Application of polarization interferometry to plasma diagnostics

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Abstract. Polarization interferometer has some significant advantages over beam-splitting ones in a wide range of applications. Most of restrictions in interferometry regarding to optical elements quality and vibration protection can be neglected in Nomarski scheme, it is easy in alignment and allows studies in a broad spectral range without the replacement of mirrors. We present a description of two- and three-wavelength polarization interferometers and a technique for measurement of transparent media optical properties with high spatial (~ 10 μm) and temporal resolution (~ 10 ns) in UV-NIR (~ 380-900 nm) spectral range. As a result, atom and electron number densities have been evaluated in the case of about equal input of each of these components in refraction index change. Application of the proposed scheme to birefringent objects can be limited, but it also provides abilities to visualize strong electric and magnetic fields due to electro- and magneto-optical effects.

1. Introduction
Optical methods are widely used to study kinetics of chemical reactions and dynamics of inhomogeneous media. Widely used spectrophotometers have low temporal (10³–10⁻¹ s) and no spatial resolution. For partial elimination of these shortcomings, polychromators can be used, incl. those with imaging diffraction gratings. Anyway, these devices are recording transmission (absorption) only; additional data on refractive index can significantly increase output of the study. Obtaining both optical constants is possible with partial overlapping of ordinary and extraordinary rays in a polarization interferometer, when the interference and absorption patterns of the region of interest are formed. The most common scheme of polarization interferometer is Nomarski differential interference-contrast microscope [1]. However, it was suggested to visualize phase shifts much smaller than wavelength and does not allow evaluating absorption and refractive indices for macroscopic objects.

To study the dynamics and macrostructure of laser-induced plasma flows, the following three methods are most often used: emission spectroscopy, interferometry and shadowgraphy (absorption photography). Each of these methods has its own advantages and disadvantages, and serves to record different, but partially overlapping, characteristics of such flows. Instability of impact radiation parameters and local properties of the target imposes a number of limitations on the processing of experimental results recorded under separate impacts, albeit under similar conditions. To eliminate these limitations, simultaneous application of several experimental techniques is desirable for the subsequent complex processing of the results obtained [2].
Emission spectroscopy, incl. LIBS, has been developing rapidly as an analytical technique, and led to release of commercial spectrometers for data recording with high temporal and spectral resolution. Interferometry, if obtained results are processed properly, is also a very informative technique [3]. But its high sensitivity is demanding to quality of the optical elements used and optical system vibration isolation. In some cases, additional alignment is required when buffer gas pressure changes in the experimental volume, especially if the mirrors (for example, due to lack of space) are located outside the gas cell or vacuum chamber. Proper (interferometric) quality wide-aperture windows for hermetic volumes, beam-splitters and mirrors are expensive. The quality requirements for optical elements can be significantly reduced for polarization interferometer [4-6]. Since probing beam is split into orthogonally polarized components close to the sensor, the distortion of the recorded interference pattern by optical elements is minimized.

The sensitivity of interferometers to vibrations can be significantly reduced by using short and ultrashort pulses of probing laser radiation [7]. An important problem in the implementation of beam-splitting interferometers with ultrashort probing pulses (especially for long paths) is matching spatial and temporal coherence, simultaneous pulses arrival, which requires high-precision linear motors for optical shoulders difference compensation. This problem is easily eliminated in polarization interferometer, since split beams optical paths difference is minimized and could be easily adjusted by the Wollaston prism inclination.

The disadvantage of the described scheme for randomly polarized sources is a relatively high radiation power (> 50 mW) required, since it is necessary to select only components that are linearly polarized at an angle of 45°. The advantages of this scheme are especially evident in multi-wavelength interferometer, an example of which is given below. For birefringent objects, the application of the proposed scheme can be limited, but also provides abilities to visualize strong electric and magnetic fields [8] due to corresponding electro- and magneto-optic effects.

2. Experimental layout
The principle of the interferometer (figure 1) is as follows. The probing radiation of DPSS lasers 1-3 (Lasever LSR 405NL-300, LSR 532NL-300, LSR 671NL-300), linearly polarized at 45° using half-wave plates, passes through the optical inhomogeneity in a single beam (unlike the classical Nomarski scheme). After that it is separated in a Wollaston prism 11 into two divergent beams (in our case, at an angle of ~10°, the angle is chosen according to the size of the region of interest). One of these beams is polarized vertically, and another one – horizontally. The distance between axes of the ordinary and extraordinary rays in the plane of the sensor can be changed (with an equal scale of the image) in proportion to the focal length of the lens 10. The Wollaston prism 11 is located near the focus of the lens 10, change in its position affects period of the interference pattern. This period is determined by probing wavelength and distance from the prism 11 to the sensor 13, 14 divided by the product of the angle of ordinary and extraordinary beams divergence and the distance between focusing lens 10 and the prism 11 [9]. Easy period adjustment is very convenient for photoelectric mixing interferometers.

Using achromatic (Edmund Optics NT46 55x Δλ ~ 200–300 nm) or tunable (zero order, e.g., Alphalas PO-TWP or liquid-crystal series, e.g., Thorlabs LCC series) half-wave plates 4-6, tunable lasers could be used without the replacement of optical elements and adjustments similarly [8]. Interference pattern is formed in the area of ordinary and extraordinary beams overlap, after passing through the Wollaston prism. Since the orthogonally polarized components do not interfere with each other, it is necessary to align the polarization plane of both beams again at 45° by rotating the polarization filter 12 to approximately equal intensity in both beams, and so, maximum contrast of the interference pattern. A shadowgraph (absorption photo) of the investigated region is formed outside the overlapping region (figure 2).

Color CCD camera (Videoscan-205/C-USB) allows to use a single sensor, because blue (400–450 nm), green (530–570 nm), and red (610–670 nm) colors can be easily extracted from the resulting image (Figure 3), providing the possibility of selecting resonant absorption bands in each of these ranges. In the case of insufficient sensitivity of usual CCD or in need to achieve high temporal
resolution using continuous lasers, intensified cameras, e.g., based on microchannel plates (Nanoscan Nanogate-2) can be used. For single sensor registration, it is necessary to separate probing beams with an optical wedge located before the Wollaston prism. The advantages of such a solution are especially obvious when there is no need in 2D spatial resolution — using a broadband coherent radiation source (e.g., Fianium laser) a number of spectral intervals of interest can be cut out by slit diaphragms. The boundaries of 380–900 nm working spectral range are determined by the characteristics of the commercially available CCD’s (190–1100 nm), optical elements of the scheme (350–2200 nm) and commercial laser diodes or DPSS lasers (365–971 nm), and could be expanded.

![Diagram 1](image1.png)

**Figure 1.** Optical schemes of experimental installations based on a polarization interferometer with monochrome and color sensors lasers: 1–405 nm, 2–532 nm, 3–671 nm; half-wave plates: 4–350–500 nm, 5–532 nm, 6–600–800 nm; 7–telescope, 8–vacuum chamber window, 9–object, 10–collecting lens, 11–Wollaston prism, 12–polarization filter, 13–CCD camera with image intensifier, 14–color CCD camera, 15–vacuum chamber, 16–color filter.

![Diagram 2](image2.png)

**Figure 2.** To the formation of shadowgraph (4) and interferograph (5) images: 1 – probing beam, 2 – optical inhomogeneity, 3– Wollaston prism.

The refractive index resolution is determined not only by the features of the optical scheme, but also by the algorithm of the interferographs processing, and can reach $\delta \Delta n L \approx \lambda / 200$ [7] (where 200 characterizes the discreteness of the phase shift detection), i.e., for the optical path $L \approx 10$ mm in the standard photometric cell it will be $\delta \Delta n \approx (1-4) \cdot 10^{-7}$. The upper limit of the refractive index value measured is limited only by the absolute deviation of the probing beam (it is important for large optical paths and small transverse dimensions of the sample); for automated processing, it is undesirable for the phase shift to exceed $2\pi$ [2]. Resolution on the absorption index is determined by the dynamic range of the sensor used (usually in the range from 8 to 14 bits), the instability of the
spatial distribution of the radiation brightness along the profile of the probing beam and the optical path length; for the standard cell it is \( \delta \alpha \sim (1-4) \cdot 10^{-3} \text{ cm}^{-1} \). It should be noted that these resolutions are mostly determined by random errors caused by fluctuations in the intensity of the probing radiation, CCD noise, convective currents, etc. These errors values and statistical processing capabilities should be evaluated for each particular installation. The limiting time resolution is determined by the duration of the probe radiation pulse \( \sim 10^{-14} - 10^{-13} \text{ s} \) or the exposure time of the camera (for usual CCD cameras \( \sim 10^{-5} - 10^{-6} \text{ s} \), with MCP \( \sim 10^{-9} - 10^{-8} \text{ s} \), streak-cameras \( \sim 10^{-13} \text{ s} \)).

3. Results and discussion

Interferometry in plasma physics is used primarily to study the electron number density distribution by local refractive index analysis, which causes the phase shift of the probing radiation wave front. This approach is limited by the fact that the change in the refractive index depends not only of electrons but also of atoms and ions [10], experimental establishing of each of these components influence is possible with multi-wavelength interferometry only [11].

As a result of processing using fast Fourier transform algorithm, the spectral refractive indices obtained in different color channels of interferograms of colliding laser-induced plasmas (Figure 4). The values obtained are substantially different for different wavelengths. The characteristic values of electron concentrations for 405 nm and 671 nm are determined respectively as: \( 2,4 \cdot 10^{18} \text{ cm}^{-3} \) and \( 4,5 \cdot 10^{17} \text{ cm}^{-3} \). This difference occurs because the contribution of electrons to the refractive index formation not predominant \( (n-1)_{e}/(n-1)_{a} \sim 1 \) in the considered case. When the results obtained for both wavelengths are processed simultaneously, the characteristic value of \( n_{e} \) is \( \sim 1.1 \cdot 10^{18} \text{ cm}^{-3} \), and the concentration of atoms is \( n_{a} \sim 2,3 \cdot 10^{19} \text{ cm}^{-3} \).

![Figure 3](image)

**Figure 3.** The use of a color CCD camera in a multi-wavelength interferometer: a – the recorded image; b, c, d – blue, green and red channels, respectively.

4. Conclusions

A multi-wavelength, tunable in a wide spectral range, polarization interferometer for simultaneous recording of spectral refractive and absorption indices of optically inhomogeneous media with high spatial and temporal resolution was developed and implemented for the first time. Features of the optical scheme described can significantly reduce its sensitivity to optical elements quality, vibrations, and simplify the alignment, especially when using ultrashort probing laser pulses.
Figure 4. The distribution of the refractive index change relative to the initial for 405 nm (a) and 671 nm (b)

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