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Abstract.- The production of a time scale based on the use of an oscillation period of a highly stable laser is first reported. The new time standard allows to transfer frequency characteristics of a highly stable laser in the frequency range from 0 to 10^{14} Hz with no losses in accuracy. Radio-frequency oscillators were synchronized with the aid of fast-response systems of phase offset lock at division of laser frequencies.

1.- As is known, a usable atomic time scale is the oscillation period of a microwave oscillator the frequency of which is stabilized to a resonance at the transition of a hyperfine structure of the ground state of a cesium atom. By present a considerable progress has been achieved in this field /1/. However to increase an absolute frequency of a time scale is very attractive. An important step in this direction would be the transition to an optical time scale connected with an increase of frequency by 10^4-10^5 times in comparison to the existent quantum time standards. In this paper we report for the first time on the production of an optical time standard based on the use of an oscillation period of a frequency-stabilized laser as a time scale.

The transition to an optical scale will be reasonable if, at least, two problems are resolved. The first one is related to the production of optical frequency standards, i.e., lasers the frequency stability of which is of the same order or better than that of ultrahigh-frequency oscillators. The solution of the second problem requires a direct comparison of the unit of a time scale, a second, with the period of optical oscillations. To put it another way, this means the need for phase synchronization of microwave oscillators to the laser frequency by dividing its frequency and, consequently, transfer of stability of a laser frequency to microwave oscillators as well as to the other oscillators in the frequency range from 10^{12} to 10^{14} Hz.

Owing to the efforts of many researchers over the last years a considerable progress has been schieved in the field of frequency stabilization (see /2/). In our laboratory the following methods for obtaining supernarrow Doppler-free resonances have been proposed: the method of saturated absorption, of two-photon resonance and the method of separated optical fields (see /3/) that are now widely used in superhigh resolution spectroscopy and in frequency stabilization of lasers. The best results on frequency stabilization have been obtained by using saturated absorption resonances in methane at 3.39 μm /4/. The obtained linewidth of a stabilized He-Ne laser at 3.39 μm was about 0.1 Hz. The short-term frequency stability of this laser largely exceeds frequency stabilities of masers, the long-term stability and reproducibility are of the same order. This fact and the possibility to obtain supernarrow optical resonances by using the method of separated fields or the other ones with a relative width of 10^{-13} have made us think on the works on production of a time standard on the basis of lasers. Thus, the most vital aspect in the problem of production of an optical time scale is now frequency division up to a microwave range with no losses in accuracy.

Our many-year efforts in solving the above problems have been crowned with success this year. We have managed for the first time to synchronize a microwave oscillator to the frequency of a highly stable He-Ne/CH_4 laser, to compare standards and thereby to produce an optical time scale. Some results presented here have been obtained by V.M.Klementyev, M.V.Nikitin, V.G.Goldort, V.F.Zakharyash, and B.A.Timchenko.

2.- The optical time scale is based on the He-Ne laser with a methane cell made in our laboratory. Its arrangement and stability characteristics were described earlier. Here we focus our attention at the problem of division of a light frequency by a factor of 10^5 and of obtaining highly stable ultrahigh-frequency oscillations of a frequency synchronized He-Ne/CH_4 laser. The frequency division is performed stage by stage through phase synchronization of a long-wave oscillator with frequency f_1 to a short-wave one with frequency f_2. The phase synchronization is executed over a low-frequency beat signal f_{int} between harmonic nf_1 and frequency f_2 ($f_{int} = nf_1 - f_2$) with the aid of fast-response electron systems of phase offset lock (POL).

Figure 1 shows a relative instability between a reference laser

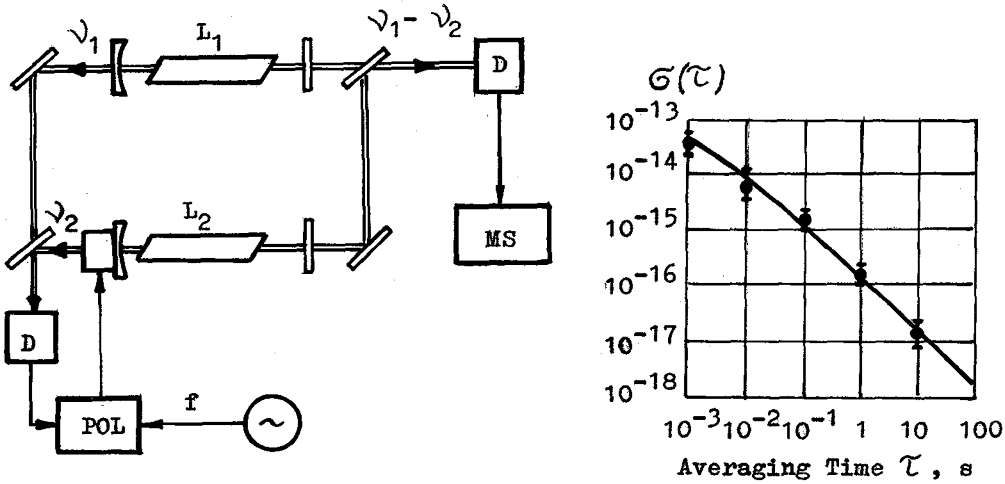

Fig. 1: Scheme of phase locking of lasers and frequency instabilities between them. D - detectors, MS - measuring system

and a phase-locked laser. For the time $\tau = 1$ s the instability is very small about 10^{-16}. This means that the synchronized laser has practically the same instability as the reference one. Phase locking of lasers in different ranges with the aid of fast-response electron systems was first performed in /5/.

The beat signal and harmonic are obtained by using fast-response diodes on the basis of point metal-oxide-metal contacts that are widely used in solving the problem of absolute measurements of optical frequencies /6, 7/. Point metal-semiconductor contacts were used in the submillimeter range. Note that the diode as a nonlinear element is an important unit in the scheme of frequency division. A high efficiency of harmonic generation permits one to reduce the number of lasers needed for frequency division by stages.

3.- The simplified block scheme of an optical scale is shown in Fig. 2. The use of systems of phase offset lock increases requirements to protection of lasers from various perturbations and requires high values of a signal-to-noise ratio as compared with frequency locking of lasers. All lasers, except for a highly stable He-Ne/CH_4 laser, were placed on the same massive steel plate. The He-Ne laser with a power of about 50 W had a length of about 5 m. The cavity of CO_2 lasers included diffraction gratings and a spherical mirror mounted on a piesoceramics. The laser length was about 1.5 m, power about 5 W. Submillimeter lasers with an optical pumping had a waveguide construction similar to that described in /8/.

Stable ultrahigh-frequency oscillations are achieved by successive and simultaneous synchronization of a He-Ne laser, a CO_2 laser, submillimeter lasers with optical pumping on CH_2OH (70.5 μm) and HCOOH (18.6 μm) and at last of klystron oscillators with an output of 4 GHz.

Table 1 gives the signal-to-noise ratio at each stage of laser synchronization. All systems of phase offset lock were controlled with the aid of a measuring system on the basis of computer that was also used for processing of the results of measurements. The system enables us to directly compare frequency stabilities of an ultrahigh

Table 1

	Unit	Signal / Noise (db)
1	He-Ne/CH_4-L → He-Ne-L (λ = 3.39 μm)	~30
2	He-Ne-L → CO_2-L	20-25
3	CO_2-L-I → CO_2-L-II	~25
4	CO_2-L-II → CH_3OH-L	15-18
5	CH_3OH-L → HCOOH-L	12-15
6	HCOOH-L → KO	15-20

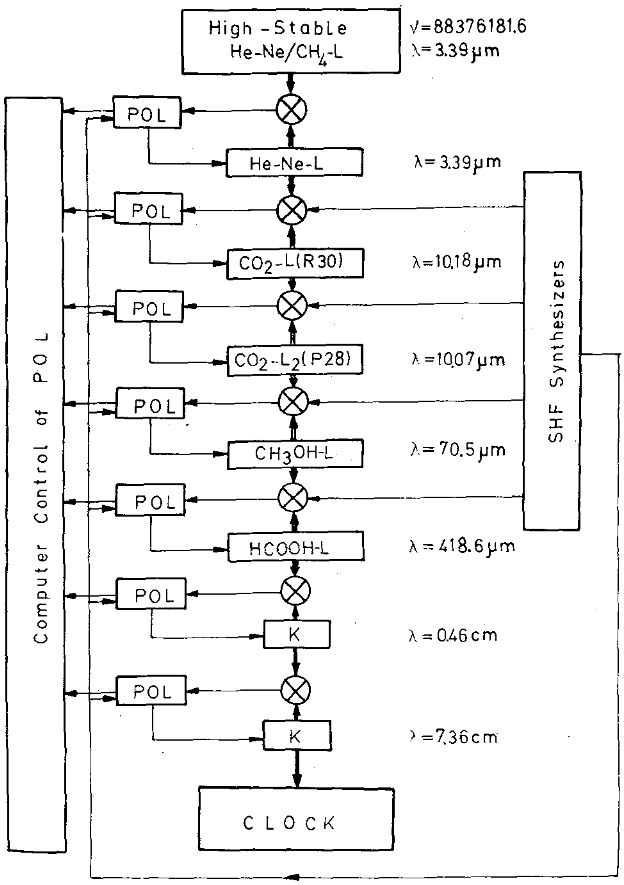

Fig. 2: Scheme of an optical time standard

frequency standard and of a laser. For this purpose the frequency of a rubidium standard was multiplied up to the frequency of 65 GHz that was close to that of the klystron synchronized over a He-Ne/CH_4 laser. The frequency characteristics of the signal of beatings between klystrons synchronized over the laser and the rubidium standard corresponded to instabilities of the frequencies of the laser and of the rubidium standard.

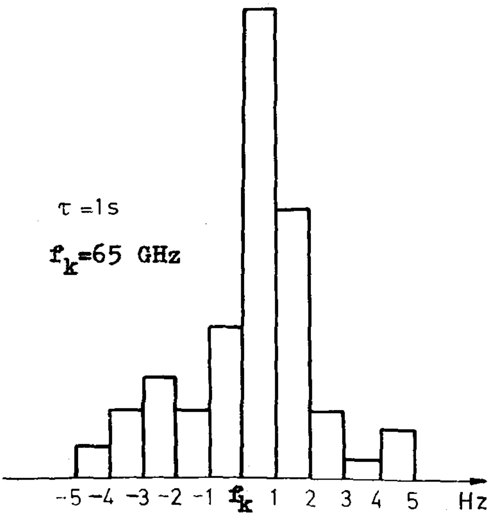

Fig. 3: Histogram of the beat signal between the klystrons synchronized over a He-Ne/CH_4 laser and a rubidium standard

Figure 3 shows the results of these measurements. Since the frequency stability of He-Ne/CH_4 considerably exceeds the stability of the rubidium frequency standard we use, these results correspond to the frequency stability of the rubidium standard.

The production of an optical time standard implies at the same time the solution of the following problems that are of independent significance: optical frequency standards, united time and length standard, absolute measurements of frequencies in the infrared and optical bands.

The transfer of frequency characteristics of the most stable oscillator in the range from 0 to 10^{16} simultaneously solves the problem of a united time and length standard. Naturally, we assume that a light speed is constant. Then the accuracy of determination of a wavelength will be determined by the accuracy of frequency measurements and by the definition of light speed.

4.- The comparison of the frequency of an ultrahigh-frequency oscillator synchronized to a laser with the ultrahigh-frequency standard through a known division coefficient gives an absolute measurement of laser frequency. By present a considerable progress has been achieved in the field of measurement of absolute infrared and optical frequencies. In the United States, England and the Soviet Union there have been produced large measuring systems for measurement of absolute laser frequencies of infrared and optical ranges. Our system differs considerably from those available at present.

The phase synchronization of laser provides the transfer of an absolute value of frequency with no losses in accuracy. The accuracy of measurement of an absolute value of frequency in the optical band will be therefore determined by the stability (accuracy) of an ultrahigh-frequency standard and by the frequency stability of a laser whose frequency is measured.

We have carried out the preliminary measurements of the frequen-

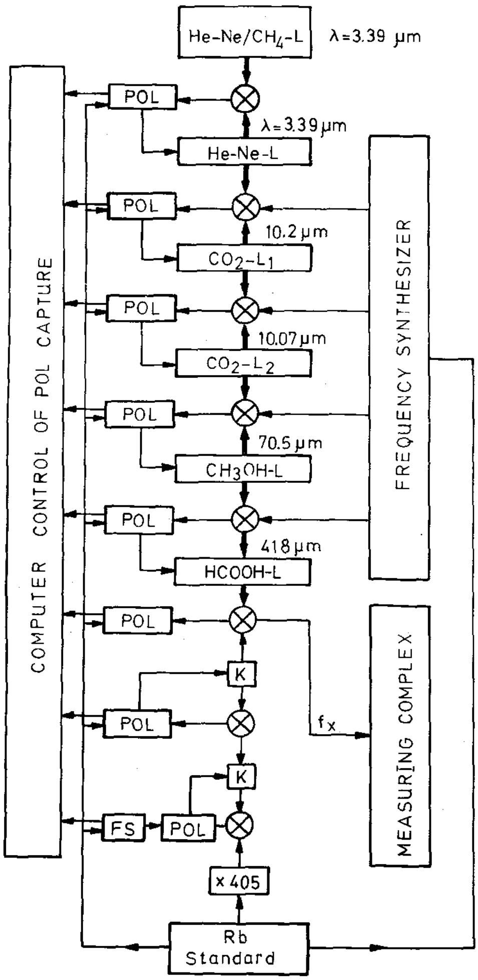

Fig. 4: Chain of measurement of the frequency of a He-Ne/CH_4 laser

cy of a He-Ne/CH_4 laser stabilized to the resonance of saturated absorption in methane. The frequencies of this laser were measured earlier in /9-11/. Unfortunately, the latest and most precise results differ. New measurements are therefore of undoubted interest.

The scheme for measurements is given in Fig. 4. In order to decrease the time of measurements and comparison of frequencies of the oscillator synchronized to the He-Ne/CH_4 laser and of the rubidium standard we carried out measurements at 716 GHz. We compared the second harmonic of the klystron oscillator with the frequency of a HCOOH laser. The frequency synthesis was selected in such a way that the measured difference of beat frequencies lay in the range of 10 MHz. This was also made for the considerations that standard comparators might be used for increasing an accuracy of frequency measurements. The part of the scheme that corresponds to the phase synchronization of a HCOOH laser is totally similar to that used in the production of clock.

In our experiments the presence of the HCOOH laser permitted us to do without a backward wave tube, the radiation with a known frequency in the region of HCOOH, as has been already said, was obtained in a MOM diode as the second harmonic of a klystron. In experiments we measured only the frequency f_{meas}.

In the process of measurements it has been elucidated that due to spectral distribution of noises of the contact the measured frequency f_x may be pulled towards low frequencies by a value of about 100 Hz, which may give an error in frequency measurements $f_{CH_4} \sim$ ~ 10 kHz, as the ratio of frequencies is $f_{CH_4}/f_{HCOOH} \simeq 126$. The pulling depends on the signal-to-noise ratio, the value of the frequency f_x and on the width of the beat signal determined by the characteristics of a rubidium standard. We did not change the scheme of frequency synthesis. A frequency of the He-Ne laser was measured in two schemes of synthesis and calculated from the formulas:

$$f^1_{He\text{-}Ne/CH_4} = +126 f_x + 1386 f'_{k_5} - 21 f_{k_4} + 3 f_{k_4} - 15 f_{k_2} + f_{k_1} + 106 \text{ MHz},$$

$$f^2_{He\text{-}Ne/CH_4} = -126 f_x + 1386 f''_{k_5} - 21 f_{k_4} + 3 f_{k_3} - 15 f_{k_2} + f_{k_1} + 106 \text{ MHz}.$$

where f_{k_i} is a frequency of the klystron oscillator. The sought frequency $f_{He\text{-}Ne/CH_4}$ was found as a halfsum of these values and proved to be equal to 88376181603.0±3 kHz. The results of measurements are somewhat different from those of the works /10, 11/ and well agree with the recent communication /12/.

The simplified scheme of frequency synthesis in combination with a highly stable laser will allow even in the nearest future to produce a united time and length standard. In its characteristics it can exceed the available time and length standards.

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