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Phase-contrast imaging method based on fast Kerr optical nonlinearity of air

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Abstract. **The visualisation of a transparent phase object (gas jet) and the brightness inversion at the image of a nontransparent amplitude object (metal wire) is implemented using the nonlinear phase-contrast method based on the fast Kerr nonlinearity of the ambient air.**

Keywords: *Kerr nonlinearity, phase contrast, visualisation of phase objects, nonlinear phase-contrast Zernike filter.*

1. Introduction

The classical phase-contrast method of phase object imaging [1] is based on producing a phase shift between the low-frequency part of the spatial Fourier spectrum of a laser beam and its high-frequency part, carrying the information about the object image. To this end, use is made of a Zernike filter, i.e. a disk-shaped glass plate with a diameter equal to the Fourier spectrum width of the unperturbed laser beam and a thickness providing a phase shift equal to $\pm\pi/2$. The limitations of the method are related to the complexity of the optical scheme alignment and its sensitivity to external factors, including vibration, temperature deformation, and air turbulence. In this connection, during three last decades, nonlinear phase-contrast methods have been actively studied, in which a layer of a nonlinear-optical medium is used as a Zernike filter [2]. In such systems, the phase shift is produced at the expense of self-phase modulation of the laser radiation spatial spectrum near the Fourier plane of the optical system. The choice of power (pulse energy) of the laser radiation illuminating the object allows the image contrast to be controlled. Efficient phase-contrast schemes with Zernike filters have been developed using the following types of nonlinearity: Kerr [3, 4], photorefractive [5, 6], thermal [7–9], and saturated absorption nonlinearities [10], as well as orientation nonlinearity of bacteriorhodopsin [11] and liquid crystals [12–16].

In the present paper, the nonlinear Zernike filter is based on the fast cubic nonlinearity of ambient air due to bound electrons. The phase-contrast method of imaging of a transparent object (gas jet) and a nontransparent amplitude objects (metal wire) was implemented by focusing high-power femtosecond laser radiation in air under normal conditions. The results of the study are interesting for the diagnostics of fast processes, as well as for remote atmosphere sensing applications.

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2. Experiment

The experiment is schematically presented in Fig. 1. To form a phase-contrast image we used the radiation of a Tsunami-Spitfire femtosecond laser system (Spectra-Physics Lasers Inc.). The system generated laser pulses at the wavelength 800 nm with the energy 1 mJ, the duration 50 fs, and the repetition rate 1 kHz. The single-mode collimated laser beam with a diameter of 8.4 mm at the e^{-2} level passed through the studied objects placed in the object plane of the optical system and was focused into the air using a lens with a focal length of 100 cm. In the observation plane, the CMOS matrix of the Motion Pro x3 camera (Redlake Inc.) with 12 × 12 μm pixels was located. The distances from the object plane to the lens and the observation plane were equal to 200 cm, which provided the imaging without changing the scale.

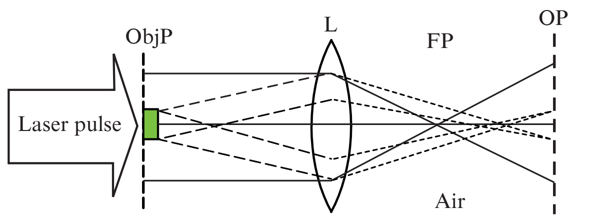

Figure 1. Schematic of the experiment:
(ObjP) object plane; (L) lens; (FP) Fourier plane; (OP) observation plane.

In the present scheme, the Zernike filter is based on the optical nonlinearity of ambient air. The necessary phase modulation of the Fourier spectrum of the high-power laser beam occurs under its self-action near the Fourier plane (FP). Due to Kerr nonlinearity arising at the radiation passage through the air medium in the region of the beam waist (FP), the laser pulse acquires a phase shift that provides the dephasing of spatial frequencies and leads to a change in the contrast of the object images.

The test object was a jet of gaseous neon streaming from a slit nozzle with the cross section 2.4 × 0.5 mm under the pressure ~1 atm into the atmosphere air. Figure 2 presents the images of the neon flow obtained by the phase-contrast

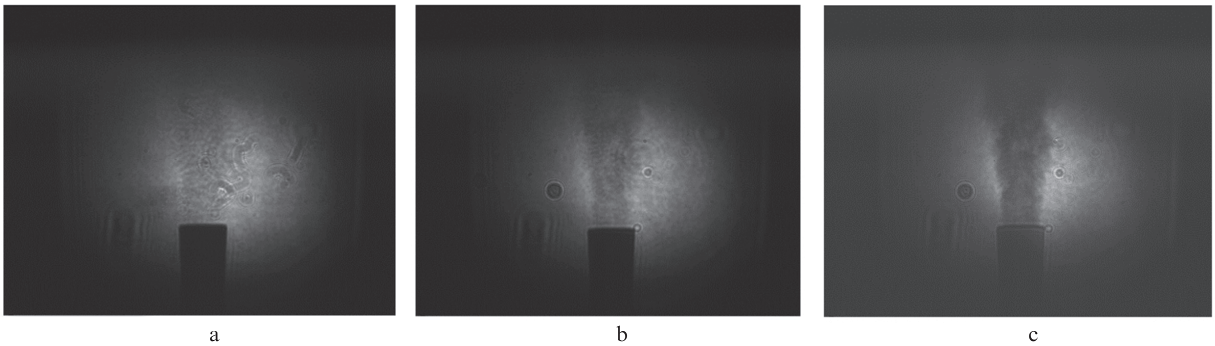

Figure 2. Phase-contrast images of a neon jet in air (the visible nozzle size is 2.4 mm) with the femtosecond laser pulse energy of (a) 100, (b) 200, and (c) 500 μJ.

method at different energies (100, 200, and 500 μJ) of the incident laser pulse. As seen from Fig. 2, the use of fast Kerr nonlinearity of the air layer near the FP as a phase-contrast Zernike filter allows phase objects to be visualised without additional precision alignment of the optical system. Another positive feature of the implemented approach is the immediacy. In contrast to the interferometric method that requires postprocessing, the phase object visualisation occurs in every laser pulse at the sensor of the camera (if the phase of the object is sufficient). Note also that the method possesses femtosecond resolution determined by the duration of the laser pulse, i.e., it is applicable to the study of fast processes. Figure 2 shows that the contrast of the gas flow images, defined by the relation $K = (I_{\rm beam} - I_{\rm obj})/I_{\rm beam}$, where $I_{\rm obj}$ and $I_{\rm beam}$ are the image brightness in the region of the object and the image brightness of the unperturbed laser beam, respectively, depends on the laser pulse energy and increases with increasing energy.

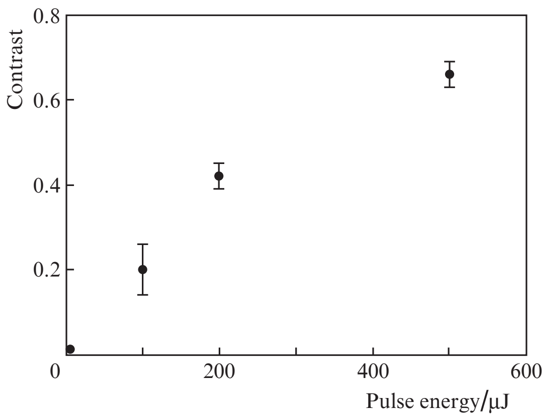

Figure 3. Contrast of the gas jet image as a function of the laser pulse energy.

Figure 3 present the dependence of the contrast of the gas flow image on the laser pulse energy. Under the conditions of the experiment, the contrast of the transparent phase object image linearly increased with increasing energy up to 200 μJ. At larger energies, the dependence declined from the linear one, and the maximal contrast ($K \approx 0.65$) was achieved at the maximal energy 500 μJ of the laser pulses used in the experiment.

Figure 4 presents the images of a nontransparent (amplitude) object. In our experiments, it was a metal wire with the diameter 100 μm. The images were obtained using the nonlinear phase-contrast method with femtosecond laser pulses having the same energy as in the gas jet experiments.

In comparison with the case of phase objects, the relationship between the contrast of the amplitude object image and the laser pulse energy is inverse. At small energies the contrast of images is high, and a shadow from the object is observed in the beam (Fig. 4a). With increasing laser pulse energy, the image contrast at first decreases (Fig. 4b), and then the image of the object becomes inverted (Fig. 4c), i.e., the brightness of the image exceeds the laser beam itself.

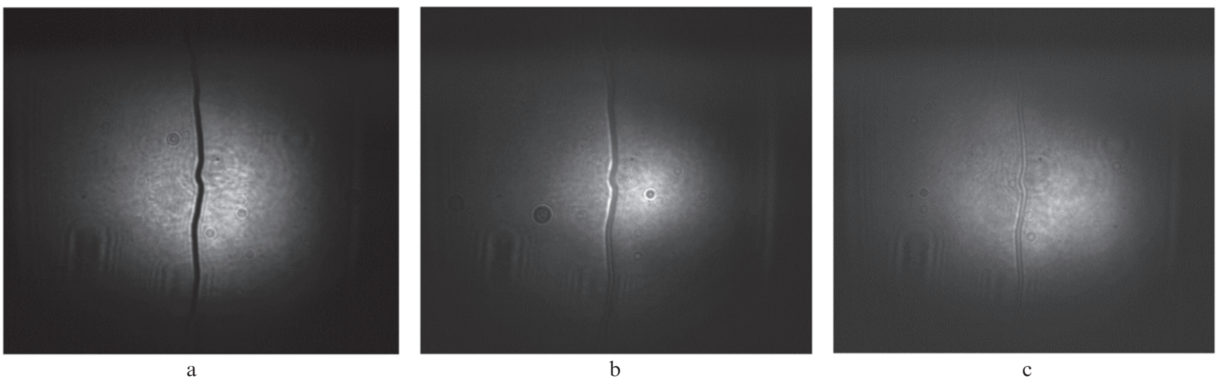

Figure 4. Phase-contrast images of the amplitude object (a wire with a diameter of 100 μm) at a pulse energy of (a) 100, (b) 200, and (c) 500 μJ.

3. Conclusions

A nonlinear phase-contrast method based on the fast Kerr nonlinearity under the focusing of femtosecond laser radiation into ambient air at normal conditions is proposed and implemented experimentally. The possibility of obtaining phase-contrast images of transparent phase objects and images of amplitude objects with inverted brightness is demonstrated for the first time.

Using a fast-response medium as a Zernike filter based on the fast Kerr nonlinearity, one can apply the presented method to the diagnostics of fast processes with a high spatial and temporal resolution, such as the filamentation of femtosecond laser radiation in atmosphere, accompanied by the formation of plasma channels.

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