Interferometry diagnostics of plasma channel of femtosecond filament

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Abstract. Results of the electron density dynamics in the plasma channel of a femtosecond filament in air, nitrogen and argon from the moment of ionization up to hundreds of picoseconds after it are presented. Anisotropy of the refractive index was found, which is preceded and accompanied by ionization of the gas at the time of passage of high-intensity femtosecond laser pulse.

1. Introduction
Femtosecond laser plasma is the subject of intense research in recent decades. One of the directions is to study the filamentation process of ultrashort laser radiation \cite{1}. Filamentation phenomenon is the result of a nonlinear optical interaction between the transparent medium and the femtosecond laser pulses of a high power. If the pulse peak power exceeds the critical self-focusing power, the intensity increases with approaching the nonlinear focus. With its increase up to the threshold of photoionization, a laser-produced plasma is formed where defocusing of the light restricts the further growth of intensity in a nonlinear focus. Dynamic balance of Kerr self-focusing and plasma defocusing leads to the stability of the parameters in a long filament.

One of the methods for measuring the electron density and the decay time of the plasma filament during the initial (picosecond) time interval since its birth is the interferometry which uses a weak intensity light beam directed perpendicular to the plasma filament \cite{2}. The process of the plasma decay in air goes through several channels of recombination of electrons with various ions including the complex ions \cite{3}.

Performing the experiments on the decay of the plasma channel in pure gases allows to reduce the number of possible recombination channels, and thus a simple interpretation of the electron density dependence on time can be expected.

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2. Experimental facility
The experimental setup is shown in figure 1. The plasma channel was formed during filamentation of a femtosecond laser pulse ($E = 2.5 \text{ mJ}, t = 40 \text{ fs (FWHM)}, D = 12 \text{ mm (1/e^2)}, $ lens focal length $f = 50 \text{ cm}$). This channel was enlightened with a weak probe laser pulse either at the moment of ionization of the medium or after that at a time instant regulated by the optical delay line. The interferograms of the medium with the plasma channel ("signal") and without it ("background") were taken with the CCD camera. The presence of a phase-changing object, the plasma channel, on the way of the probe beam led to a change in the interference pattern. Processing the interferograms with the Fourier filtering method yielded the difference between the "signal" and "background" phase distributions, which corresponds to the contribution of the plasma (Figure 2(a)). Further, assuming cylindrical symmetry of the plasma the refractive index was calculated using the phase shift, and the electron density was evaluated using the Drude model (Figure 2(b)).

![Figure 1. Experimental installation scheme.](image)

3. Results
Thus the time dependence of the electron density during the decay of plasma channel in air and nitrogen was obtained during the time interval of 0-150 ps (Figure 2 (b)). It was found that the decay in argon is much slower than that in nitrogen and air. It was also found that the decay in nitrogen is faster than that in air.
Figure 2. The images of plasma phase shift at different time instants counted from the moment of ionization (a); the peak electron density in the plasma channel filament as a function of time (b).

Thanks to improvement of interferogram processing method due to averaging over a series of frames, the sensitivity of the method was increased, that allowed to observe the decay in the air up to 1 ns after the moment of ionization (Figure 3).

Figure 3. The linear electron density in the plasma channel (air) as a function of time up to 1 ns.

While studying the stage of formation of the plasma channel, anisotropy of the refractive index was discovered, associated with the passage of the high-power laser pulse in air and inert gases (Figure 4). In this case, the phase shift (and the index of refraction) in different regions has both the positive and negative values, that may indicate on the influence of the high-order Kerr effect on the propagation of laser radiation at filamentation.
Figure 4. The images of phase shift at the moment of formation of the channel, for various polarizations of the probe beam, which show the anisotropy of the refractive index (↔ - horizontally polarized probe pulse, ↑ - vertically polarized probe pulse, both for vertically polarized ionizing pulse).

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