Study of objects visualization and image inversion by the phase-contrast method with linear and nonlinear filters

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Abstract. The adaptive phase-contrast method with nonlinear (photothermal) and linear Zernike filters was investigated. Liquid and polymer media partially absorbing radiation served as photothermal Zernike filters. Efficient visualization and inversion of images of small-scale model objects were demonstrated experimentally. Growth-sector boundary in a nonlinear crystal was visualized.

1. Introduction
The phase-contrast method is widely used for visualizing small-scale weak (phase $\varphi<1$) objects [1-3]. To transform the phase modulation induced by the studied object into the illuminating beam to the amplitude modulation, a phase screen (Zernike filter) is placed in the focal plane of the lens (Fourier plane). The Zernike filter introduces a selective shift $\theta_Z=\pm\pi/2$ (for objects with phase $\varphi<<1$) between the zero and higher spatial frequencies participating in imaging the object. The phase-contrast method proposed by Frits Zernike in 1934 was initially used mainly in microscopy. Later its application was extended to plasma physics (measurement of weak fluctuations), acoustic waves, gas flows, and so on.

This work concerns investigation of the phase-contrast method using nonlinear Zernike filters [2,4-25], when spatial frequency phase shift occurs in a cubic nonlinear medium (nonlinear Zernike filter) situated in the Fourier plane where the spatial harmonics are separated. As compared to the schemes with linear Zernike cells, the nonlinear schemes are more flexible adaptive systems where a needed phase shift is attained by selecting appropriate light intensity in the nonlinear medium. Phase objects are visualized in phase-contrast schemes with Zernike filters using the following types of nonlinearity: Kerr [4-7], bacteriorhodopsin [8,9], photorefractive [10], orientational liquid crystal [11-16], thermocapillary [17], supersaturation nonlinearity [18], and others (see, e.g., [19,20]). In the present work photothermal filters [9,21-25] based on the thermal mechanism of nonlinearity were used in the phase-contrast scheme. This mechanism is the most low-threshold one for cw and quasi-cw laser generation in simple available media.

2. Experimental study
The optical schemes used in experiments are shown in fig. 1 (solid line – direct light, dash line – diffracted wave on the object). A green laser module SLM-417 with wavelength $\lambda=530$ nm was used as a radiation source.
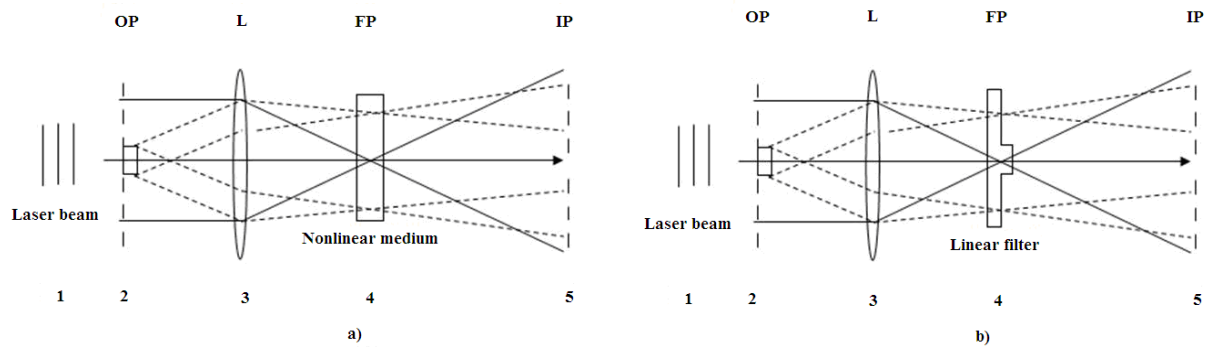
Figure 1. Optical schemes used in experiment.

The source power did not exceed $P \leq 10$ mW. Object 2 was located in the object plane OP. The object was exposed to laser radiation focused by lens 3 on a cell with absorbing liquid (5,a) or on a linear filter with a 265 nm high step (5,b) located in the Fourier plane FP. The obtained image was recorded by a CMOS-camera situated in the image plane IP.

The results of phase object visualization are presented in fig. 2. It follows from this figure that the visualization is efficient, which is important for constructing schemes for measuring weak medium absorption [18]. It is also seen that acceptable image quality persists at the initial stage of thermal self-action (fig. 2 b,c,d) and further deteriorates due to a strong thermal lens.
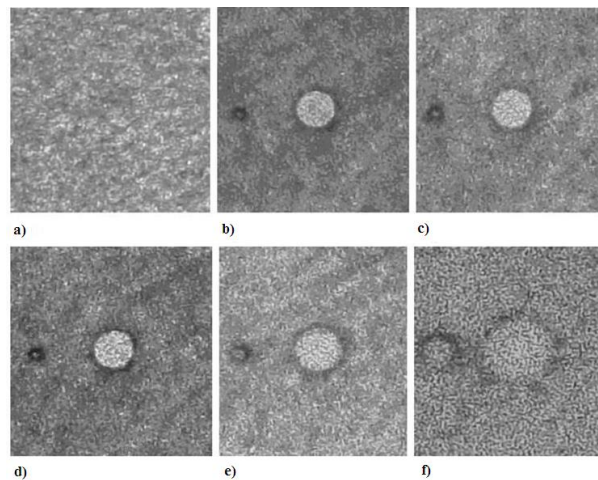

Figure 2. Visualization of transparent object with phase shift $\lambda/2$ using a liquid cell (alcohol doped with iodine) as a function of power of laser radiation. Circle diameter d = 150 μm.

Visualization of a phase object (grating) by means of a linear filter with a step 265 nm high in the Fourier-plane of the lens is depicted in fig. 3. Structures for measurements were formed by the method of electron-beam lithography from thin PMMA 950 films deposited on fused silica or glass substrates. The structure was exposed on the SUPRA 50VP (Carl Zeiss) electron microscope equipped with a system for electron lithography ELPHY PLUS. At the finishing stage, the required relief depth (PMMA film thickness) was obtained by means of dry etching in oxygen plasma.

The relief depth was controlled either by an atomic force microscope or by the optical interference microscope Talysurf CCI 2000. As follows from fig. 3, the image obtained with a photothermal filter is free from false structures caused, in particular, by boundary effects arising during alignment of a Zernike phase disk with a diameter of 150 μm.
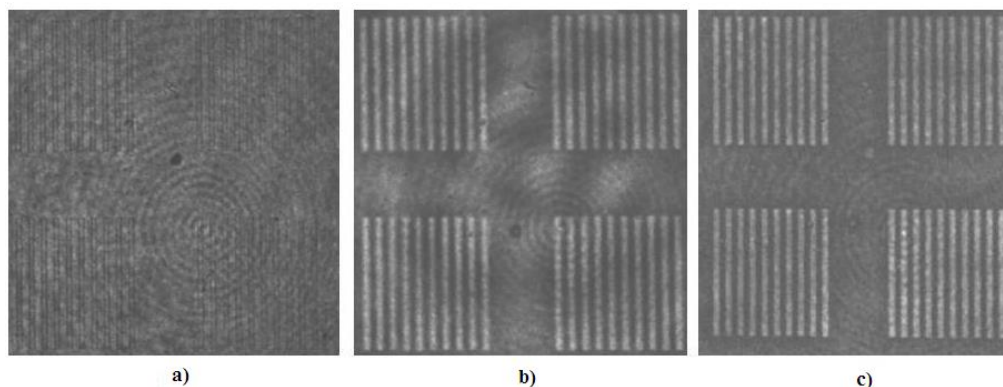
Figure 3. Visualization of a phase object by means of linear and a photothermal filters: a) without filters, b) linear filter (Zernike disk) placed in the Fourier-plane, c) photothermal filter also placed in the Fourier-plane.

Direct and inverted microimages of the abbreviated names of the institutions with which the authors of the paper are affiliated are presented in fig. 5. The height of the letters is 30 μm. The images were obtained on a 2 mm thick polymer plate used as photothermal filter.

Figure 5. Direct and inverted microimages of the name of the institutions. Letter size 30 μm.

The visualized image of the growth-sector boundary in a nonlinear KDP crystal is shown in fig. 6. Such a boundary was earlier recorded by the schlieren method and by the fluorescence technique in the works [26, 27].
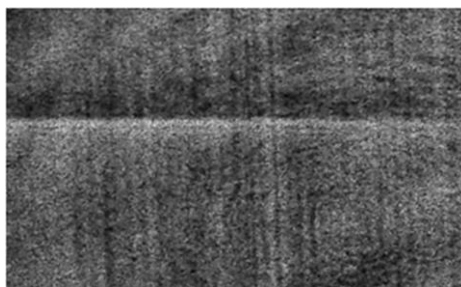

Figure 6. Image of growth-sector boundary in KDP crystal.

3. Conclusion

To conclude, we have registered good-quality images of transparent objects and structures and also inverted images of nontransparent objects using a simple phase-contrast technique. Model objects as well as an intersectorial boundary in a nonlinear KDP crystal have been visualized.

References

[1] Fransson M 1952 *Phase-contrast and interference microscopes* (Paris: Revue d'Optique)

[2] Vorontsov M A., Koryabin M A, Shmalgausen V I 1988 *Controlled optical systems* (M.: Nauka) [in Russian]

[3] Davydenko V I, Ivanov A A, Weissen G 1999 *Experimental methods of plasma diagnostics. The Lecture. Part 1* (Novosibirsk, NSU) [in Russian]

[4] Chernega N V, Brekhovskikh G L, Kudryavtseva A D, Kirsanov B P, Sokolovsky A I 1989 *Quantum.electronics* **16** 2530

[5] Goy A, Psaltis D 2011 *Physical Review A* **83**, 031802(R)

[6] Zhengyan L., Chih-Hao P., Yen-Yu C. 2013 *Optics Letters* **38 (23)** 5157

[7] Bubis E L, Korytin A I, Stepanov A N, Malkov Y A, Arsenev A A, Yashunin D A 2015 *Proceedings of the XIII International conference "OMFI -2015"* (Moscow) p 152

[8] Iturbe Castillo M D, Sanchez-de-la-Llave D, Ramos Garcıa R, Olivos-Pérez L, González L A, Rodríguez-Ortiz M. 2001 *Optics Engineering* **40 (11)** 2367.

[9] Treviño-Palacios C G, Iturbe-Castillo M D, Sánchez-de-la-Llave D, Ramos-García R, Olivos-Pérez L I 2003 *Applied Optics* **42** 5091

[10] Liu J, Xu J, Zhang G, Liu S 1995 *Applied Optics* **34** pp. 4972-4975

[11] Vorontsov M A, Justh E W, Beresnev L A. 2001 *J. Opt. Soc. Am. A* **18** 1289

[12] Bubis E L, Budagovsky I A, Zolot'ko A S, etc. 2016 *Pribory i tekhnika experimenta* **4** 4

[13] Porras-Aguilar R, Ramirez-San-Juan J C, Baldovino-Pantaleon O, May-Arrioja D, Arroyo Carrasco M L, Iturbe Castillo M D, Sánchez-de-La-Llave D, Ramos-Garcia R 2009 *Optics Express* **17 (5)** 3417

[14] Yu M, Vorontsov M A 2005 *Proceedings of SPIE*, **5998**

[15] Yelleswarapu C S, Kothapalli S, Aranda F J and Rao D V G L N 2006 *Appl. Phys. Lett.* **89**

[16] Yelleswarapu C S, Kothapalli S, Rao D V G L N 2008 *Optics Communications* **281** 1876

[17] Bubis E L 2008 *Technical Physics Letters* **34 (6)** 510.

[18] Pavlov A, Pavlov A, Golubev M. 2012 *16th Int Symp on Application of Laser Techniques to Fluid Mechanic* (Lisbon, Portugal)

[19] Kurian P A and Vijayan C 2009 *Applied Optics* **48 (28)** 5259

[20] Komorowska K, Miniewicz A, Parka J, Kajzar F. 2002 *J.of Appl.Phys.* **92** 5635

[21] Bubis E L 2011 *Quantum electronics* **41 (6)** 568.

[22] Bubis E L, Matveev A Z 2012 *Quantum electronics* **42 (4)** 361

[23] Bubis E L, Gusev S A, Loshkarev V V, Kozhevatov I E, Martynov V O, Silin D E, Stepanov A N 2014 *Instruments and Experimental Techniques* **57 (5)** 620

[24] Bubis E L, Gusev S A, Kozhevatov I E, Martynov V O, Mamaev A Yu, Sergeev A S 2012 *Prikladnaya fizika* **5**, 16

[25] Bubis E L, Gusev S A, Kozhevatov I E 2013 *Uspekhi prikladnoi fiziki* **1(4)** 408

[26] Pommie`s M, Damiani D, Le Borgne X 2007 *Optics Communications* **275** 372

[27] Chang J, Zhao Y, Hu G, Wang Y, et al 2015 *Chinese Optics Letters* **13 (8)** 081601