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# Some Properties of a Single-Frequency He-Ne Laser and a Laser Interferometer

The paper describes some properties of single-frequency He-Ne lasers. The applications of these types of lasers to the laser "sub-standard" of length and to a laser interferometer for length measurements are discussed.

## 1. Introduction

Gas lasers are of a great significance in many scientific and technical branches which need precise measurements. Hence, it is very important to study the properties of lasers and to construct lasers with special properties. One of them is a gas laser with a single-frequency output which provides high coherence and high frequency stability of the output radiation. The radiation of such a laser operating on a single-frequency can manifest its coherence up to hundreds or even thousands of metres. This property can be utilized successfully in interferometric measurements of great distances. The radiation frequency stability of a single-frequency laser is comparable; in some types of lasers these stability is better than that of the contemporary international standard of length (krypton 86). The output power of laser radiation is by 7 to 9 orders of magnitude higher than the upper limit of detection attainable by contemporary types of semiconductor detectors. Under these conditions the laser can serve as a "sub-standard" of length and in the future it will probably replace the present international standard of length.

For practical applications the possibility of the direct comparison of the wavelength of laser light with the international standard is of great importance. The knowledge of the accurate absolute wavelength of laser light permits to use single-frequency lasers in laser interferometers for length measurements.

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## 2. Some properties of single-frequency He-Ne lasers

A sufficient output power of radiation, a narrow width of the spectral line and a high frequency stability of the output radiation are the most important properties of single-frequency He-Ne lasers. The problems regarding the output power of laser radiation were discussed elsewhere [1, 2]. For a laser interferometer an output power of hundreds of microwatts coming out from a laser with a short resonator is sufficient. Such a laser provided by frequency stabilization yields the highest frequency stability, too. If designed appropriately the frequency-stabilized laser has also a high output power stability in the steady state. Fig. 1 shows a record of the output power radiation for a period of 15 minutes. During this period of time the stability of the output power keeps within from some hundredths of percentage. If the single-frequency laser is to serve as a light source for a laser interferometer, the knowledge of the absolute wavelength of radiation of single-frequency lasers is very important.

In the very beginnings of laser interferometry, the measurements of the absolute wavelength of single-frequency He-Ne lasers were measured independently in several laboratories throughout the world [3] and a long-term stability of wavelength with these types of lasers was investigated [4, 5]. Also for lasers made in

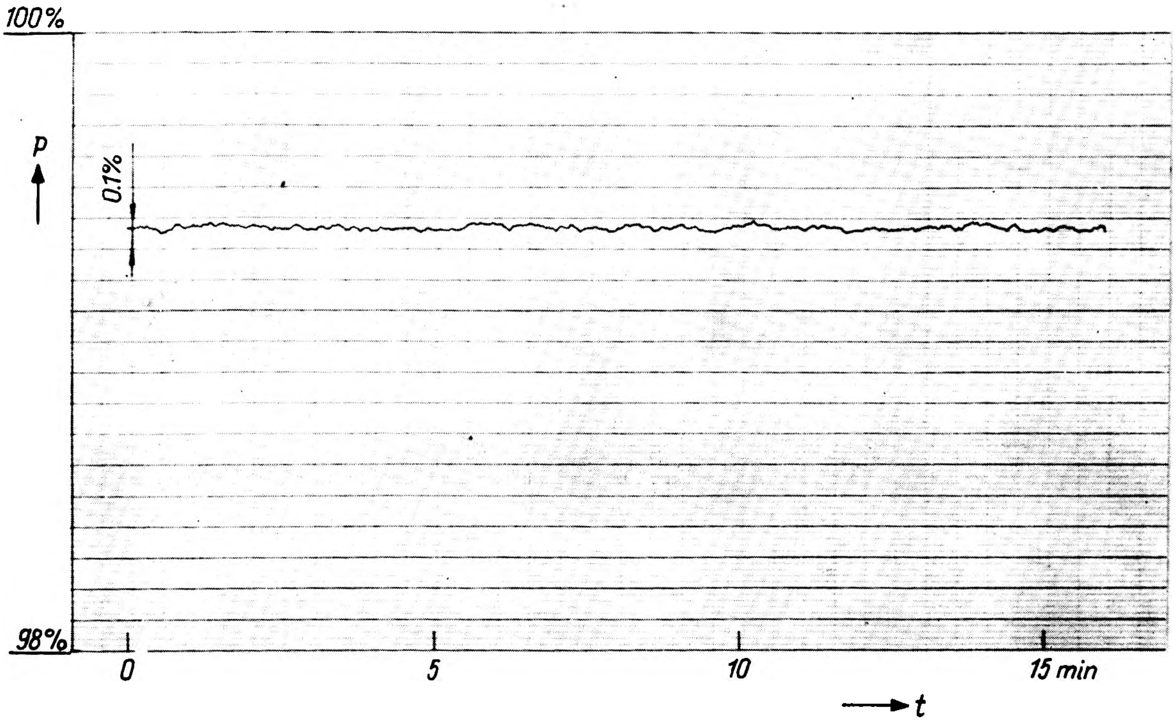


Fig. 1. Stability of the output power of the output radiation of a single-frequency laser with frequency stabilization

Czechoslovakia the wavelength of several single-frequency lasers was measured by comparing with the wavelength of the international standard of length, the line 0.6057 μm of a discharge tube filled with krypton 86 in Physikalisch-Technische Bundesanstalt, Braunschweig and in VNIM Leningrad. The obtained values are given in Chapter 3. With respect to the long-term operation of the device the long-term stability of wavelength must be high. In the case of stabilization to the centre of the active line ("Lamb dip") the variations in the wavelengths are chiefly due to the change in the ratio of components and to the change in the total pressure of the gas medium in the discharge tube. The wavelength stability of single-frequency lasers produced in Czechoslovakia was also measured in PTB Braunschweig by means of the Kösters interferometer and during 300 hours no variations were observed within the measuring accuracy of about $\pm 1 \cdot 10^{-8}$ μm.

In order to obtain a sufficient coherence length of the laser radiation, which is necessary for some applications the spectral line should be narrow enough and the high short-term frequency stability of a laser is important. Theoretically, this stability is essentially given by a spontaneous emission of atoms of the active gas medium at a given transition, by thermal fluctuations of the resonator construction [6], and by hypothetical effects of the statistic gas density fluctuations in the resonator [7]. Practically, the short-term stability is mainly determined by irregular changes in the refractive index in the resonator, by the influence of vibrations and by the final amplification in the loop of the stabilizing servosystem [8]. The short-term frequency stability of two independent frequency-stabilized lasers was measured with the aid of the radio-frequency method, i.e. the stability of the beat frequency between the two lasers has been determined. The beat signal between radiations of the two lasers, frequency-stabilized to the centre of the active line, can be seen in Fig. 2. The figure shows frequency modulation used for frequency stabilization. However, for rapid detection systems used in the laser interferometer this modulation does not decrease the contrast and the coherence length of laser radiation, as it will be also evident from Chapter 4 presenting some examples of long distance measurements made by means of the laser interferometer.

The record of beat signal stability between radiation of two frequency-stabilized lasers is given in Fig. 3. The frequency stability of individual lasers can be deduced from the stability of independent lasers, which in this case amounts to about $2 \cdot 10^{-9}$. Fig. 4 shows a beat signal of two frequency-unstabilized (free running) lasers without frequency modulation. The beat was recorded for a relatively long sweep period of about 10 s. In the line width, which in this case is about 100 kHz, the short-term frequency variations in time of about 500 ms are also included.

From the mentioned values of wavelength stability, i.e. the short-term and the long-term stabilities, it is evident that a calibrated set of single-frequency lasers can serve as a laser "sub-standard" of wavelength. The lasers which have a precisely calibrated wavelength

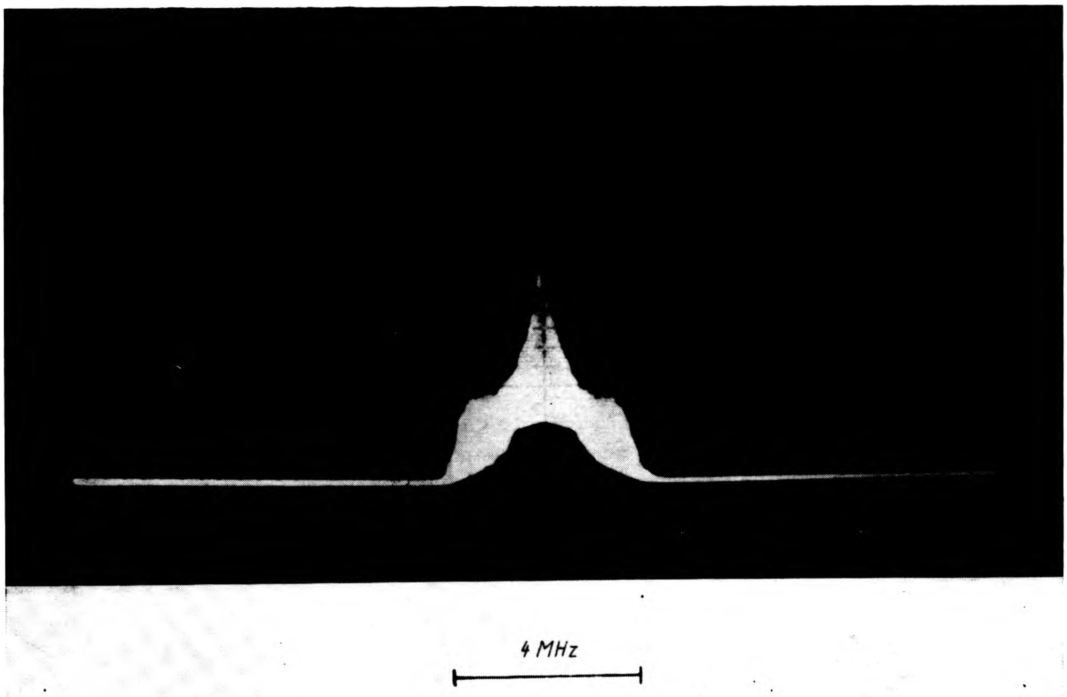


Fig. 2. A beat signal of two single-frequency lasers, frequency-stabilized to the line centre "Lamb dip"

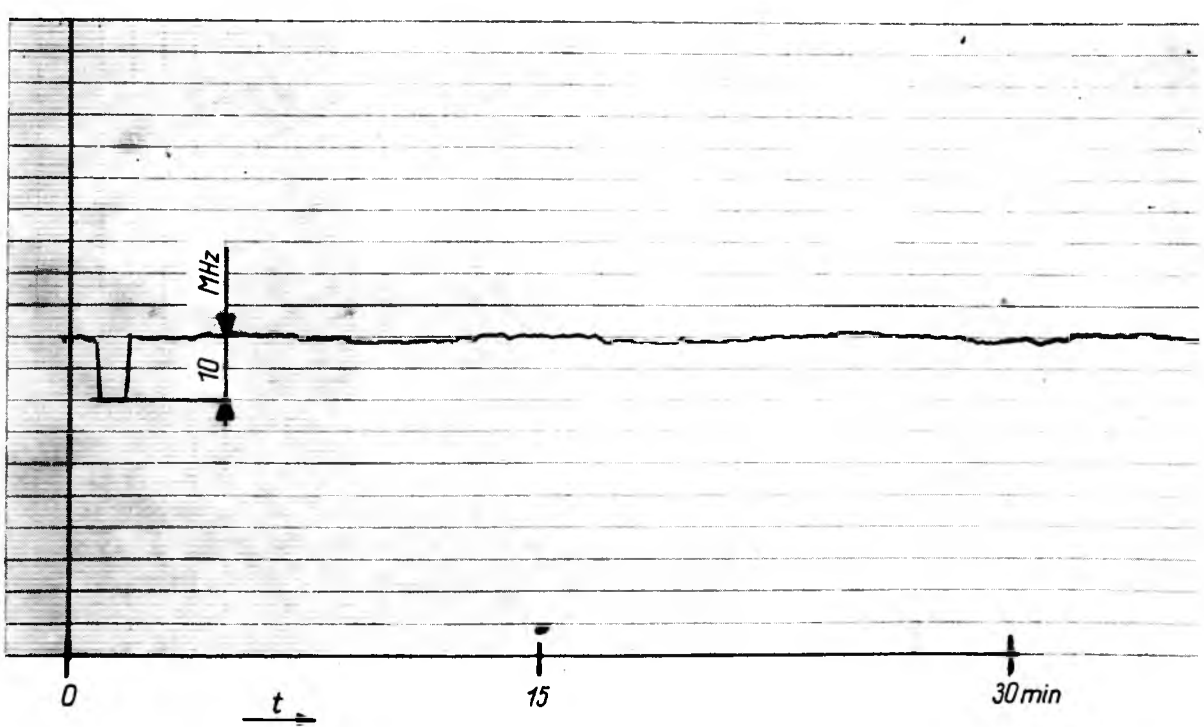


Fig. 3. A recording of frequency stability of two independent frequency-stabilized lasers

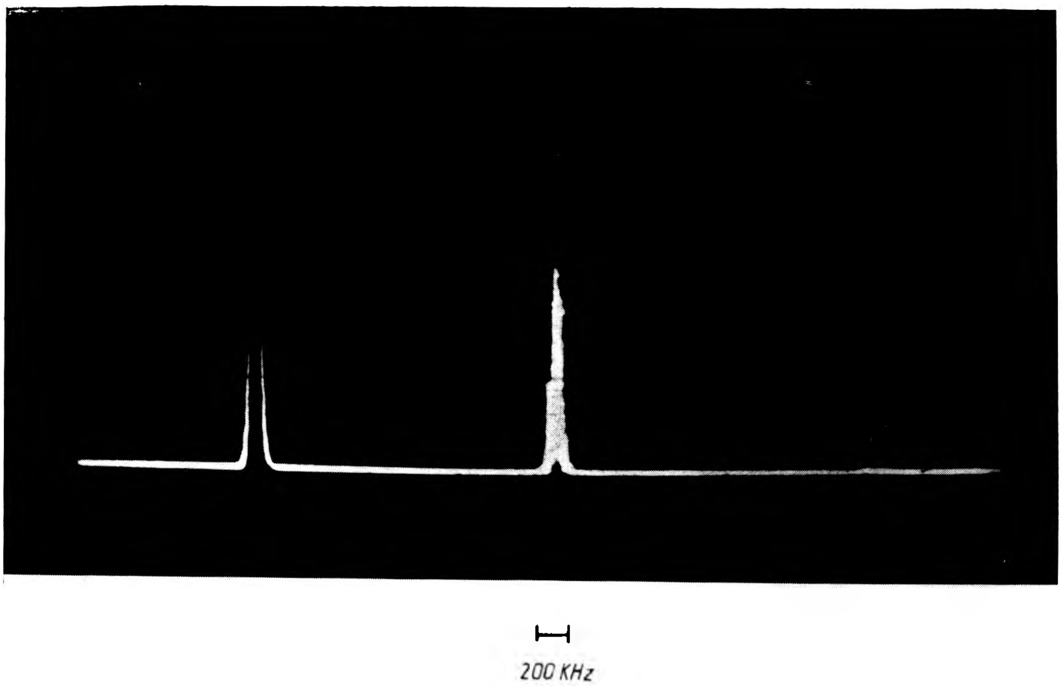


Fig. 4. A beat signal of two frequency-unstabilized lasers (without modulation)

by comparing with the international standard of length (krypton 86) may be used for determination of wavelengths of other lasers by means of the radio-frequency method, i.e. by measuring beat frequencies between the calibrated lasers and the measured one.

This method is much simpler than the measurement e.g. by means of the Kösters interferometer.

## 3. Laser "sub-standard" of wavelength

The laser "sub-standard" is formed e.g. by five calibrated single-frequency He-Ne lasers. Two of them must have sufficiently differ in their wavelength so that the difference be greater than the measurement error of the absolute wavelength of the Kösters interferometer. In this case the wavelengths of the used laser are precisely defined. Wavelengths of all lasers are defined in vacuum. Let us suppose that all lasers have been calibrated with equal accuracy and, considering the absolute wavelength, the standard mean wavelength of the set $\lambda_s$ is defined by the term

$$\lambda_s = \frac{1}{n}\sum_{i=1}^{n}\lambda_i,$$

where $n$ is the number of lasers in the set, $\lambda_i$ is the absolute wavelength of the $i$-th laser.

Fig. 5 depicts positions of wavelengths of individual lasers and the mean wavelength of the set. It is evident from the figure that on the basis of measuring radio-frequency beats bet-

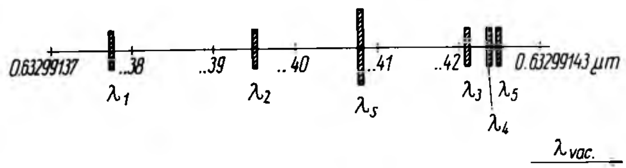


Fig. 5. Wavelengths of the set of calibrated lasers, according to measuring charts PTB and radio-frequency measurements

ween individual lasers it is possible to determine differences in wavelengths between individual lasers. For the difference of wavelengths $\Delta\lambda_{l,m}$ between the laser $l$ and the laser $m$

$$\Delta\lambda_{l,m} = \frac{\Delta\nu_{l,m}}{\nu_l}\cdot\lambda_m$$

holds,

where

$\Delta\nu_{l,m}$ – is the difference in frequencies between lasers $l$ and $m$, respectively,

$\nu_l$ – is the frequency of the laser $l$,

$\lambda_m$ – is the wavelength of the laser $m$.

In this way from all measured beat frequencies (ten in our case) the differences in wavelengths may be determined for all combinations of lasers. Considering the mean wavelength as standard, the corrected wavelengths of individual lasers determined on the basis of the radio-frequency beats may be defined.

For example, for the wavelength of the first laser of the set it holds:

$$\lambda_1' = \lambda_s - \frac{1}{10}(\Delta\lambda_{51} + \Delta\lambda_{21} + \Delta\lambda_{32} + \Delta\lambda_{43} + \\ + \Delta\lambda_{54}) - \frac{1}{10}(\Delta\lambda_{41} + \Delta\lambda_{31} + \Delta\lambda_{42} + \\ + \Delta\lambda_{53} - \Delta\lambda_{52}) - \frac{1}{10}(2\Delta\lambda_{31}) - \frac{1}{10}(2\Delta\lambda_{21});$$

the wavelengths of other lasers in the set can be determined analogically.

In the following we introduce values of wavelengths of individual lasers, according to measuring charts which were obtained in PTB Braunschweig, by comparing with the international standard of length (krypton 86). For individual lasers arranged according to wavelengths we have

$$\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4 < \lambda_5.$$

Let us note that we use the values obtained on the basis of RF beats measurements and not the ones resulting from the absolute measurement of wavelength. Results are given in Table 1.

Table 1

| | |
|---|---|
| $\lambda_1 = 0.632\,991\,38_5 \pm \pm 1\times10^{-8}$ µm | $\lambda_1' = 0.632\,991\,37_{74}$ µm |
| $\lambda_2 = 0.632\,991\,39_1 \pm \pm 1\times10^{-8}$ µm | $\lambda_2' = 0.632\,991\,39_{51}$ µm |
| $\lambda_3 = 0.632\,991\,42_0 \pm \pm 1\times10^{-8}$ µm | $\lambda_3' = 0.632\,991\,42_{10}$ µm |
| $\lambda_4 = 0.632\,991\,42_3 \pm \pm 1\times10^{-8}$ µm | $\lambda_4' = 0.632\,991\,42_{37}$ µm |
| $\lambda_5 = 0.632\,991\,42_0 \pm \pm 1\times10^{-8}$ µm | $\lambda_5' = 0.632\,991\,42_{50}$ µm |

The differences in wavelength, found for individual lasers with the aid of the radio-frequency method, have been determined with a higher accuracy than absolute wavelengths when compared with krypton 86 in the Kösters interferometer. The standard deviation of wavelengths differences in radio-frequency measurements was $m_2 = 1\cdot10^{-9}$ µm. Under these conditions the relations between individual wavelengths determined with the aid of the radio-frequency method can be considered as correct, and the differences between newly obtained values of wavelengths and the original ones have been determined according to measuring charts. Results are summed up in Table 2. New wavelengths of individual lasers depend on the mean wavelength of the set from the standpoint of the absolute wavelength. The standard deviation due to procedure determining the absolute wavelengths is then $m_v = 5\cdot10^{-9}$ µm. This value agrees both with the data in the measuring charts and with the data of PTB 9. In view of these results one may conclude that "sub-standard" allows to determine absolute wavelengths of other lasers with nearly the same accuracy as in the original calibration. The advantage consists in a simpler way of performing measurement. There is however one condition: a long-term stability of the wavelength of the laser "sub-standard" which from time to time must be compared with krypton 86. As an example of application the determination of wavelength of the laser LA 1000 produced in METRA Blansko Works for DAMW in Berlin can be mentioned. The arrangement of laser heads with a detector form a radio-frequency measurement of beat frequencies is illustrated in Fig. 6. A rapid semiconductor detector to 100 MHz was used. Fig. 7 shows a view on the laser "sub-standard".

Table 2

| Laser | $\lambda_{vac}$ µm | $\lambda'_{vac}$ µm | $\Delta\lambda$ µm |
|---|---|---|---|
| 1 | $0.632\,991\,38_5$ | $0.632\,991\,37_{74}$ | $-7.6\times10^{-9}$ |
| 2 | $0.632\,991\,39_1$ | $0.632\,991\,39_{51}$ | $+4.1\times10^{-9}$ |
| 3 | $0.632\,991\,42_0$ | $0.632\,991\,42_{10}$ | $+1\times10^{-9}$ |
| 4 | $0.632\,991\,42_3$ | $0.632\,991\,42_{37}$ | $+0.7\times10^{-9}$ |
| 5 | $0.632\,991\,42_0$ | $0.632\,991\,42_{50}$ | $+5\times10^{-9}$ |

In this case single-frequency lasers can serve for metrology of lengths. In a larger scale single-frequency lasers may be used in laser interferometers for direct measurements of lengths, velocities, flatness, angles, etc.

## 4. Use of single-frequency He-Ne lasers for a laser interferometer

The single-frequency He-Ne laser is a very suitable source of radiation for a laser interferometer. Its great coherence length of the output

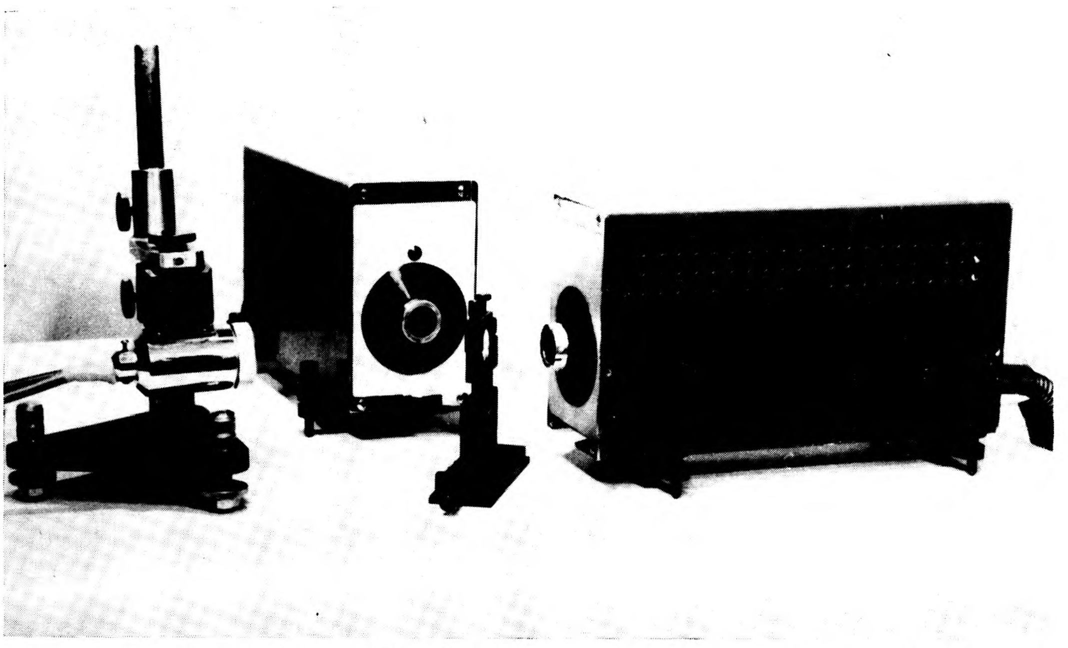

Fig. 6. An arrangement of laser heads with a detector for radio-frequency measurements of beat frequencies

radiation makes it also possible to perform measurements of long distances with a high resolution and a high accuracy. The scheme is given in Fig. 8. The device consists of a single-frequency laser, an interferometer, and an electronic computing system. The description and functions of individual parts are given in the literature [10, 11]. In this paper only some accessories and some results are discussed.

For calibration measurements a recording of deviations from accurate values with respect to the coordinates of the measured object is very important. Fig. 9 shows the electronic part of the device with an X-Y recorder of deviations. Digital data of the electronic computing system are converted to analog quantities. These are then used as input signals for the $x$ and the $y$ axes of the X-Y recorder. The instrument allows to record deviations from integer numbers of the measured values by the coordinate $y$ within the range $\pm 5$ µm or $\pm 50$ µm, respectively. The range of the coordinate $x$ can be chosen as a dimension of the measured object up to 40 m. A recording of deviations from correct values during a test of a precise recirculating ball screw is reproduced in Fig. 10. The device is also equipped with an automatic correction unit to correct for the laser wavelength in the atmosphere.

We also tried to use the laser interferometer for measurements of great distances. Good results were obtained in measurements of distances of 40 and 80 m. Recordings of stability with an uncovered path of the interferometer (without protective shields) are reproduced in Figs. 11 and 12 respectively. For the rapid electronic system of the universal laser interferometer limitations for measurements of great distances are not due to the operation of the stabilizing servosystem, but to the quality of optical elements of the interferometer and to fluctuations in the atmosphere along the measured path. The coherence length of radiation of the single-frequency laser remains within the range of some hundred to thousand metres. Fig. 13 shows the basic parts of the universal laser interferometer.

## 5. Conclusion

At present the lasers are successfully used in measuring techniques. The interferometric measuring methods appear to be of a great importance. Nevertheless, the progress in these interferometric measuring methods depends also on achievable quality of optics, integrated digital electronics and many other scientific and technical branches.

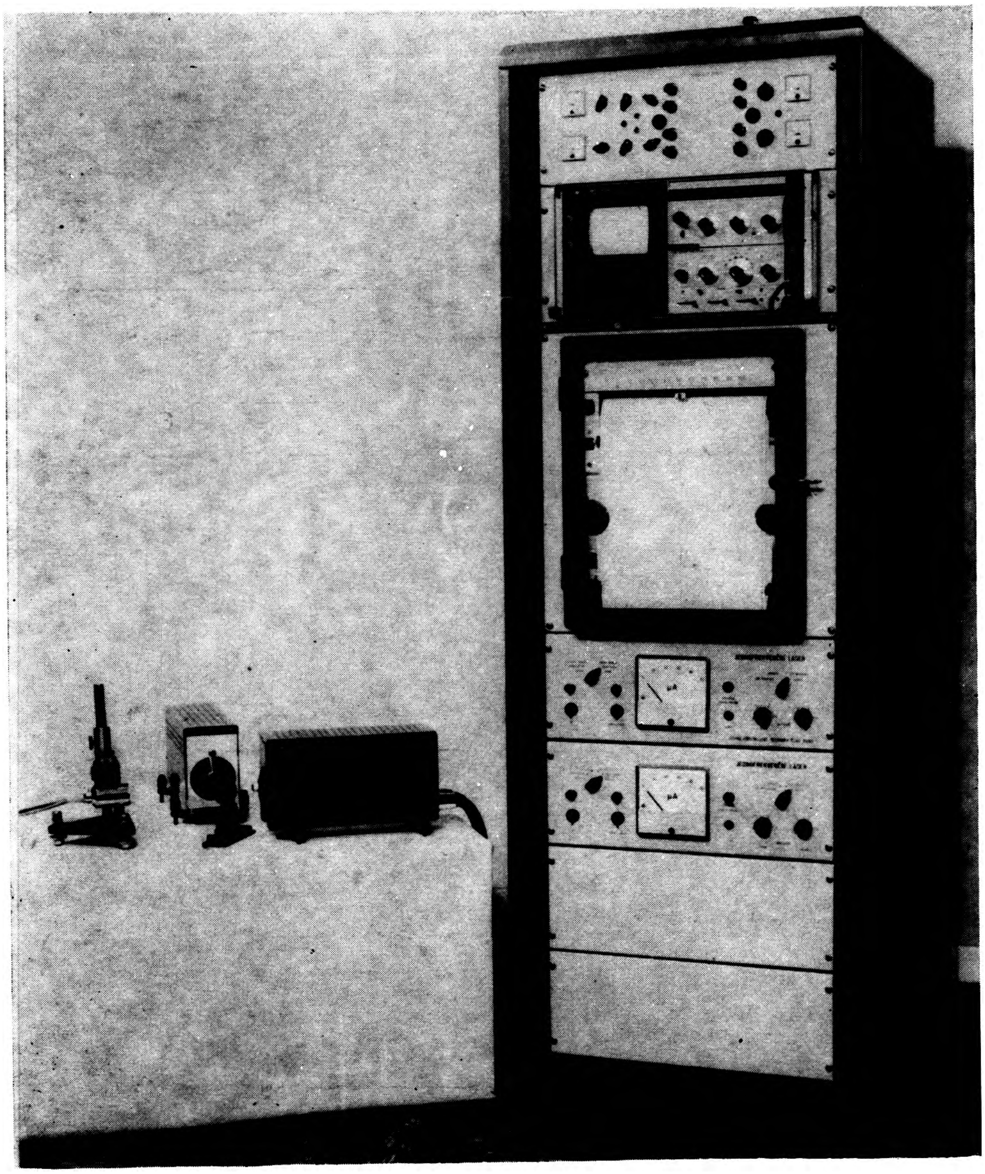

Fig. 7. A view on the laser "sub-standard" of wavelength

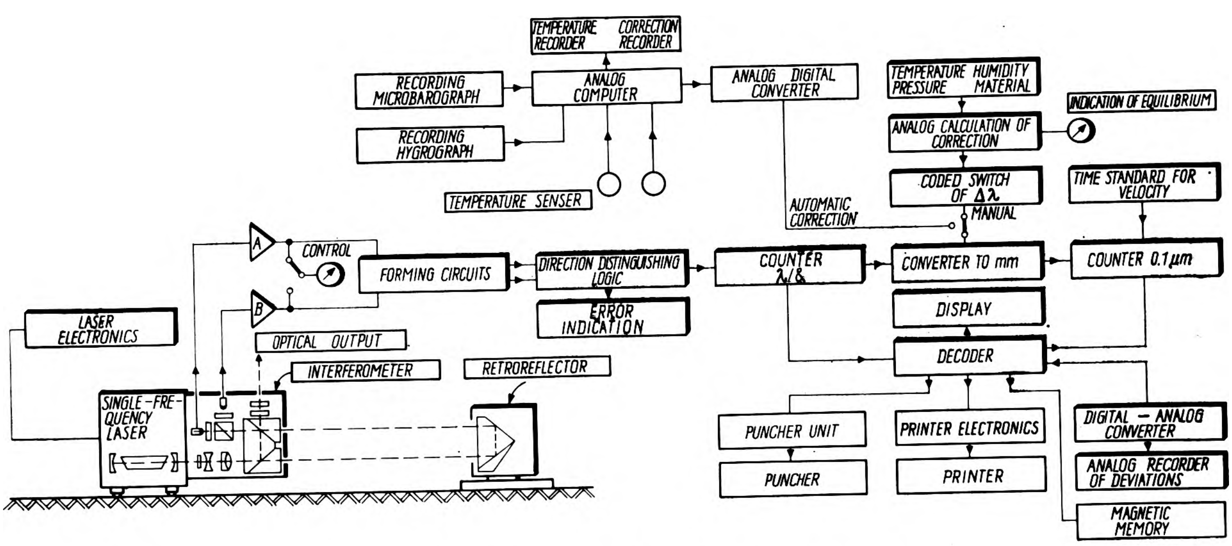


Fig. 8. A block diagram of the laser interferometer

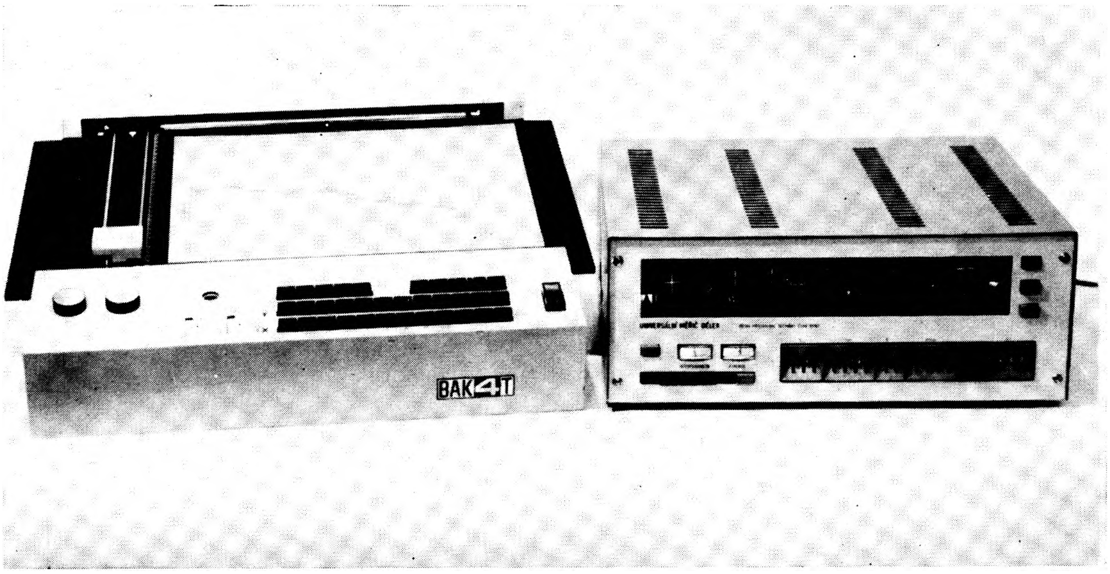


Fig. 9. The electronic part of the device with an X-Y recorder of deviations

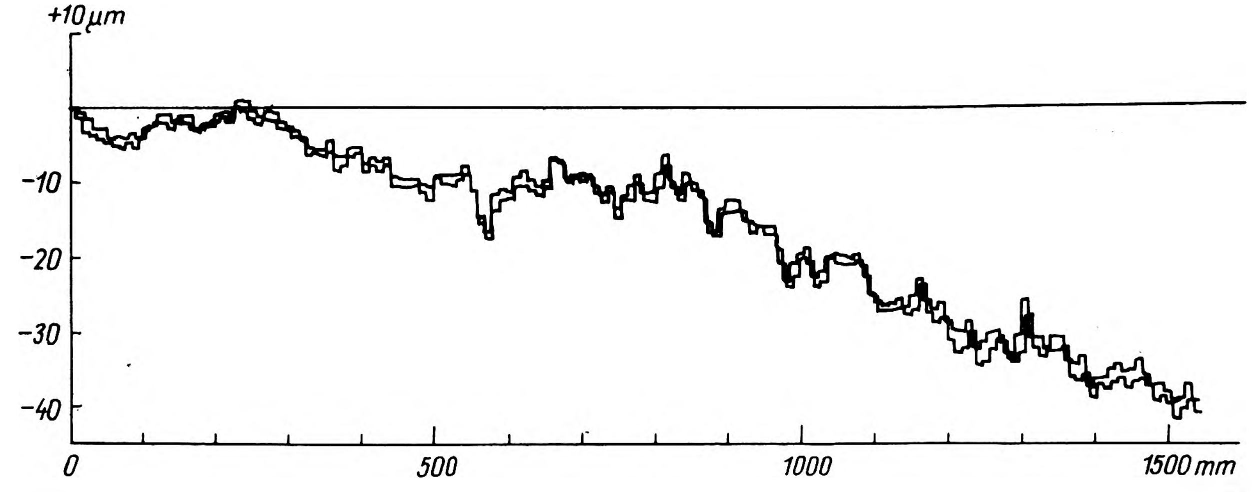


Fig. 10. A recording of deviations from correct values of a precise recirculating ball screw. Measured in TOS Kuřim Works

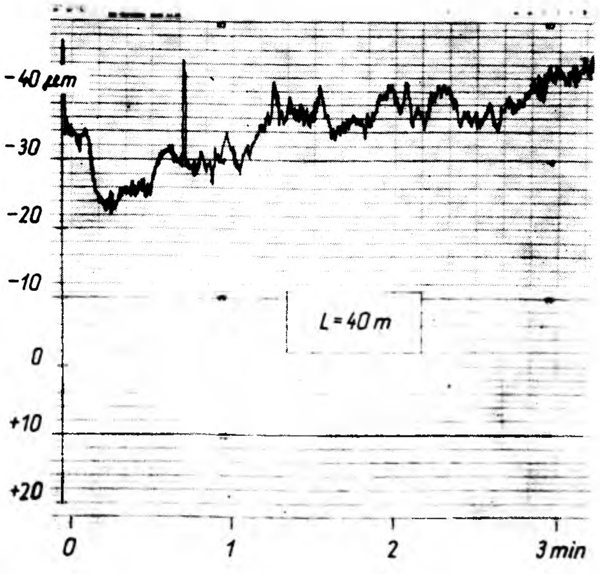


Fig. 11. A recording of measuring conditions at a distance of 40 m

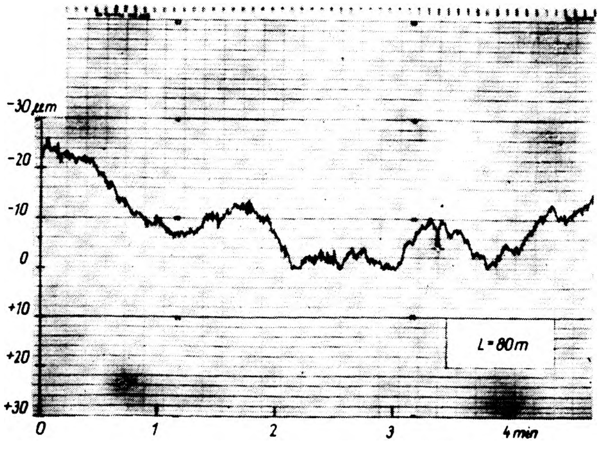


Fig. 12. A recording of measuring conditions at a distance of 80 m

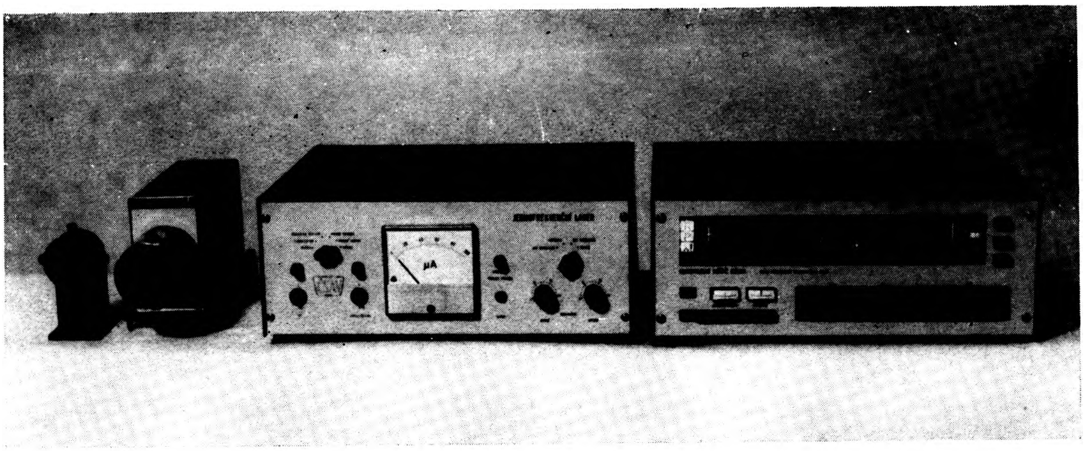

Fig. 13. Basic parts of the universal laser interferometer

## Quelques propriétés du laser He–Ne à fréquence simple et de l'interféromètre à laser

On a examine l'application de ce type de lasers dans le cas d'un interféromètre et à la détermination d'un "sous-étalon" de longueur.

## Некоторые свойства лазера на гелий-неоновой смеси с одиночной частотой и лазерная интерферометрия

Описаны некоторые свойства лазера на гелий-неоновой смеси с одиночной частотой. Обсуждено применение лазера этого типа в лазерных эталонах длины, а также лазерных интерферометров для измерения длины.

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