_2$ of about 3.2 GW in air for the laser wavelength $\lambda = 800$ nm, where $n_2 = 3.2 \times 10^{-19}$ cm^2/W in air [11]. The laser beam is focused before the geometrical focus [12, 13]. Many nonlinear effects, for example high-order multiphoton ionization, occur due to the increase of the laser intensity. Electrons are generated mainly by the process of MPI, and the electrons contribute negatively to the index of refraction of air: $n_{\rm plasma} = -\omega_{\rm p}^2(r)/2\omega^2$, where $\omega_{\rm p} = (4\pi e^2 n/m)^{1/2}$ is the plasma frequency and n is the plasma density [11]. The two opposite effects on the refractive index of air result in the long propagation of the fs laser pulses, resulting in plasma channels. Such a plasma channel can propagate over a distance of thousands of meters, exceeding many Rayleigh lengths of the laser beam [5, 14, 15]. The long channel has potential applications such as remote sensing, lightning control, and so on.

However, due to recombination of electrons to parent ions [16] and the strong attachment of electrons to oxygen molecules [17, 18], the lifetime of the plasma channel is only several nanoseconds. This is too short for practical applications that require the channels with not only long distance but also long lifetime. Therefore, it is important to prolong the lifetime of the plasma channel.

The idea of prolonging the plasma channel by adding a delayed long laser pulse has been suggested by our earlier work [17] and also discussed in the context of high voltage discharge control by Zhao et al. [18]. In this paper, we present our systematic investigations of the prolongation of the lifetime of plasma channels in air generated by fs laser pulses. In the experiments, a succeeding sub-nanosecond (sub-ns) laser pulse is injected into the plasma channel. We find that the lifetime of the plasma is prolonged by several tens of times than the case without the succeeding pulse. As far as we know, this is the first experimental study of the prolongation of the lifetime of plasma channels.

2 Experimental setup

The laser system is a home-made Ti:sapphire chirped-pulse amplification system (JG-II) with a repetition rate of 10 Hz, a pulse duration of 30 fs, and a central wavelength of 800 nm. At the output of the compressor stage, the beam profile is nearly Gaussian, and the initial beam-waist radius is 1.5 cm. The maximum output energy of the laser system is 640 mJ per pulse. However, an energy of only tens of mJ is used in the experiments. The experimental setup is shown in Fig. 1. The fs laser pulse is focused with a $f = 35$-cm lens to produce a plasma channel in air first, and then a sub-ns laser pulse with a duration of 0.3 ns is injected into the plasma channel after a delay time of 10 ns. The sub-ns laser pulse is a portion of the laser beam before the compressor stage. It is adjusted accurately to propagate along the plasma channel induced by the fs pulse. The lifetime of the plasma can

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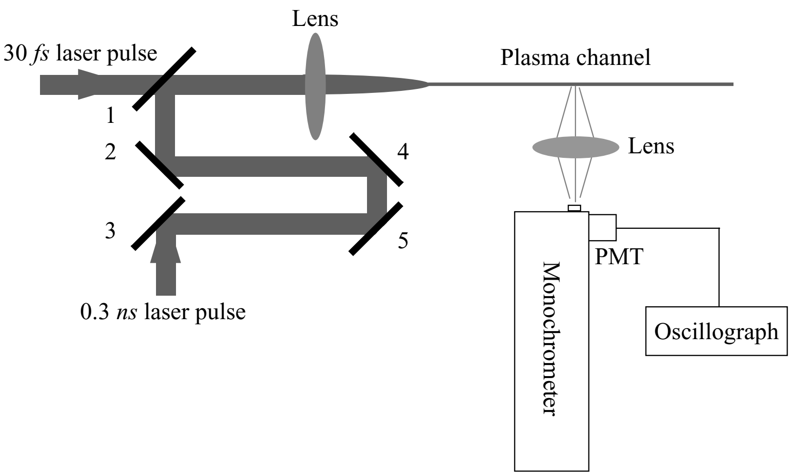

FIGURE 1 Schematic diagram of the experimental setup. 1 is a half-transmission and half-reflection mirror, 2–5 are 45° high-reflection mirrors, PMT is a photomultiplier tube coupled to the monochromator

be manifested by the time history of the fluorescence from the electron–ion recombination in the channel [13, 19, 20]. The fluorescence emitted from the channel is collected by a $f =$ 10-cm lens into a monochromator, which singles out the spectral line of 504.5 nm (N^+: $3p(^3S)$–$3s(^3P^0)$ transition). The line can be an indicator of the plasma-channel lifetime. The emission of the spectral line is recorded by a digital oscillograph after being amplified by a photomultiplier tube (PMT).

3 Experimental results and discussion

In order to postpone electron recombination and detach electrons from O^- and O_2^-, we launch another succeeding sub-ns laser pulse to prolong the lifetime of the plasma channel and find that the lifetime is greatly prolonged. In Fig. 2a, a typical fluorescence signal is shown. The energies of the fs and sub-ns laser pulses are 38 and 17 mJ, respectively. The dotted curve 1 represents the free decay of the plasma channel without the sub-ns laser pulse; the solid curve 2 represents the temporal evolution of the plasma channel with the sub-ns laser pulse. The lifetime of the plasma channel generated by a single fs laser pulse is 12 ns at the full width at half maximum (FWHM) and the bottom width is about 40 ns obtained from the tail of the signal. The tail ends at the time position when the signal decays to below 5% of its maximum. When a succeeding sub-ns laser pulse is injected after the fs laser pulse, the FWHM is increased to be 26 ns and the tail lasts more than 200 ns. For the case with the sub-ns laser pulse, the intensity of the fluorescence signal is also greatly enhanced. In order to emphasize the difference in the signal decay time, the derivatives of the curves 1 and 2 are presented in Fig. 2b. From the trends of the derivatives, we can conclude that the fluorescence lasts a much longer time after we add the sub-ns laser pulse. However, the signal without the second laser pulse decays fast to zero at a time of about 35 ns.

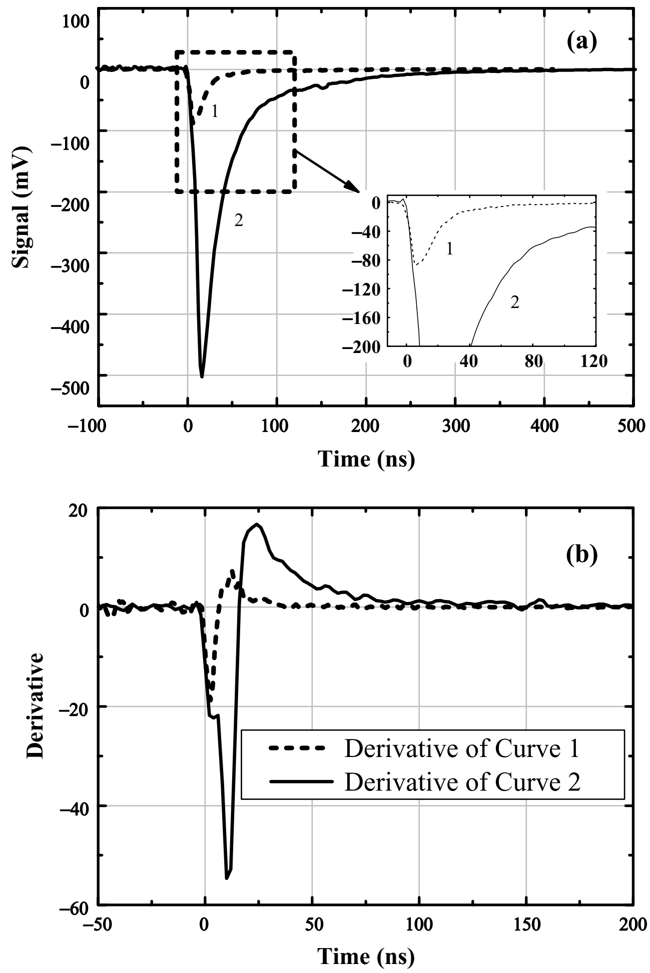

FIGURE 2 Typical fluorescence signals recorded by a digital oscillograph (**a**) and their derivatives (**b**). The *dotted curve* represents the free decay of the plasma; the *solid curve* represents the temporal evolution of the plasma with a succeeding sub-ns laser pulse after the fs laser pulse

Figure 3 shows the dependence of the lifetime of the plasma on the energy of the sub-ns laser pulse. The energy of the fs laser pulse is 38 mJ. The FWHM of the signal is prolonged to 200 ns when we add the succeeding sub-ns laser pulse with an energy of 42 mJ, as shown in Fig. 3a. More interestingly, the tail width of the signal is greatly extended to about 1.5 μs (microseconds) as shown in Fig. 3b. We can see that the more the energy of the sub-ns laser pulse that is injected, the longer the lifetime of the plasma is prolonged. The error bar of the signals measured in our experiments includes both the standard deviation of the measurements and the uncertainty in the reading of the tail. The dotted curves in Fig. 3 represent the

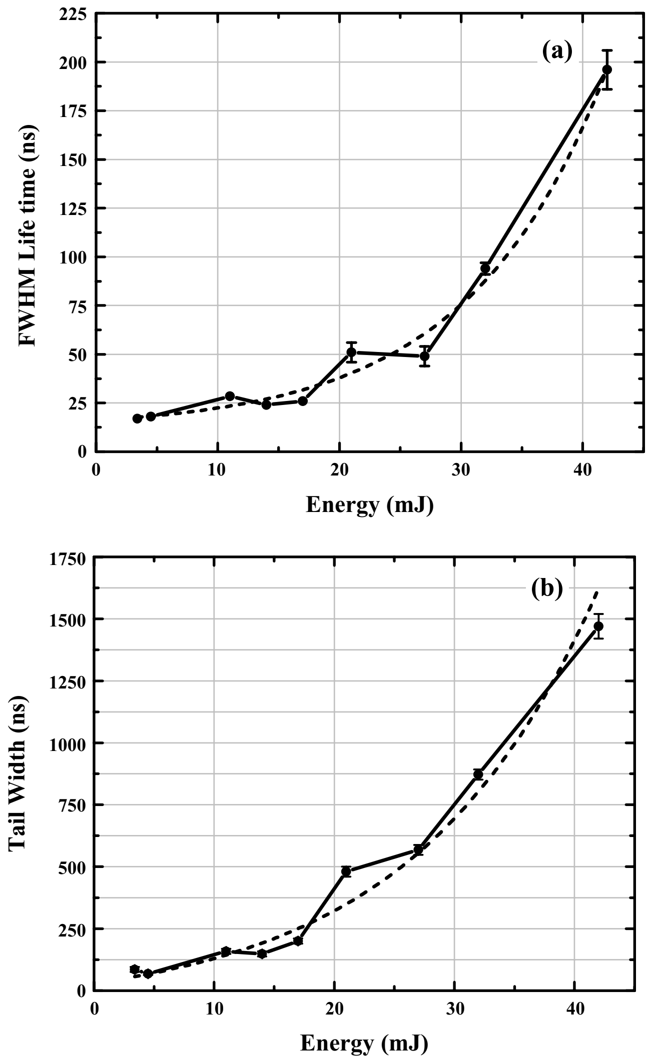

FIGURE 3 The lifetime of the plasma versus the energy of the sub-ns laser pulse. The fs laser pulse energy is 38 mJ and the time delay is 10 ns. **a** Represents the lifetime at the FWHM; **b** represents the lifetime at the tail width of the fluorescence signal. The *dotted curves* represent the exponential fitting

exponential fitting. The fitting results show an increase of $\sim \exp(0.08 \times E_{\text{sub-ns}})$ for the FWHM and $\sim \exp(0.07 \times E_{\text{sub-ns}})$ for the tail width, respectively. They are quite similar.

We also measured the lifetime of the plasma by changing the delay time between the fs and the sub-ns laser pulses to 20 ns. The experimental results demonstrate that the 10-ns delay time is much better than 20 ns. The characteristic relaxation time of the electron attachment is about 16 ns in the standard air conditions [21], so the electrons in the plasma channel have no time to attach to neutral molecules when the succeeding laser pulse arrives with a 10-ns delay. Otherwise, when the delay time is greater than 16 ns, for example 20 ns, the attachment of electrons to neutral molecules causes the electron density to decay exponentially, so that the electron density is too low to maintain a long lifetime [21].

According to our previous study [17], when the power of the succeeding laser pulse is lower than the threshold of the ionization of air, the main mechanism of the lifetime prolongation is the detachment of electrons from O^- and O_2^-. But, in Ref. [17], the succeeding laser pulse is considered to contribute to the detachment all the time until the arrival of the next fs laser pulse. So, in our experiments, it is impossible to get results similar to those described in Ref. [17] because the duration of the sub-ns laser pulse is not long enough to satisfy the need of the detachment mechanism. We find that the lifetime remains constant when the energy of the sub-ns laser pulse is lower than the ionization threshold in our experiments. So, the detachment is not the main mechanism in our experiments.

When the energy of the sub-ns laser pulse, for example 3.4 mJ, corresponding to a beam waist of 10 μm and a power density of $\sim 10^{12}$ W/cm^2 in theory, exceeds the threshold for air ionization [22], the lifetime of the plasma is greatly prolonged as shown in Fig. 3. In this situation, on the one hand, the long laser pulse ionizes the air molecules and generates free electrons; on the other hand, these electrons in the plasma channel absorb laser energy by the process of the inverse bremsstrahlung during the sub-ns pulse duration. These electrons result in further ionization of air molecules via collisions between electrons and air molecules. Furthermore, the process of the electron recombination to air molecules becomes slower because of the increased energy of the electrons in the air (ions and neutral molecules) in the channel. Therefore, the electron density in the plasma channel can be maintained for a longer time, and then the corresponding lifetime of the plasma is greatly prolonged. We can see from the experimental results that the lifetime can be extended to the order of microseconds, as shown in Fig. 3.

Therefore, in the condition of our experiments the detachment proposed in Ref. [17] is not the main mechanism, and the relevant important mechanism is the multiphoton ionization induced by both the laser pulses and the inverse bremsstrahlung which heats electrons to a high energy level to induce further ionization.

It is noted that the configuration of our experiments is a strongly focused laser beam, which produces a plasma channel with much higher electron density than in filaments propagating at long distance. Therefore, the mechanism based on the inverse bremsstrahlung absorption is much more efficient in the experiments than that in long filaments. The second pulse should be powerful enough to generate electrons first and to prolong its lifetime further in the latter condition.

In order to further prolong the lifetime, we plan to carry out further studies on the following two schemes. Firstly, considering the electron-detaching mechanism, a longer duration laser pulse should be used to replace the sub-ns laser pulse. The longer the pulse duration is, the better it is, and a CW laser is desirable. Our previous study [17] described this theoretically and concluded that the lifetime can also be prolonged to the order of microseconds in this case. Instead of a single, delayed pulse a sequence of high-repetition-rate short pulses can also be used. The reference [19] demonstrated that the detachment efficiency of a short pulse sequence with a high repetition rate is higher than that of a continuous laser with the same wavelength and average power. For example, for rectangular pulses with 10-ns delay and 1-ns duration, during the interval to the next pulse the electron density can be maintained at a high level, but it decays fast if we change the time interval from 10 to 100 ns [21]. Furthermore, considering that the photodetachment cross section is related to the wavelength of the laser, the second laser can be a shorter-wavelength laser, 532 nm for example, whose photodetachment cross section is much higher than that of a 800-nm laser; secondly, on the basis of the first scheme, a fs laser pulse train with a fixed separation time can be used to generate the plasma channel instead of a single fs laser pulse. For this case, the requirement for the parameters of the additional long laser pulse could not be so rigorous. Our experiments have demonstrated that a double fs laser pulse with 10-ns delay could also result in a large lifetime prolongation of the plasma channel. It is expected that the second scheme could be favorable to form a longer lifetime of the plasma channel.

4 Conclusion

We have investigated the lifetime prolongation of long plasma channels by launching a sub-ns laser pulse into the plasma channel induced by a fs laser pulse. It is found that the lifetime of the plasma can be prolonged by tens of times as compared to the single-pulse case. The main prolongation mechanism is that the electrons generated by both the fs and the sub-ns laser pulses are heated to a higher energy through the inverse bremsstrahlung absorption by the latter laser pulse and induce further ionizations.

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