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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

ON SOME NEW EFFECT OF LASER RAY PROPAGATION IN ATMOSPHERIC AIR

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The laser beam space uncertainty σ was measured during ray propagation in atmospheric air (*a*) and in atmospheric air inside the tube (*t*) with both ends closed by optically transparent windows. For the studied case of the 70 m passed distance, the sigma values were discovered to differ greatly: $\sigma_a/\sigma_t \approx 100^x$. The observed effect may represent a physical basis for the creation of an extended laser ray to be used as a coordinate axis in the high-precision metrology when assembling a big-length research equipment (accelerators, detectors, etc.) or in civil engineering tasks.

Были измерены неопределенности положения лазерного луча σ при распространении его в атмосферном воздухе (*a*) и в атмосферном воздухе внутри трубы (t), оба конца которой закрыты оптически прозрачными окнами. В исследованном случае прохождения расстояния 70 м обнаружено значительное различие сигма-величин: $\sigma_a/\sigma_t \approx 100^x$. Обнаруженный эффект может быть физической основой для создания протяженной координатной оси в прецизионной метрологии больших расстояний (сооружение ускорителей, детекторов и т. д.) и в задачах гражданского строительства.

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INTRODUCTION

Construction and operation of large-scale research facilities for TeV energies (accelerators, colliders, detectors) require high accuracy both in relative «alignment» of the main structural elements and in the on-line adjustment in the course of operation. A stable extended coordinate axis with respect to which all the required changes and adjustments are made is necessary for precise geodesic support of the above tasks. A laser beam can be used as this axis.

As the laser beam propagates in the air, the uncertainty $\sigma(L)$ in the spatial localization of the laser beam axis increases with increasing propagation length L [1–5], which drastically restricts the region of its metrological application.

A possibility of substantially decreasing $\sigma(L)$ was reported in [6], where the effect of a considerable decrease in $\sigma(L)$ was observed. It was experimentally established that when the laser beam propagated in the air inside a tube 10 m long, $\sigma_t(L)$ decreases by an order of magnitude as compared with $\sigma_a(L)$ of its propagation in the air without a tube.

In [7] the authors pointed to a possible relation between the observed effect and the established fact that a standing sound wave induced by environmental wide-band noise exists in the tube[1].

[1]The authors plan to carry out additional investigations for better substantiated test of the assumption that standing sound waves affect stabilization of the laser beam position in a closed tube.

In this work the observed phenomenon was investigated over the lengths up to 68 m. The resulting data qualitatively confirmed the result [1] for 10 m and showed a stable increase in the effect: the ratio $\sigma_a(L)/\sigma_t(L)$ increased with increasing length L. The authors believe that this phenomenon may be a fundamentally new physical basis for developing large-distance precision laser metrology devices.

EXPERIMENT

The setup schematically shown in Fig. 1 was used for the measurements.

After it traveled a distance L, the laser beam was as brought into coincidence with the center of the dee photodetector (DPD) [3]. DPD signals *1* and *2* were fed into two channels of the 24-bit ADC and, after digitizing, were recorded in the personal computer (PC). The experiment was carried out in a forced-ventilation room. A rectangular prism was used to increase the laser beam propagation length (Fig. 2).

On passing through the prism, the beam traveled the way that did not coincided with the initial one.

The diffraction divergence of the laser beam resulted in that the beam spot in this setup exceeded the DPD size beginning with the length $L = 30$ m. This decreased the DPD sensitivity to the beam displacement and led to a decrease in the accuracy of subsequent coordinate measurements made to determine $\sigma(L)$. This drawback was eliminated by using a telescopic attachment (Fig. 3) which simultaneously increased the initial diameter of the laser beam and effectively collimated it in measurements over lengths $L > 30$ m.

In this layout the laser beam, after passing through the collimator, was focused on the half length and, reflected in the prism, was expanded to the initial diameter $D = 1$ cm.

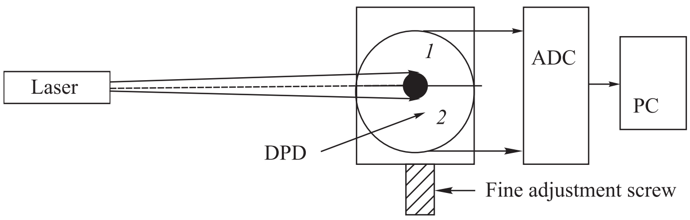

Fig. 1. Block diagram of the setup for measuring the uncertainty $\sigma(L)$ in the spatial localization of the laser beam

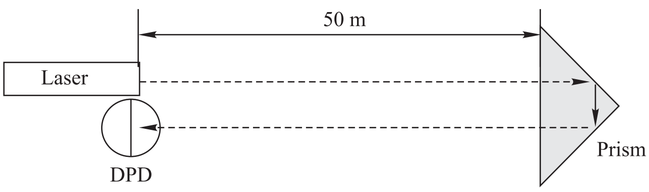

Fig. 2. Experimental layout for lengths over 50 m in the air

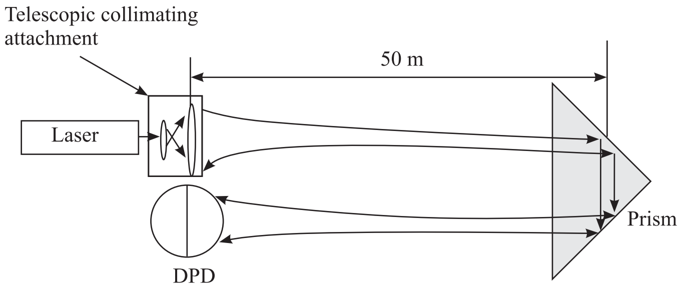

Fig. 3. Collimation of the laser beam in the experiment with lengths over 50 m

Since the beam diameter changed with length, calibrations were carried out in each measurement: the DPD was shifted perpendicularly to the beam axis by a known distance using the precision micrometer positioner (positioning accuracy ± 0.3 μm).

The beam shifting for calibration purposes was carried out in the following way. The positioner with the photodetector attached to it was roughly adjusted using the fastener so that the DPD center visually coincided with the laser beam. The DPD was oriented up–down (Fig. 1).

Next, the preliminary measurement of signal was performed using the ADC. On the basis of these data, the position of the laser beam spot relative to the boundary line of the photodetectors was determined. The DPD boundary line was brought into coincidence with the laser beam center using the positioner. The values of the signal detected by the ADC became equal ($l_1 \approx l_2$). Then signals l_1, l_2 were continuously recorded in the PC. During the measurements the DPD was shifted relative to the laser beam axis for a short time by the fine adjustment screw for test (calibration) purposes. A typical form of the recorded signal $U_1 - U_2$ with the calibration shift of the DPD by $\Delta = 50$ μm is shown in Fig. 4. The signal was recorded in the text file for subsequent processing.

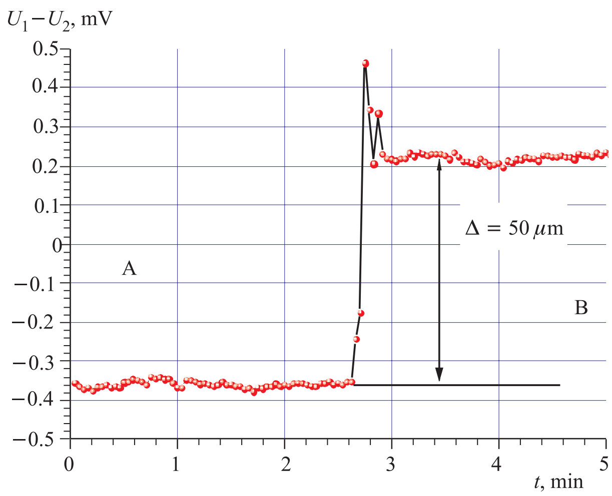

Fig. 4. Record of the laser beam «position» on the dee photodetector after the travel over a distance of 34 m in a tube plugged with optical glasses; calibration shift $\Delta = 50$ μm

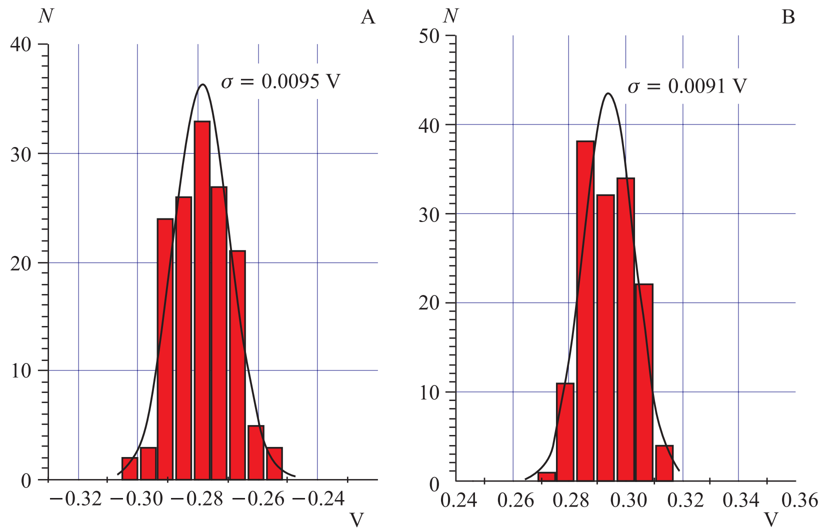

Fig. 5. Histograms correspond to the projections of lines A and B onto the vertical axis of Fig. 4

With $\Delta \ll D_l$, where D_l is the diameter of the laser beam at the measurement point, the comparison of $\Delta = 50$ μm with the value of the misbalance $\overline{(U_1 - U_2)}_{\rm A} - \overline{(U_1 - U_2)}_{\rm B}$ made it possible to convert DPD readings from mV to μm.

Histograms in Fig. 5 correspond to segments A and B projected onto the vertical axis of the plot (Fig. 4). The root-mean-square deviations $\sigma_{\rm A} = 9.5$ mV and $\sigma_{\rm B} = 9.4$ mV are similar, which indicates a stable position of the photodetector and its noninterference in the measurements. Calculated from the calibration results in Fig. 4, values σ over the length 34 m in a plugged tube were $\sigma_{\rm A} = 0.83$ μm and $\sigma_{\rm B} = 0.82$ μm.

Similar measurements and calibrations at different lengths of laser beam propagation allowed $\sigma(L)$ values to be determined.

The following measurement runs for laser beam behavior in the air were carried out: (A) no collimator, no tube, $L = 0{-}50$ m; (B) collimator, no tube, $L = 0{-}100$ m; (C) collimator, plugged tube, $L = 0{-}68$ m.

The laser used was Diod Lablaser VLM2 with the power $P = 1$ mW and the radiation wavelength $\lambda = 0.65$ μm. The laser was fixed in a thick brass tube to reduce the influence of small air temperature fluctuations. The tube was fastened to a holder 2 m above the floor. The dee photodetector was fixed at the same height.

RESULTS OF MEASUREMENTS

(A) Measurements without the collimator and the tube, $L = 0{-}50$ **m (Fig. 2).** The output laser beam diameter was 5 mm, the data-sheet divergence angle was $\theta \leqslant 5 \cdot 10^{-4}$ rad. Under these experimental conditions (the beam diameter is not larger than the DPD diameter) the laser beam could be used at a distance no larger than 50 m.

The $\sigma(L)$ values were measured over the lengths 0–34 m with an average step of 2.5 m and additionally over the length 50 m. The processing results are shown in Fig. 6. The duration of one measurement was $t = 2.5$ s.

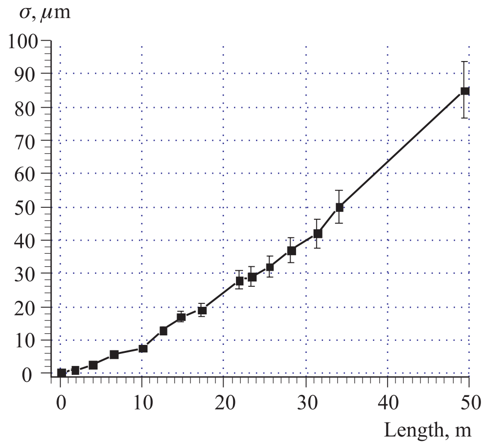

Fig. 6. Uncertainty $\sigma(L)$ in the spatial position of the laser beam axis as a function of the distance covered by the beam in the air; no collimator was used

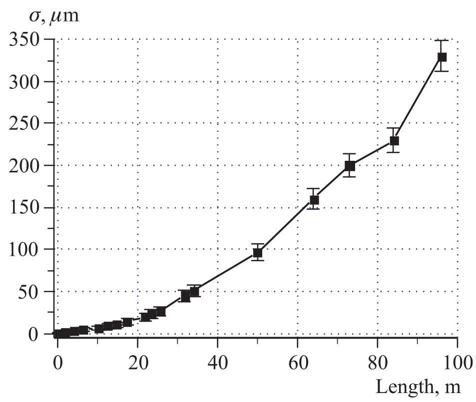

Fig. 7. Uncertainty $\sigma(L)$ in the spatial position of the laser beam axis as a function of the distance covered by the beam in the air; a telescopic collimating attachment and a rotating prism are used

The value σ (10 m) in the air without a tube practically coincides with the earlier obtained value [2]; we believe that this confirms the stability of the parameters of the equipment used and the reproducibility of the data processing results.

(B) Measurements with the collimator and without the tube, $L = 0{-}100$ **m (Fig. 3).** The main objective of this measurement run was to determine $\sigma(L)$ over larger lengths than in [1], where the data were limited to $L \leqslant 9$ m. The results are shown in Fig. 7.

The collimator lifted the limitation caused by the setup geometry and the room length and allowed measurements to be performed over larger lengths. A comparison of Figs. 6 and 7 shows that the use of a collimator does not change the dependence of σ on L either qualitatively or quantitatively. Now the data in Fig. 7 should be compared with the results of measurements in the tube.

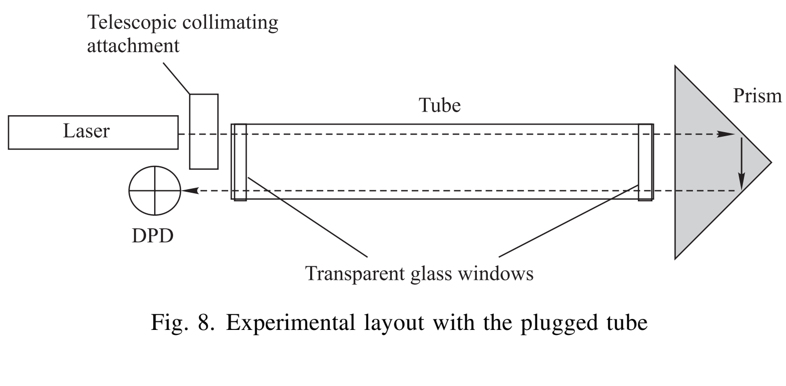

Fig. 8. Experimental layout with the plugged tube

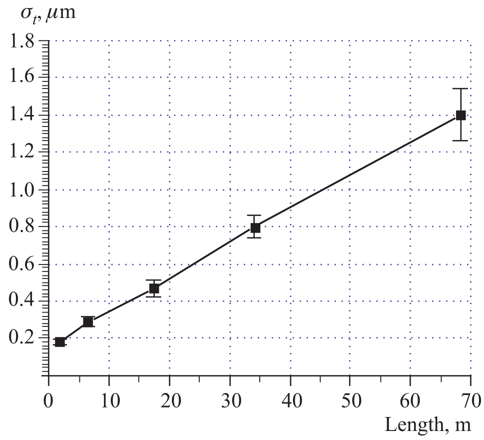

Fig. 9. Dependence $\sigma_t(L)$ on the distance covered by laser beam in the plugged tube; a telescopic collimating attachment and a rotating prism are used

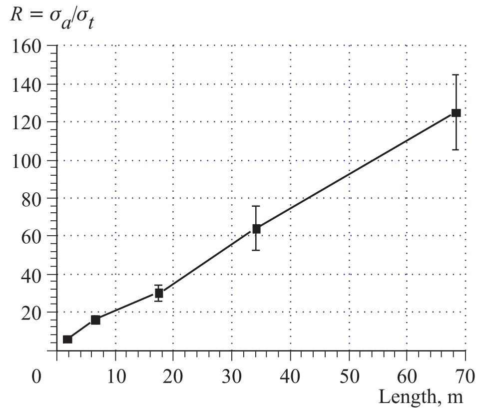

Fig. 10. Dependence of the «resolution improvement» coefficient $R(L)$ on the laser beam travel length

(C) Measurements with collimator in a plugged tube, $L = 0{-}68$ **m (Fig. 3).** The main objective of these measurements, which are main goal of the work, is to confirm experimentally the effect of suppression of fluctuation oscillations of laser beam over large lengths observed in [2].

Recall that measurements of $\sigma(L)$ for a laser beam in the air at $L \leqslant 9$ m [1] revealed that a tube with open ends decreases σ. A distinguishing feature of the experiment under discussion is that there were built-in glass windows at the ends of the tube used (Fig. 8).

The tube of length $L = 34$ m was mounted on «point» supports at a step of 2–3 m. As in the experiment in the air, the rotating prism allowed investigations over lengths up to 68 m. Figure 9 shows dependence of σ on the laser beam travel length.

The effect of a considerable decrease in $\sigma_t(L)$ for the laser beam traveling in a tube relative to $\sigma_a(L)$ for the laser beam traveling in the open air observed in [1] was observed at larger distances in this experiment. A fundamental feature (which is not obvious a priori) is that the «resolution improvement» coefficient $R(L) = \sigma_a/\sigma_t$ increases with increasing distance and comes to a quite large value $R\,(68\text{ m}) = 124$ at the distance $L = 68$ m (Fig. 10).

CONCLUSIONS

The effect of suppression of the fluctuation oscillations of the laser beam axis in a tube observed in [1] is experimentally detected at larger distances (up to 68 m) as well.

It is established that the effect practically linearly increases with increasing distance and comes up to quite a large value $R\,(68\text{ m}) = 125$.

This fact (linearity) allows assuming quadratic dependence of the uncertainty in the spatial position of the laser beam $\sigma_a(L)$ on the distance L traveled by it in the open air (without a tube), which was not mentioned in the literature before.

It seems that suppression of the fluctuation oscillation of the laser beam in a plugged tube at rather large distances often faced with in practice may be a physical basis for development of large-distance precision laser metrology devices.

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