INVESTIGATION OF HIGH-PRECISION LASER INSTRUMENT FOR DISTANCE AND DISPLACEMENT MEASUREMENTS

Iurii Minin[1], Igor Bulatov[2], Nikita Korobov[2], Mstislav Dubrov[2], and Maxim Fedorov[1]
[1]Skolkovo Institute of Science and Technology: CDISE; [2]Moscow Institute of Physics and Technology: DREC
iurii.minin@skoltech.ru, bulatov.is@phystech.edu, korobov.na@phystech.edu

Introduction To date, there is an interest at the improvement of measuring tools, increasing the accuracy and order of measurements. Such tools are based either on the radio-optical method of determining distances to objects or laser-interferometric principle of measuring displacements and a distance to an object. In this paper, we study the proposed method and device for high-precision measurement of distances and displacements, combining the advantages of both methods, namely, such 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 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.

Methodology The proposed device combines the advantages of laser-interferometric and radio-optical measurement methods (Fig.1). Namely: interference accuracy (fractions of a wavelength λ), small size (there is no need to move any external mirrors throughout the measuring base) and the possibility to measure distances of the order of $10^{-2} - 10^4$ m. The device uses amplitude modulation of radiation when generating optical modes, the number of which depends on the cavity length. In addition, the visibility of the interference pattern is controlled by adjusting the optical modes of the laser cavity by precisely changing its length. First, to roughly measure the distance to the reflecting object, the number of spatial periods of the envelope signal at the moment when the visibility of the interference pattern is minimal is calculated Second, for precise measurements we calculate the number of interferences fringes whose period is $\lambda/2$. The radiation is excited only at frequencies within the line width of the bell-shaped profile of Doppler-broadened gain curve (Doppler profile). When the cavity expands due to heating, the frequency of each optical mode decreases This results in their different locations relative to the Doppler profile. Fig. 2 shows the locations of the optical modes in the Doppler profile when the laser cavity length is increased by one-eighth of a $\lambda/2$, as well as their corresponding visibility plots on the right. The visibility depends on the distance to the reflecting object and the ratio between the intensities. The derived formulas

$$V_1 = 2\frac{\sqrt{\delta_1}}{1+\delta_1};$$

$$V_2(l,L) = \frac{\sqrt{1+\delta_2^2+2\delta_2 cos(\frac{4\pi\Delta\nu(L)}{c}l)}}{1+\delta_2};$$

$$V(l,L) = V_1 V_2(l,L)$$

describe the dependence of the visibility $V(l,L)$ (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_2 (light beams of one mode) and δ_1 (light beams of two modes). Thus, the interfering of in-phase ($l = Lw$, where w is an integer, L is the cavity length of a laser) light waves of two modes $V(l,L) \approx V_1$, where V_1 coincides with the visibility of interference pattern formed by one-mode regime.

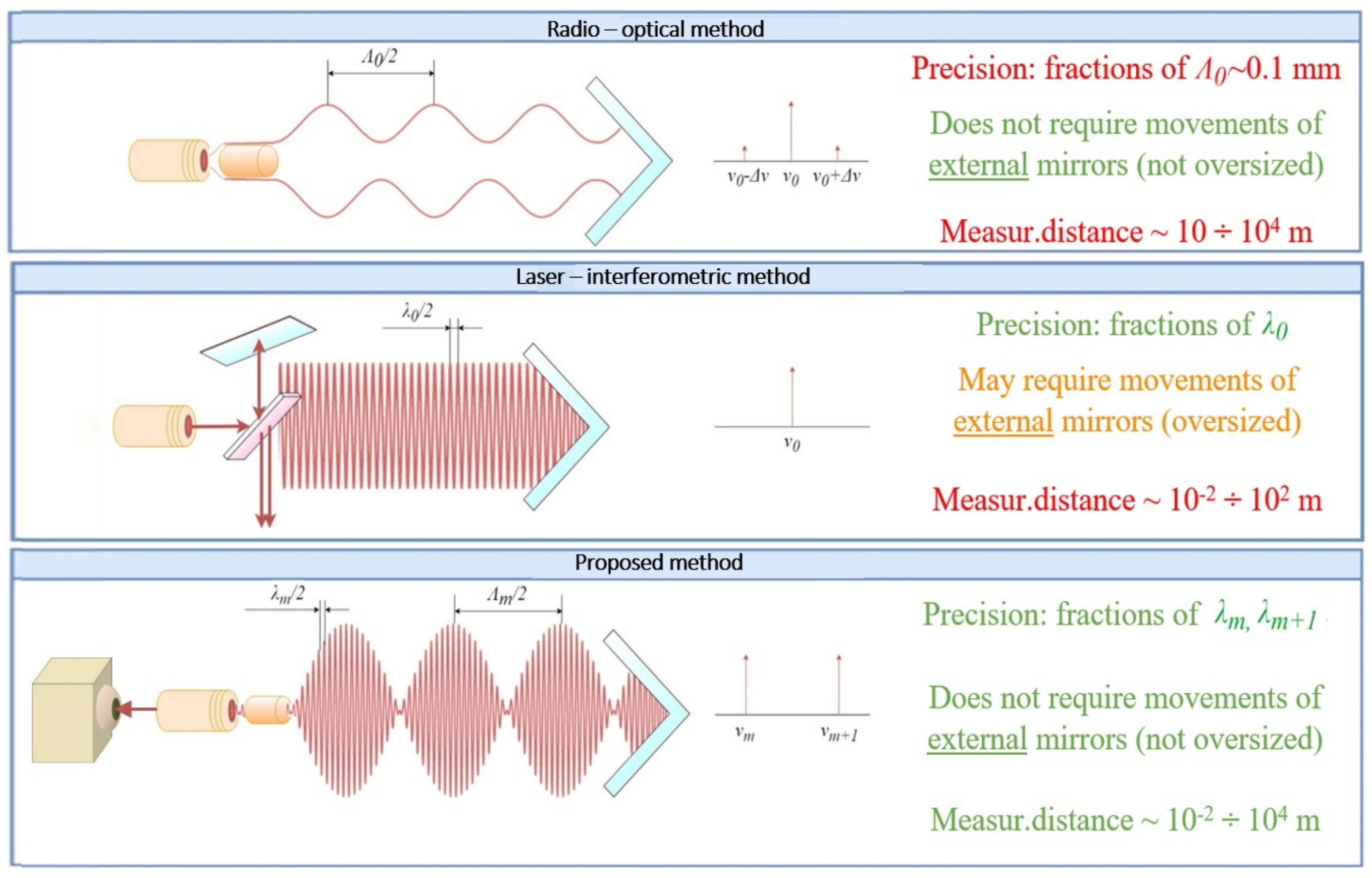

Figure 1: Comparison of the proposed method with laser-interferometric and radio-optical methods

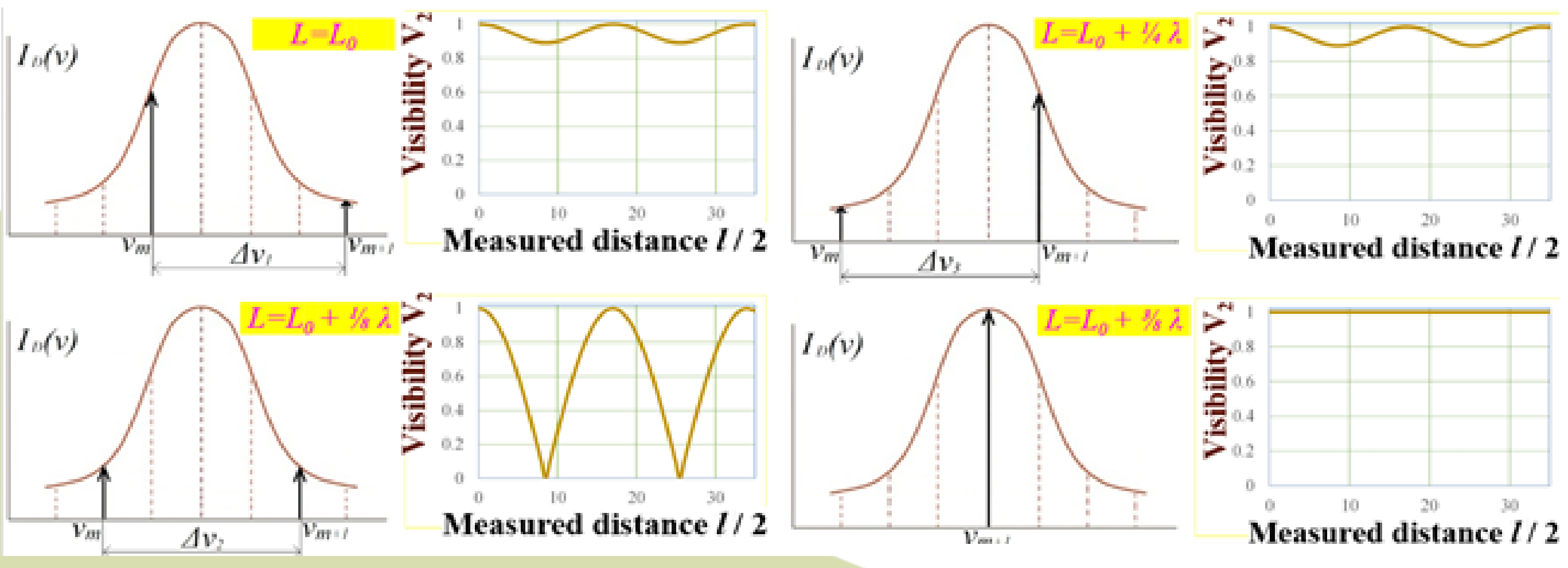

Figure 2: Positions of modes in the Doppler profile (in the odd figures from the left to the right) versus visibility V2 curves (in the even figures)

Equipment Amplitude modulation of the proposed device is based on physical existence of multiple modes. In addition, the proposed device uses the control of the visibility of the interference pattern by adjusting the optical modes of the laser cavity 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 100 m). The device consists of four units: Laser unit, Mirror unit, Heterodyne photodetector unit and Analytical unit. Mirrors 1, 2 form a beam of laser radiation, which is directed through the electro-optical modulator EOM and then falls on the mirror 3, fixed on the measured object, and is reflected back. Accuracy of the device can be increased by using shielding tubes with optical windows between the EOM and mirror 3. Interference signal (channel ch1) and intermodal signal are formed at the output of photodetector, which from output of Heterodyne photodetector unit goes to Analysis unit (channel ch2). Microcontroller processes signals of intermodal frequency and visibility and forms signals on how much and in what direction it is necessary to change the laser cavity length. The light beam is shielded by a tube with portholes. The EOM is connected to a reference signal generator, and its signal and the signal of the broadband photodetector are received by means of a digital-analog phasemeter. The digital-analog phasemeter is used to determine the fraction of the interference fringe. From the digital-to-analog phasemeter the signal is fed to the microcontroller.

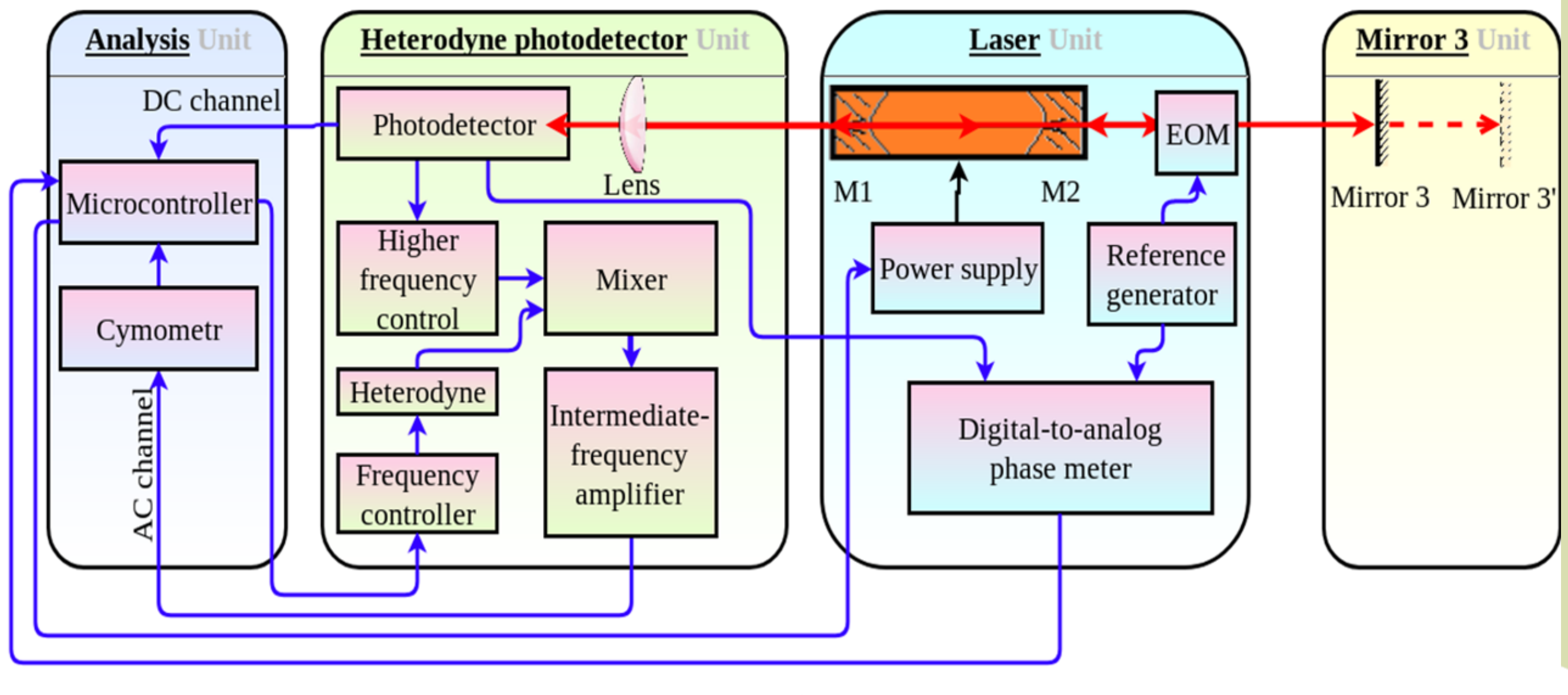

Figure 3: Block diagram of the proposed device

Results Experiments were conducted by using the He-Ne laser OKG-16 (cavity length L of 16 cm, λ = 633 nm). The visibility was measured in three mirror interferometer schemes (Fig. lc). At local minima, the curve of visibility versus time under fixed measured distance L of 8 cm (Fig. 6) is sharp. The represented visibility values vary with time because of laser self-heating. The change in cavity length L is connected to intermodal frequency $\delta\nu(L) = c/2L$ that directly affects visibility. Furthermore, represented curve of visibility changes its behavior abruptly periodically (period is ≈ 85 s) at points such as 12 s, 41 s, 91 s, 91 s, 120 s, 178 s, 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 $m-$th and $(m+1)-$th modes under Doppler profile of He-Ne laser which width equals 1.5 GHz. The experimental curves of the visibility versus the distance l to the reflecting object (Fig. 4) are periodic, the period is equal to the cavity length L. The visibility V varies in the range of $0.04 - 0.14$. The minimum of this curve (detailed in Fig. 5) is sufficiently abrupt. Such an experimental minimum sharpness corresponds to theoretically derived formula of visibility V in the equation 1.

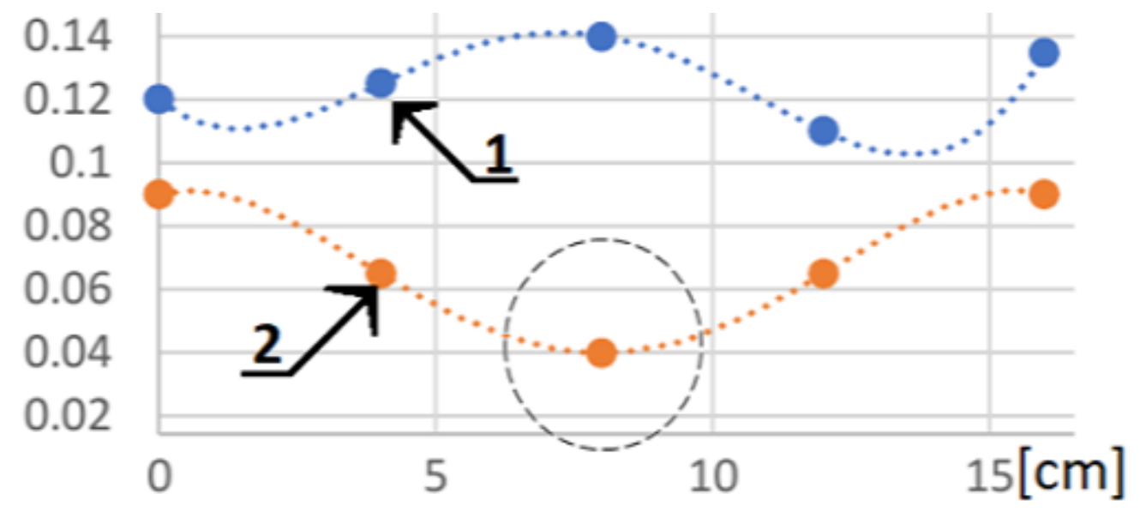

Figure 4: Visibility V vs. distance l

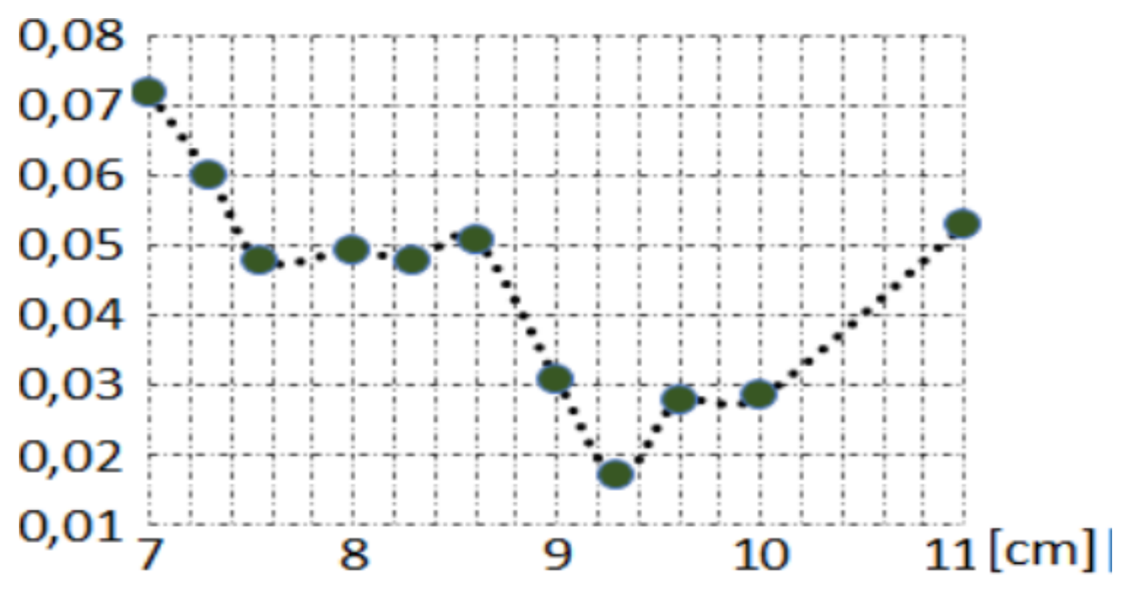

Figure 5: Part of V vs. l

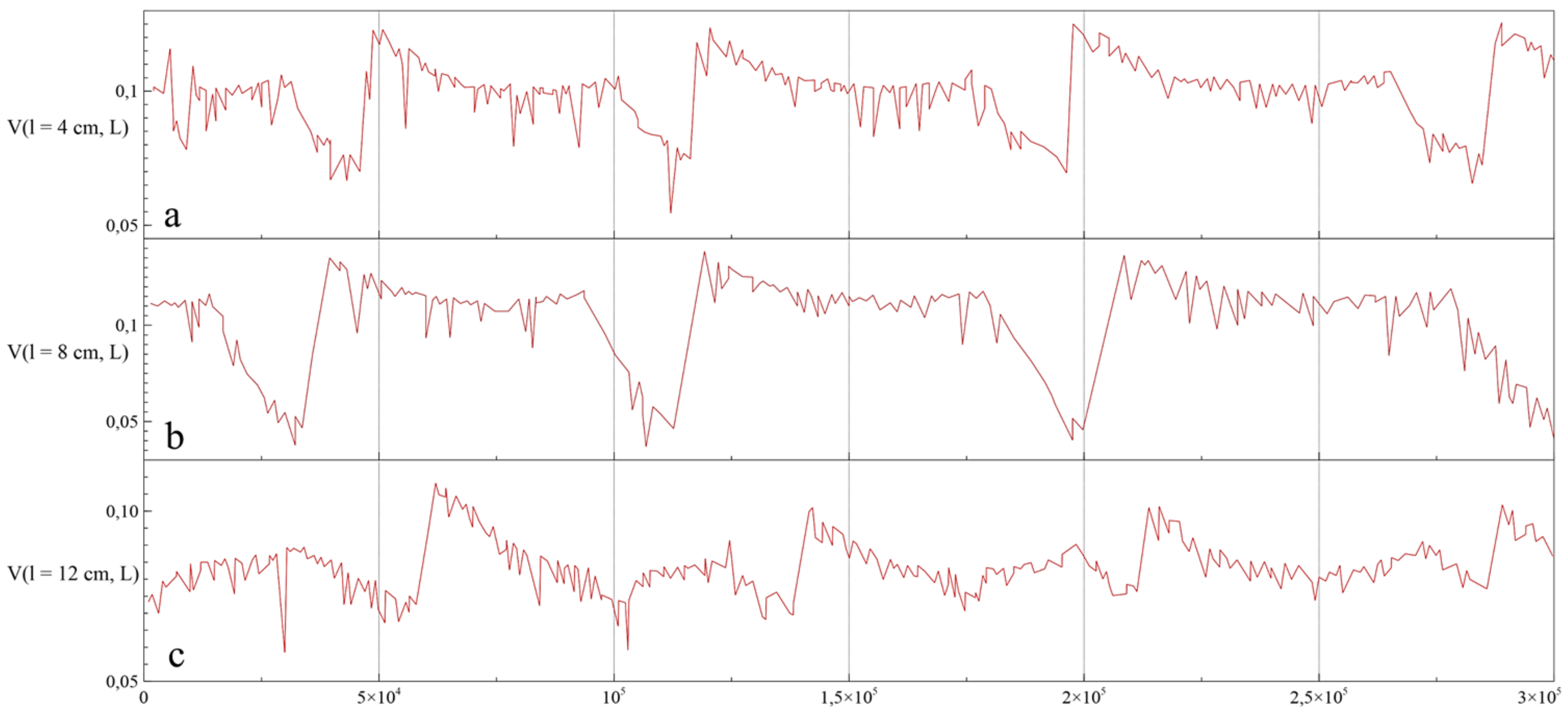

Figure 6: Visibility vs. time (ms)

Application 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. In such measurements, stable tunable lasers are used with the possibility of precise control of the radiation frequency. 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. 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. For example, in Japan 2-3 years ago mine was dug and placed in it high-precision measuring instruments for disaster prevention, but we suggest increasing the accuracy tenfold compared to the Japanese. 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, which will be built in 2034 with the participation of ESA, NASA.

Conclusion The derived visibility formula gives us knowledge at which values of laser cavity length and the distance to the reflecting object we have a two-mode regime, and at which we have a single-mode regime. The two-mode regime was observed near the visibility minima, and the single-mode regime was observed near the maxima. The derived visibility formula allows us to determine how sharp the minimum is in comparison to the maximum. This theoretical difference between minimum and maximum is confirmed experimentally on graphs. However, the experimental visibility curves do not coincide with the theoretical ones. This, for example, is due to the presence of Lamb dips in the Doppler profile.