Investigation of High-Precision Laser Instrument for Distance and Displacement Measurements

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Abstract: The novel high-precision measurement method was proposed. The considered method possesses laser-interferometric precision, does not require to move any external mirrors over full measuring basis, and can be applied to measure distances of $10^{-2} - 10^5$ m.

OCIS codes: (120.3930) Metrological instrumentation; (140.4130) Molecular gas lasers; (230.0040) Detectors.

High-precision measurements of large lengths are important for detailing the gravitational field and seismicity of the Earth, as well as for creating a prototype of a space gravitational wave antenna [1,2]. In such measurements, stable tunable lasers are used with the possibility of precise control of the radiation frequency [3]. Well-known high-precision measuring devices and installations are based on either on the radio-optical (modulation), or on the interferometric method for determining distances.

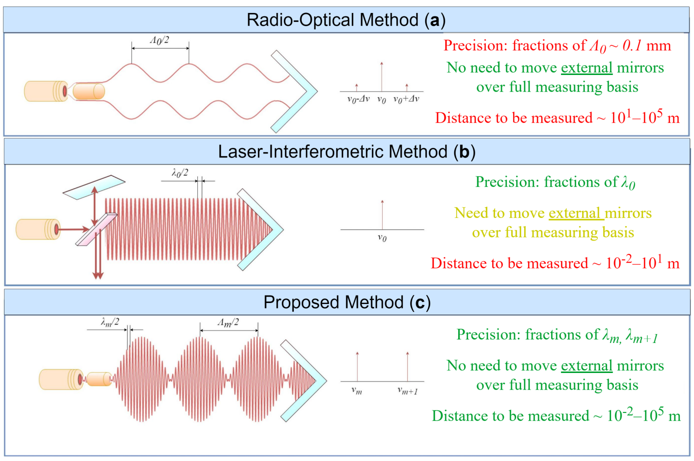

Fig. 1. Comparison of the proposed method with laser-interferometric and radio-optical methods

The proposed device increases precision of measurements in different areas. For example, by using it, the fidelity is higher for such actions as monitoring of construction stability of high-rise buildings; prospecting natural resources (e. g., oil and gas); forecasting natural disasters; and detecting gravitational waves.

In this paper, we study the proposed method and device for high-precision measurement of distances and displacements [4], combining the advantages (Fig. 1) of laser-interferometric and radio-optical measurement methods. The scientific novelty of the method consists in combining the advantages of radio-optical and interferometric methods for determining distances and displacements, namely, such advantages as: interference precision (fractions of the wavelength) and small-sized (there is no need for movement of any external mirrors over full measuring basis). This means that the proposed device [5] will not require the movement of any bulky equipment (providing the precise mirror displacement) and will have a precision of measuring the distance to the reflecting object of the order of the interferometer precision. The proposed device uses the amplitude modulation of radiation when generating optical modes, the number of which is set by the He-Ne laser parameters. In addition, the proposed device uses the control of the visibility of the interference pattern by adjusting the optical modes of the laser resonator by accurately varying the cavity length. The characteristic measured distance is in the order range of $10^{-2} - 10^5$ m (practical implementation is of 10^2 m).

The derived formulas

$$V_1 = \frac{2\sqrt{\delta_1}}{1+\delta_1}; \qquad V_2(\ell, L) = \frac{\sqrt{1+\delta_2^2+2\delta_2\cos\left(\frac{4\pi\Delta\nu(L)}{c}\ell\right)}}{1+\delta_2}; \qquad V(\ell, L) = V_1 V_2(\ell, L); \qquad (1)$$

describe the dependence of the visibility $V(\ell,L)$ (one-mode and two-mode regime of a laser) on the geometric distance between laser and the third mirror ℓ, on the intermodal frequency $\Delta\nu(L)$, and on intensity ratios δ_1 (light beams of one mode) and δ_2 (light beams of two modes). Thus, the interfering of in-phase ($\ell = Lw$, where w is an integer, L is the cavity length of a laser) light waves of two modes $V(\ell,L) \approx V_1$, where V_1 is the visibility of interference pattern formed by one-mode regime.

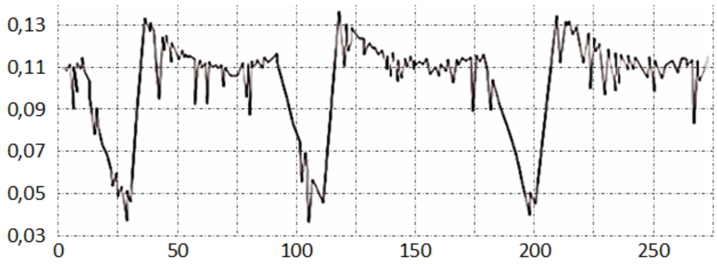

Fig. 2. Visibility vs. time (seconds)

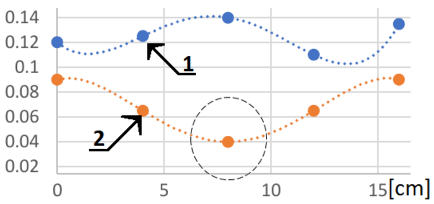

Fig. 3. Visibility V vs. distance ℓ

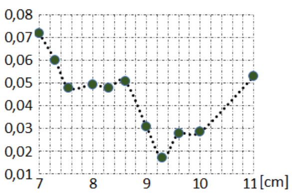

Fig. 4. Part of V vs. ℓ

Experiments were conducted by using the laser OKG-16 (cavity length L of 16 cm). The visibility was measured in three-mirror interferometer scheme (Fig. 1**c**). At local minima (at points such as $\approx$ 34 s, $\approx$ 117 s, $\approx$ 201 s), the curve of visibility versus time under fixed measured distance ℓ of 8 cm (Fig. 2) is sharp. The represented visibility values varies with time because of laser self-heating (cavity length L increases). The change in cavity length L is connected to intermodal frequency $\Delta\nu(L) = c/(2L)$ [6] that directly affects visibility $V(\ell,L)$ values (eq. 1). Furthermore, represented curve of visibility changes its behaviour abruptly periodically (period is $\approx$ 85 s) at points such as $\approx$ 12 s, $\approx$ 41 s, $\approx$ 91 s, $\approx$ 120 s, $\approx$ 178 s, $\approx$ 208 s. Abrupt changes in such points are caused by changes in laser regime between one-mode and two-mode. The changes in number of modes is determined by mode positions $\nu_m(L) = \frac{2\pi c}{L} m$ of m-th and $(m+1)$-th modes ($m \approx 10^6$) under Doppler profile of He-Ne laser (width equals 1.5 GHz) [6].

The experimental curves (curves **1** and **2** – one-mode and two-mode regimes) of the visibility versus the distance ℓ to the reflecting object (Fig. 3) are periodic, the period is equal to the cavity length L. The visibility $V(\ell,L)$ varies in the range of $0.04 - 0.14$. The minimum of this curve (detailed in Fig. 4) is sufficiently abrupt. Such an experimental minimum sharpness corresponds to theoretically derived formula of visibility $V(\ell,L)$ in the equation 1.

Our technology is in demand in the safety maintenance and construction of high-rise buildings such as Moscow International Business Center, Lakhta Center, especially in seismically active regions (Kamchatka, Japan, the North Caucasus, the Philippines, Malaysia, etc.). Every day, it is necessary to use seismic data to track the current situation.

Furthermore, the precision of geological exploration can be improved in the detection of underground deposits of hydrocarbon raw materials. Moreover, the proposed device can be applied at a space station for detecting gravitational waves ELISA [2], which will be built in 2034 with the participation of ESA, NASA.

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