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Fiber-based multichannel heterodyne interferometer for studying the pulsed plasma properties

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A fiber-based four-channel heterodyne interferometer has been developed to study the properties of pulsed plasma. The accuracy of phase measurements was 0.03 rad, which corresponds to an error in measuring the concentration of free electrons of $\pm 1 \cdot 10^{19}\,\mathrm{m}^{-2}$. Measurements of the electron density and plasma velocity of the plasma accelerator have been carried out..

Keywords: laser interferometer, fiber-based interferometer.

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Laser interferometry is one of the most widely used and accurate methods for electron density measurements. It does not perturb plasma and provides an opportunity to estimate the number of free electrons without the use of complex analytical models [1]. With multichannel recording, one may switch from integrated measured quantities to local ones and estimate the plasma velocity [2]. Heterodyne interferometry is used to enhance the accuracy of measurement of the concentration of free electrons in plasma [3].

The IR range is considered to be the optimum one in balancing accuracy and ease of use. CO_2 lasers are used most often as diagnostic light sources. However, photodetectors operated in the middle IR range require cooling, and traditional optical materials, such as quartz and glass, are inapplicable in this range. If one switches to a diagnostic wavelength of $1.5\,\mu$m, it becomes possible to use a wide range of fiber circuitry and fiber sources of laser radiation, which ensure versatility and scalability of the instrumentation system. Thus, the wavelength of $1.5\,\mu$m is a reasonable compromise between visible and near IR ranges, since it offers high sensitivity and is not fraught with the typical difficulties of measurement in the near IR range. A multichannel heterodyne interferometer operating at $1.5\,\mu$m was designed for plasma diagnostics at various types of plasma systems.

The measurement system based on a fiber heterodyne interferometer features four diagnostic channels and two units (diagnostic unit and power supply). The power supply is intended to provide 6 h of autonomous operation. The diagram of the diagnostic unit is presented in Fig. 1. Elements within the dashed contour are mounted inside its case. The rack-mounted 2U Eurocard diagnostic unit is $437 \times 132 \times 420$ mm in size.

The system is designed to be operated with single-frequency 1550 nm continuous-wave fiber laser radiation source *1* (the lasing spectrum width is below 1 kHz). In the present study, we used an R56-L2605RE laser produced by VNIITF with its optical output power adjustable within the range from 40 mW to 2 W.

Light is introduced into single-mode beam splitter BS and is split in a ratio of 0.1/0.9 of the input power between the reference and diagnostic arms of the interferometer. Fiber acoustooptical modulator *2* is mounted in the reference arm. A reference variable signal with frequency $f = 40$ MHz is fed to it from generator *3*. Module *4* with a fiber attenuator and a power meter is mounted in the reference arm to monitor the contrast of the interference pattern. The attenuator provides an opportunity to adjust the radiation intensity within the range from 0 to 32 mW. Collimators *5* and *6* are used for radiation coupling.

The obtained signal is fed to a photovoltaic converter board that features an I/Q demodulator as its key component [4]. The detected optical signal is converted into a pair of quadrature analog signals, which are used to derive the time dependence of phase and are subsequently corrected [5].

The time resolution of the interferometer in measurements of phase incursions smaller than 2π is set by the band of the photodetector or filters [3]. In the present case, the detection band is restricted by the low-pass filter in the 2 MHz range. Thus, the limit time resolution of the interferometer in the present configuration is 170 ns.

Having analyzed the noise level in the measurement channel, we estimated the error of phase measurements at 0.03 rad, which corresponds to an error of $\pm 1 \cdot 10^{19}\,\mathrm{m}^{-2}$ for measurements of the liner electron density.

Four-channel measurements of the spatial distribution of electron density in the plasma flow at a plasma accelerator were performed next. The experimental set-up and the obtained results are presented in Fig. 2. Four pairs of collimators were positioned above each other at a distance of 25 mm. The plasma flow interacted with radiation from diagnostic channels. The maximum measured linear electron density was $7.5 \cdot 10^{20}\,\mathrm{m}^{-2}$ at $t = 637\,\mu$s. The measurement system revealed a nonuniformity of the concentration of

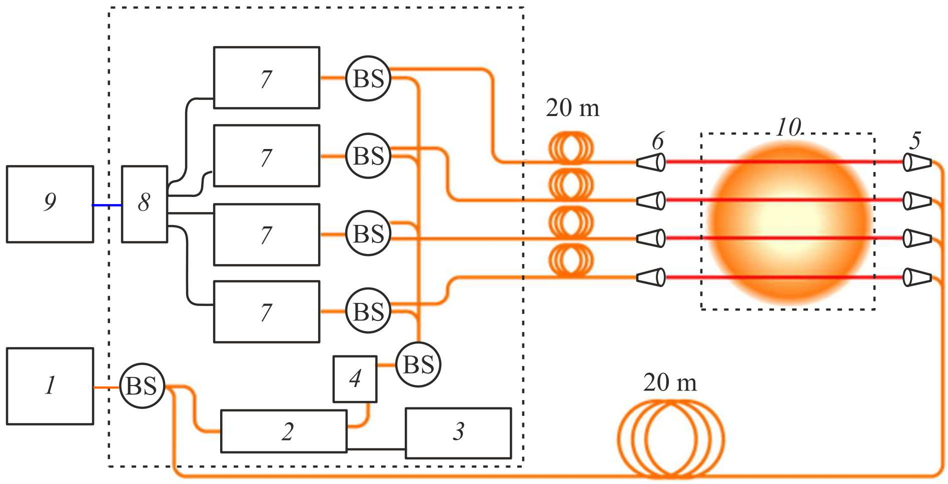

Figure 1. Diagram of the system for measurement of the electron density of plasma based on a fiber heterodyne interferometer. *1* — Fiber laser with diode pumping, *2* — acoustooptical modulator, *3* — generator of signals with $f = 40$ MHz, *4* — attenuator and power meter module, *5* – Thorlabs CFC11P-C collimators, *6* — Thorlabs F220APC-1550 collimators, *7* — optoelectronic converter board with a low-noise bandpass intermediate-frequency amplifier, *8* — Ethernet module, *9* — PC, and *10* — vacuum chamber.

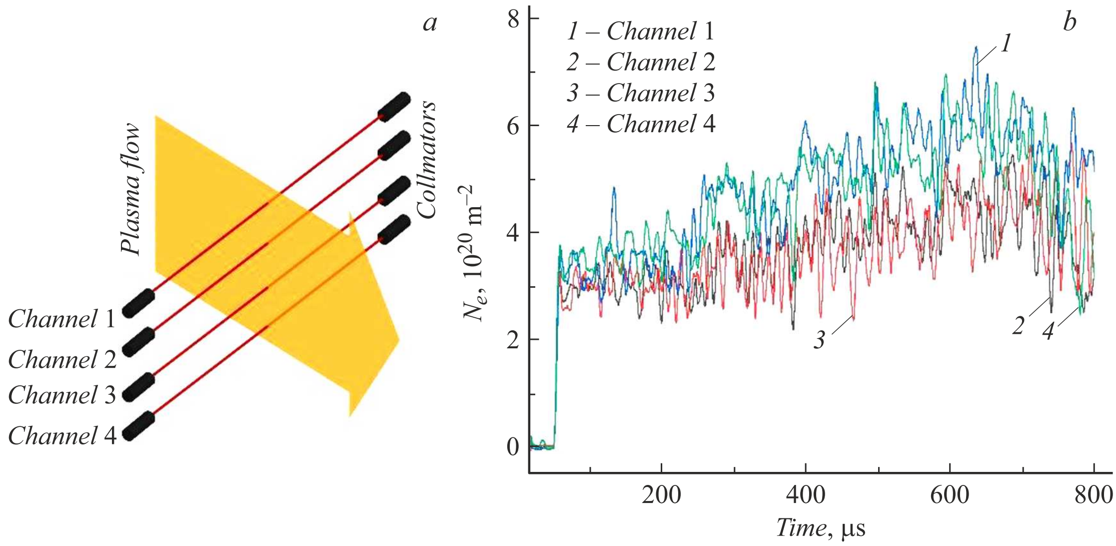

Figure 2. *a* — Experimental set-up; *b* — measured electron density of hydrogen plasma.

free electrons in the cross section of plasma (Fig. 2, *b*) and pulsations of the electron density of plasma with a characteristic time on the order of 20 μs.

Two measurement channels positioned horizontally one after another (at a distance of 100 mm) in the direction of propagation of the plasma flow were used in the next experiment. The results of these electron density measurements are shown in Fig. 3. It can be seen that characteristic concentration variations are discernible in both detection channels. It is safe to say that the motion of plasma „bunches" is observed The flow velocity may be determined during almost the entire period of existence of this flow by measuring the interchannel detection delay for a certain „bunch." The time of flight was estimated by the distance between the characteristic extrema of plots. The measured velocity values for several characteristic peaks are listed in the table.

Results of measurement of the plasma flow velocity at four chosen points

Parameter	Point number			
	1	2	3	4
Velocity , km/s Time, μs	65 ± 3 188	52 ± 3 397	72 ± 3 458	34 ± 3 602

The velocity determination error is a composite of the error of distance between collimators and the error of

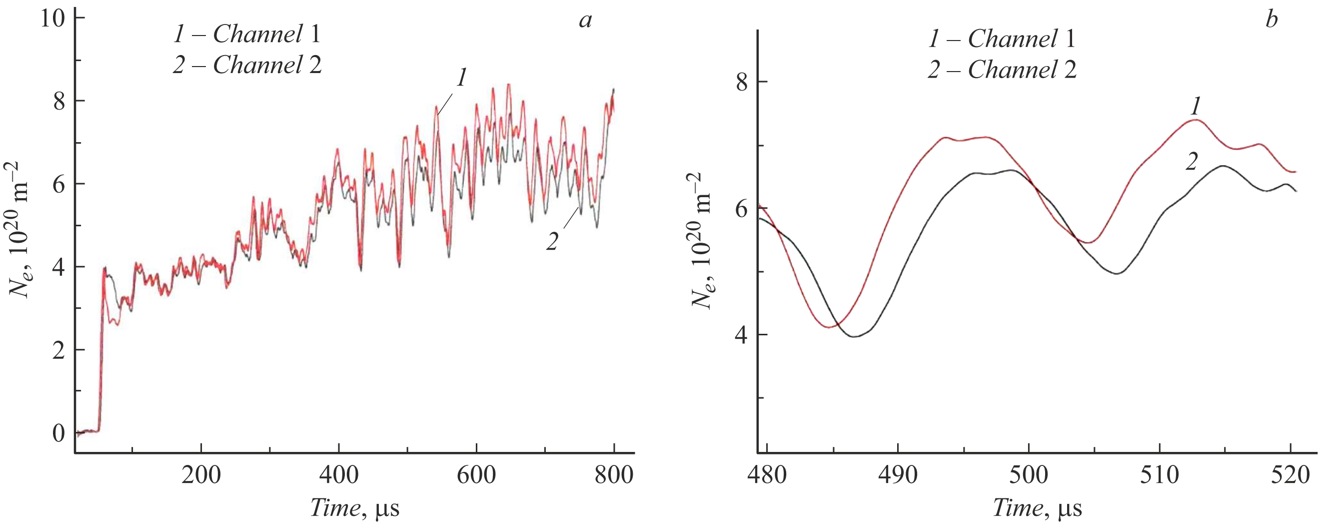

Figure 3. *a* — Results of measurement of the linear electron density of hydrogen plasma. The time-of-flight detection method was used to estimate the flow velocity. *b* — Enlarged section of the plot within the 480–520 μs interval.

determination of a local extremum of the electron density pulsation.

The propagation velocity of the plasma flow front may be estimated by timing its arrival into the detection region of the first channel. This velocity was $V = 20 \pm 3$ km/s at $t = 49\,\mu$s. The indicated value differs significantly from the velocity of the bulk of plasma (see the table). This discrepancy is attributable to the specifics of discharge initiation in the accelerator. Thus, when used for measurements of the plasma velocity, several electron-density detection channels positioned one after another provide an opportunity to determine the flow velocity during almost the entire period of existence of this flow.

Thus, a fiber heterodyne interferometer for pulsed plasma diagnostics was designed and tested. It allows one to perform multichord measurements of the concentration of free electrons in the plasma cross section and determine the velocity of a flow during almost the entire period of its existence. The intrinsic noise level is 0.03 rad, which corresponds to $\pm 1 \cdot 10^{19}\,\mathrm{m}^{-2}$. The maximum measured linear electron density of hydrogen plasma was $7.5 \cdot 10^{20}\,\mathrm{m}^{-2}$. Plasma flow velocities within the range from 20 ± 3 to 72 ± 3 km/s were measured.

The use of this multichannel fiber interferometer allowed us to determine the concentration distribution of free electrons in plasma, detect pulsations with characteristic times on the order of $20\,\mu$s, and measure the plasma flow velocity.

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Conflict of interest

The authors declare that they have no conflict of interest.

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