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Using a Multimode Laser in Interferometry of Ultrasmall Phase Inhomogeneities

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Abstract—We describe a method for measuring the concentration of low-density gas jets with the aid of a multibeam optical interferometer. Sensitivity with respect to optical thickness distortions achieved in experiments was on a level of λ/600. The proposed method is well suited for the calibration of gas targets used in experiments on laser–plasma interactions.

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In recent years, extensive investigations have been devoted to the interaction of superhigh-power laser radiation pulses with plasma. In this context, the development of approaches to creation and measurement of plasma concentration profiles necessary for studying laser–plasma interactions is a topical task. High concentrations (on a level of 10^{21}–10^{22} cm^{-3}) are necessary for accelerating ions [1] and generating attosecond light pulses [2], while low concentrations 10^{18}–10^{19} cm^{-3} are required in experiments for accelerating electrons [3–6], generating soft X-ray pulse trains [7], etc. It is convenient to study laser–plasma interactions using dynamic distributions of plasma concentration with large gradients. In the range of low concentrations, these gradients can be obtained in vacuum using gas jet nozzles of various profiles [8, 9].

The present work was aimed at studying the possibility of using the multibeam optical interferometry technique based on a multimode laser radiation source for measuring small phase distortions caused by a low-density (~10^{18} cm^{-3}) gas jet. The results of our experiments confirmed that small phase distortions induced by a low-density (~10^{18} cm^{-3}) gas jet can be reliably measured by the method of multibeam interferometry with the aid of a multimode laser.

Let us consider a He–Ne laser generating in a wavelength region of λ_0 = 632.7 nm, representing a Fabry–Perot resonator of length L_0 filled with the active medium (Fig. 1). Longitudinal modes of this resonator correspond to wavelengths obeying the following condition of phase synchronism at the output mirror:

$$\lambda_0 n = 2L_0, \quad n = 1, 2, 3\ldots \tag{1}$$

If the spectrum of the operating transition is broadened to a value on the order of or greater than the spectral distance between adjacent longitudinal modes of the laser cavity, the generation takes place on several wavelengths (Fig. 2a). Consider the generation on two wavelengths, λ_0 and $\lambda_0 + \Delta\lambda$ with mode numbers n_0 and $n_0 - 1$, which obey the conditions

$$\lambda_0 n_0 = 2L_0, \tag{2}$$

$$(\lambda_0 + \Delta\lambda)(n_0 - 1) = 2L_0. \tag{3}$$

These expressions yield the following relation:

$$\Delta\lambda = \frac{\lambda_0}{(n_0 - 1)} \approx \frac{\lambda_0^2}{2L_0}. \tag{4}$$

In the proposed scheme, radiation with wavelengths λ_0 and $\lambda_0 + \Delta\lambda$ is incident onto a multibeam interferometer of length L_1 (Fig. 1), which consists of two identical semitransparent mirrors with reflection coefficients R_1 (referred to below as the reference surfaces). Interferometer finesse F_1 is defined as [10]

$$F_1 = \pi\frac{\sqrt{R_1}}{(1 - R_1)}. \tag{5}$$

The incident radiation passes through the interferometer provided that its length L_1 obeys the condition of phase synchronism for at least one of the He–Ne laser generated wavelengths:

$$\lambda_0 m_1 = 2L_1, \tag{6}$$

$$(\lambda_0 + \Delta\lambda)m_2 = 2L_1. \tag{7}$$

During monotonic variation of interferometer length L_1, the condition of synchronism is sequentially obeyed for wavelengths λ_0 and $\lambda_0 + \Delta\lambda$.

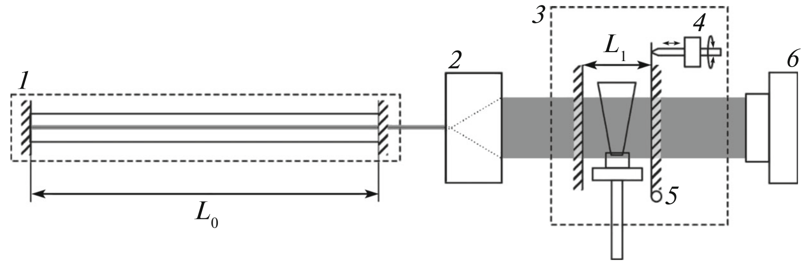

Fig. 1. Schematic diagram of the proposed technique: (*1*) laser cavity, (*2*) telescope, (*3*) vacuum chamber, (*4*) motor-driven actuator, (*5*) rotation axis, and (*6*) CCD camera.

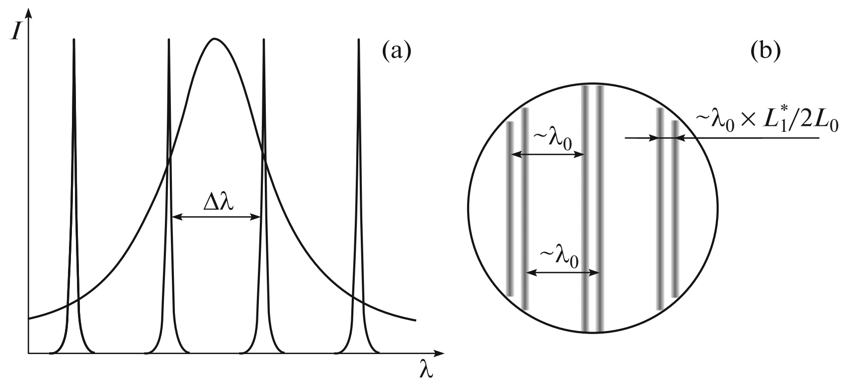

Fig. 2. (a) Spectra of the resonator and operating transition of a He–Ne laser; (b) topology of the corresponding interference pattern at the output of the multibeam interferometer.

In the case of moderate nonparallelism of the reference mirror surfaces, the multibeam interference will result in a pattern of fringes observed at the interferometer output (Fig. 2b), where the fringe width is F_1 times smaller than that for the interference of two waves. Since the laser generation proceeds on two wavelengths, the interference pattern will consist of two groups of equidistant fringes. The distance between fringes in each group will correspond to unit change in the interference order ($\Delta m = 1$), which corresponds with good accuracy to a change by $\lambda_0/2$ in the optical pathlength between reference mirrors.

Consider the case of L_1^* such that $L_1^* < L_0/2$ and obeys the conditions of synchronism for λ_0. Then, the value of ΔL_1, by which the interferometer length must be increased in order to pass to the neighboring maximum (corresponding to the synchronism for $\lambda_0 + \Delta\lambda$), can be determined as

$$L_1^* \frac{\Delta\lambda}{\lambda_0} = \Delta L_1. \quad (8)$$

Using this expression and taking into account formula (4), we arrive at then following relation:

$$\frac{L_1^*\lambda_0}{2L_0 - \lambda_0} = \Delta L_1 \approx \lambda_0 \frac{L_1^*}{2L_0}. \quad (9)$$

Thus, the relative position of the two groups of interference fringes depends on the ratio of interferometer length L_1 and laser cavity length L_0 (Fig. 2b).

Since the character of fringes fully corresponds to that observed in the Fizeau interferometer, the method of determining phase distortions can also be analogous and based on the deviation of interference fringes [10]. Phase distortion Δh caused by a gas jet produces a shift of fringes by Δm orders. Since these changes are related as

$$\Delta h = \frac{\lambda}{2}\Delta m, \quad (10)$$

the Δh value can be determined once Δm is evaluated. The Δm value is approximately equal to the ratio of a fringe shift to the distance between neighboring fringes in the group. If the shift is equal to the relative displacement between two groups, then

$$\Delta h = \frac{\lambda}{2}\frac{L_1}{L_0}. \quad (11)$$

The sensitivity of interferometric measurements is usually estimated [10] in terms of brightness. For example, if the instrument can detect changes in the brightness of transmitted light of about one-tenth of the difference between fringe maximum and background, this change corresponds to a sensitivity of 4 Å

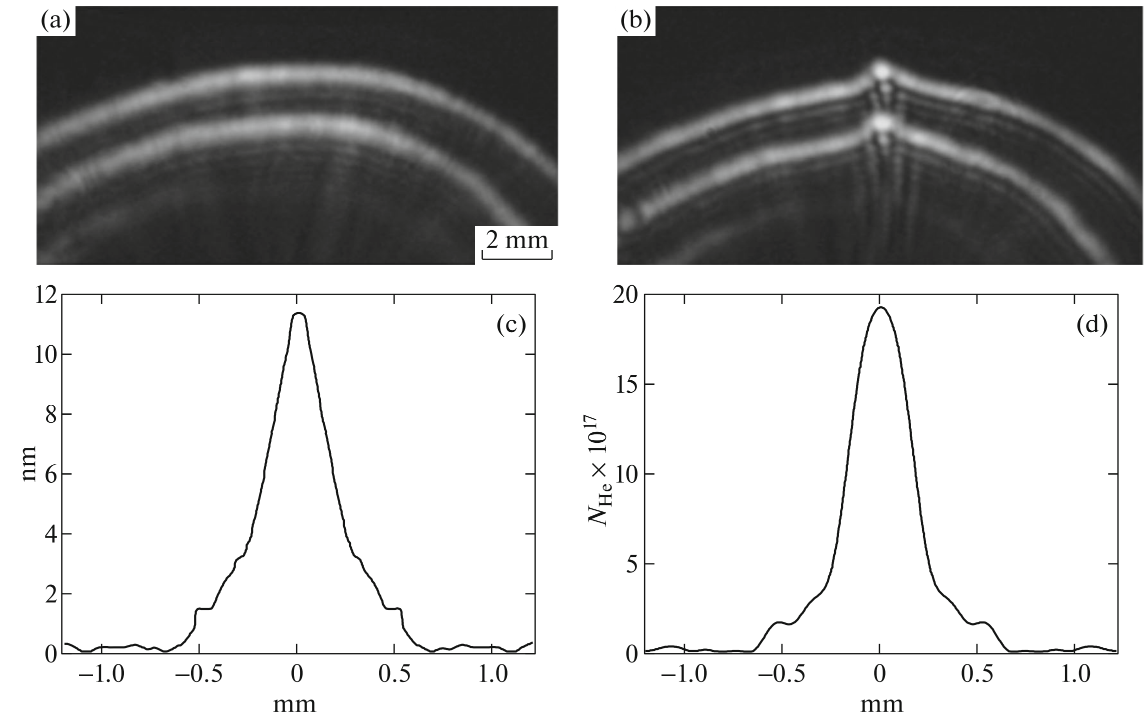

Fig. 3. Interference patterns observed in experiments (a) without and (b) with helium jet and the corresponding profiles of (c) optical thickness and (d) helium concentration in the jet.

at 632.7 nm wavelength and a finesse of about 40. Of course, this sensitivity is only achieved in the region of maximum spatial gradient of the interference fringe intensity. For measuring the entire spatial field of phase distortions, it is necessary to vary either the probing radiation frequency or interferometer length L_1. Technically, this can be readily done by moving mirrors either in the laser cavity or in the interferometer.

Model experiments were performed with a multibeam interferometer arranged in a vacuum chamber, which comprised two glass wedge plates with almost parallel surfaces spaced by $L_1 = 25$ mm. The reference surfaces were covered by an antireflection interference coating with a transmission coefficient of about 8% at 632.7 nm. A gas jet nozzle with 2-mm output diameter and high-speed valve was arranged in the gap between plates. The axisymmetric conical nozzle emitted an axisymmetric helium jet. The jet was probed by collimated radiation of a He–Ne laser with a 30-mm output aperture, which operated in a regime of generating two or three longitudinal modes of the cavity. The difference of generated mode wavelengths was determined by length $L_0 = 350$ mm of the laser cavity and amounted to ~0.57×10^{-2} Å. This value is insignificant for most double-beam interferometer applications, but it led to the appearance of a "multiplet" system of fringes in the system studied. The ratio of the laser cavity to interferometer lengths was $L_0/L_1 \approx 14$, so that a shift of the interference fringe by a value corresponding to distance between adjacent fringes in the multiplet corresponds to phase distortions on a level of $\lambda/2/14 \approx 23$ nm.

The interference pattern observed in experiment without a gas jet (Fig. 3a) represents a fragment of the set of concentric rings (in the depicted geometry, the gas jet is directed downward). Figure 3b shows phase distortions induced by the gas jet. The curvature of interference fringes is oriented toward the nozzle and reaches a maximum on the axis of jet symmetry, where the concentration of emitted gas is at maximum. The corresponding shape of phase inhomogeneity is presented in Fig. 3c, while Fig. 3d presents the profile of gas concentration in the jet reconstructed using the Abel transform with allowance for the jet symmetry. It should be noted that, in the case of using a cw laser, the temporal resolution is determined by the CCD camera exposure time, which can be readily reduced to several microseconds.

In concluding, we have described an extremely high sensitivity method for determining the concentration profile of gas jet by measuring the related phase distortions with the aid of a multibeam optical interferometer. Our experiments showed the possibility of measuring the gas concentration distribution in a low-density helium jet at the spatial resolution on a level of 1 mm. The gas concentration measured was about ten times lower than the limiting level, which admits the use of traditional interference techniques such as a

Michelson interferometer, Mach–Zehnder interferometer, etc. The sensitivity with respect to phase distortions achieved in experiments was on a level of λ/600 (~1 nm). The proposed method was successfully used in experiments on laser-induced fast electron beam generation [11].

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