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Study of laser induced plasma grating dynamics in gases

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ABSTRACT

The relaxation of a plasma grating resulting from the interference of two crossing laser filaments in molecular and atomic gases is studied experimentally. Dissipation of the grating fringes is dominated by ambipolar diffusion in atomic gases and by a combination of ambipolar diffusion and collision-assisted free electron recombination in molecular gases. A theoretical model of the grating evolution is developed and compared to experimental results. Good agreement with simulations allows extracting plasma properties such as electron density, diffusion and recombination coefficients in Ne, Ar, Kr, Xe, N_2, O_2, CO_2 and air at atmospheric pressure.

1. Introduction

Femtosecond laser filamentation has raised much interest in the last decade in various domains of applied physics such as guiding electric discharges [1,2], atmospheric monitoring through LIDAR technique [3], Terahertz generation [4], white-light continuum generation [5] or virtual radiofrequency antenna [6]. Resulting from a dynamic competition between the Kerr effect and plasma defocusing, filamentation appears spontaneously during the propagation of an intense femtosecond laser pulse, provided the initial peak power exceeds a threshold value P_{cr} (a few GW in gases). An intensity reaching 5×10^{13} W/cm^2 in air is maintained in the core of the beam over an extended length, producing a long string of plasma in the wake of the pulse [7]. In order to remotely control the filamentation process for long range applications, much attention has been given to intersecting filaments by another femtosecond laser pulse. In the intersection region, interference of the two pulses gives rise to a plasma grating [8–10]. Recent studies have highlighted the role of the grating as a way to manipulate femtosecond pulses: energy exchange [10–12], interruption of filament [13–15] or redirection of a third beam [16,17]. Measurements of the plasma density as well as the relaxation process of the plasma grating are crucial for the understanding of the phenomenon. In a recent article we reported first results concerning the experimental characterization of the plasma grating decay in several molecular and atomic gases [18].

In this manuscript we present the complete theoretical model and the experimental results allowing describing the plasma dynamics in the laser induced grating for all studied gases. We demonstrate that the plasma fringes are washed out by the ambipolar diffusion in atomic gases and by a combination of the ambipolar diffusion and collision-assisted free electron recombination in molecular gases. A theoretical model based on a Bragg diffraction is developed to interpret the experimental results. Data are fitted by the model, allowing extraction of the plasma properties such as the free electron density, diffusion and recombination coefficients in Ne, Ar, Kr, Xe, N_2, O_2, CO_2 and air. Some of these parameters were already measured several years ago but for a very low gas pressure and in a fully ionized plasma [19–21]. The recombination coefficient for air was also estimated and measured in the case of single filament, showing discrepancy between different values obtained [22–24]. In the present study we measured these quantities at atmospheric pressure in a weakly ionized gas.

The outline of this paper is the following: first, we study in Section 2 the plasma by using temporally resolved in-line diffractometry measurements to determine the initial plasma density and the recombination coefficient of the filament in the crossing area. Due to the laser field interference, this density is higher than the density in single filaments, and needs to be evaluated. We then elaborate in Section 3 a theoretical model describing the relaxation of the grating. We finally study the decay of grating using a pump-probe experiment. Best fits between calculations and

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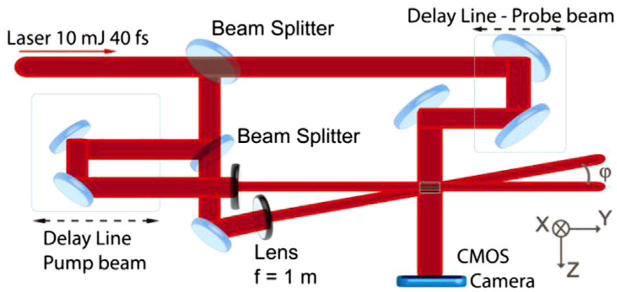

Fig. 1. Experimental set-up of the in-line diffractometry measurement.

experimental results yield the initial free electron density, its time evolution as well as the diffusion coefficient in all studied gases.

2. Study of the plasma relaxation

2.1. Experimental set-up

We used in the experiment a chirped pulse amplified (CPA) femtosecond laser system delivering 50 fs pulses at 800 nm with a maximum energy of 15 mJ at a repetition rate of 100 Hz. At the output of the CPA system the laser beam has a Gaussian spatial intensity distribution with a diameter of 14 mm. The output pulse is split into three beams by two sequential beam splitters (10%/90% and 50%/50%). Two pump laser pulses of 1 mJ with a vertical polarization are focused with a 1000 mm focal lens in a cell containing the gas at atmospheric pressure, where they form two filaments. A plasma grating is formed in the intersection region (see details in Refs. [17,18]). Measurements were performed in air, O_2, N_2, CO_2, Ne, Ar, Kr and Xe.

In this first experiment, an unfocused weak probe beam is used to illuminate the plasma grating (Fig. 1). Probe beam is sent transversely through the plasma. Since it propagates perpendicularly to the plane containing the fringes, it is only sensitive to the global phase object it traverses, but not to the plasma density modulation. The probe can be delayed with respect to the plasma formation time to record the temporal evolution of the diffraction pattern caused by the plasma bubble. We used a CMOS camera (uEYE UI-1240SE) placed at the distance $H=38$ cm away from the plasma grating. A similar in-line diffractometry method has already been used in Refs. [24–26] to determine the temporal evolution of the plasma electron density in the case of a single filament produced in air.

2.2. Calculation of probe diffraction by a plasma bubble

The plasma electron density evolution was calculated from the diffractometry measurement of the probe beam. The plasma bubble produced at the intersection of the two filaments induces a change of refractive index $\Delta\phi$ on the path of the probe beam. The plasma refractive index reads $n=\sqrt{1-\omega_P^2/\omega^2}$, where $\omega_P=\sqrt{\rho_e e^2/m_e\varepsilon_0}$ is the plasma frequency, ω is the laser angular frequency, ε_0 is the vacuum permittivity, e is the elementary charge, m_e is the electron mass and ρ_e is the electron plasma density. The ratio $\omega_P^2/\omega^2 \ll 1$ is small, so the variation of the plasma refractive index is directly proportional to ρ_e

$$\Delta n_0=\frac{-\omega_P^2(\rho)}{2\omega^2}=\frac{-\rho_e}{2\rho_c}, \qquad (1)$$

where $\rho_c=1.7\times10^{21}\ \text{cm}^{-3}$ is the electron critical density at 800 nm. Based on the crossing geometry of two filamentary beams, we assume a super-Gaussian plasma density profile along x direction and a Gaussian profile along z direction with characteristic lengths L_1 and L_2. Due to geometric considerations we expect L_2 to be slightly larger than L_1. Then the change of refractive index in the interaction area can be described as

$$\Delta n(x,z)=\Delta n_0 exp\left[-\left(\frac{x^2}{2L_1^2}\right)^a-\left(\frac{z^2}{2L_2^2}\right)\right], \qquad (2)$$

where Δn_0 is the maximum variation of the index at the center of plasma and a is the super Gaussian order. Then the phase shift due to the probe beam propagation through the plasma reads

$$\Delta\phi(x)=k\int\Delta n(x,z)dz=\sqrt{2\pi}\Delta n_0 k L_2 exp\left[-\left(\frac{x^2}{2L_1^2}\right)^a\right]. \qquad (3)$$

Assuming that the probe beam has a Gaussian spatial profile $\Psi(x,0)=A_0 exp(-x^2/2w_0^2)$ with a width $w_0\sim7$ mm, the amplitude of diffracted wave at the distance H from the plasma is expressed as follows:

$$\Psi(x,H)=A_0\sqrt{\frac{k}{\pi H}}\int dx' exp\left(-i\Delta\phi(x')-\frac{x'^2}{2w_0^2}+\frac{ik}{2H}(x-x')^2\right). \qquad (4)$$

The expression above provides a relation between the plasma electron density and the diffraction pattern of the probe intensity $I(x)=|\Psi(x,H)|^2$.

The temporal evolution of the probe diffraction pattern provides information on the plasma relaxation. It is governed by two phenomena: the free carrier diffusion and recombination. In a plasma created by filamentation, the degree of ionization is rather low and the electron recombination is based on two distinct processes: the recombination on parent ions and attachment to neutral atoms. Zhou et al. [27] demonstrated that in gases the first process is faster. The electron diffusion could be important over a distance of a few microns, comparable to the electron mean free path, but it can be neglected on the plasma scale of a few tens of microns. Consequently, the decay of the electron plasma density from the initial value ρ_0 can be expressed as [24]

$$\rho_e(t)=1/\left(\frac{1}{\rho_0}+\beta t\right). \qquad (5)$$

The electron recombination coefficient β can be found from the contrast of the fringes as the ratio $\Delta I/I_0(t)$, where I_0 is the background intensity and $\Delta I=I-I_0$ is the difference of the probe beam intensity with and without the plasma.

2.3. Experimental results and discussion

Fig. 2 presents an image obtained from the diffraction of the probe beam by the plasma bubble in air. Two images have been recorded: the probe transmitted though the plasma (a) and the background without plasma (b). The pictures shown in Fig. 2(a) and (b) were taken when the probe beam was sent $\tau=1.13$ ps after the formation of the plasma grating. After subtraction of the background we obtain the diffraction pattern shown in Fig. 2(c). The x-profile of the fringes extracted from Fig. 2(c) along the y position where the fringes are at their maximum is shown in Fig. 2(d). The contrast is calculated by dividing the profile by the maximum value of the background taken at the same coordinate y. These measurements were performed for different gases as a function of the delay between the probe beam and the formation of the plasma. The contrast extraction procedure was routinely repeated for each delay τ.

The calculated fringe profile is best fitted to the experimental one (see Fig. 3) through adjustable parameters a, L_1 and L_2 that characterize the shape of the plasma bubble. For all gases it was found $a=2$, $L_1=40$ μm and $L_2=90$ μm, except for Xenon for which $L_1=80$ μm. Once the plasma shape is fixed, the maximum contrast is linked to the

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