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Development of an Optical Time Scale*

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Abstract. A time standard based on the use of an optical oscillation period of a frequency-stable He-Ne laser as a time scale is first described. We obtained highly frequency-stable oscillations in the SHF range that were locked to the oscillations of a He-Ne laser stabilized to an absorption resonance in methane at 3.39 μm. A direct comparison of frequency stabilities of a rubidium standard and He-Ne/CH_4 laser has been made. The absolute measurement of the frequency of the He-Ne/CH_4 laser we performed gave a new value of frequency.

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The paper reports on the development of an optical time standard based on the use of an optical oscillation period of a frequency-stable laser whose frequency is 10^4 times as high as that of the available atomic time standard.

The development of a frequency standard in the optical region has become possible due to the advent of lasers whose long-term frequency stability and reproducibility are of the same order as that of the best masers, the short-term stability and reproducibility much better [1]. The laser frequency division up to the microwave range and phase locking of oscillators including quartz ones in the radio-frequency range to the frequency of a high stable 3.39 μm He-Ne laser provide a direct comparison of the second, a time unit, with the optical oscillation period in the frequency range from 0 to 10^{14} Hz.

Experimental Setup

The installation is shown in Fig. 1. The main unit is the high stable He-Ne/CH_4 laser stabilized to a power resonance in methane at 3.39 μm we produced in our laboratory [2]. The frequency of this laser is shifted by 1.7 kHz towards high frequencies from the central component 6–7 of a magnetic hyperfine structure of the $F_2^{(2)}$ line of the $P(7)$ transition of the ν_3 band in methane. Stable oscillations in the SHF range that are phase-synchronized to the oscillations of a He-Ne/CH_4 laser are achieved by successive and simultaneous synchronization of the frequency of a high-power He-Ne laser ($\lambda = 3.39$ μm), CO_2 laser ($\lambda = 10.2$ and 10.07 μm), submillimeter optically pumped CH_3OH lasers ($\lambda = 70.5$ μm), HCOOH lasers ($\lambda = 418.6$ μm) and klystron oscillators (K) at frequencies of 65 and 4.1 GHz. Frequency locking of lasers with a longer wavelength to those with a shorter one was performed through a fast-response system of phase-offset lock over the signal of beatings between the corresponding harmonic of a long-wavelength one. These systems permit the transfer of all frequency characteristics of a high stable laser from one range to another. The harmonic and beat signal are obtained by mixing laser frequencies in a point diode on the basis of a metal-oxide-metal contact (MOM diode) that has been developed to measure laser frequencies [3, 4]. In the SHF and submillimeter ranges (up to 418 μm) we used the point diodes with a metal-semiconductor (usually silicon) contact. The figure shows the SHF synthesizers used for canceling the frequency difference of 10^{-4} Hz between laser harmonics to obtain, at the output of nonlinear elements, low-frequency oscillations that are necessary for the operation of fast-

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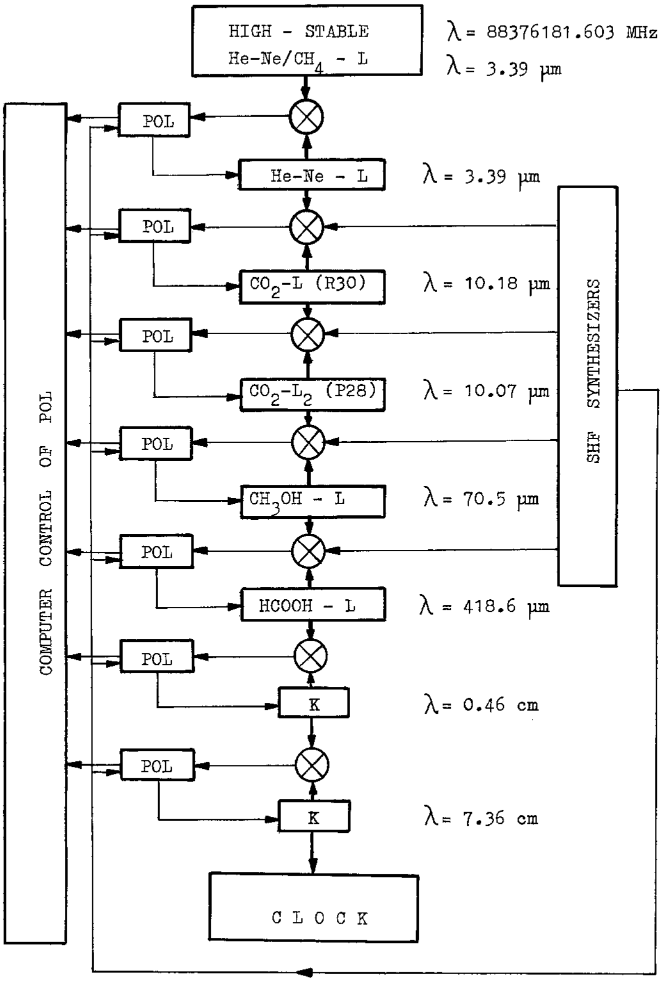

Fig. 1. Schematic of an optical time scale

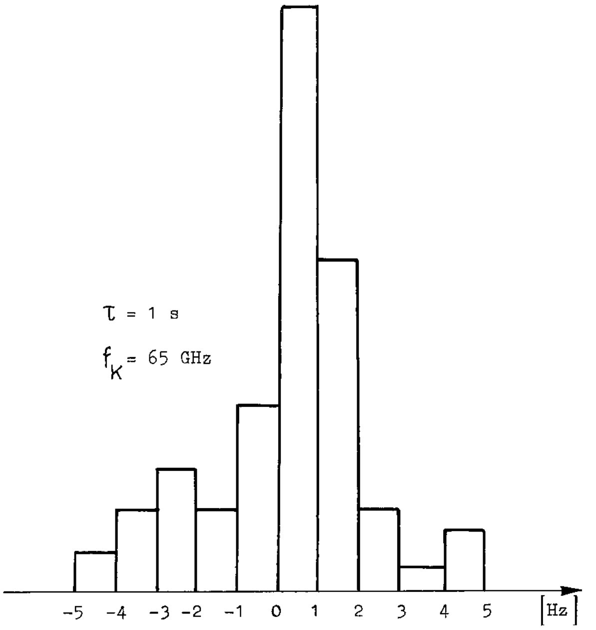

Fig. 2

response systems of phase offset lock (POL). The simultaneous locking of all oscillators to the frequency of the He-Ne/CH_4 laser was controlled by a measuring-computing system on the basis of an electronic computer (MCS).

Phase-Locking Scheme

With phase-locking to a He-Ne laser, the frequency characteristics of the He-Ne laser are transferred to the oscillators in the other ranges [5]. Due to this we first realized a direct comparison of the frequency characteristics of a SHF 65 GHz oscillator, a frequency-locked laser and a SHF standard. For this purpose the frequency of a rubidium standard was multiplied up to that of the klystron ($f_{k5} \simeq 65$ GHz) and the frequency mixing gives a signal of an intermediate frequency of 10 MHz at the output of the mixer. The results of measurements are presented in the form of a histogram in Fig. 2. The histogram characterizes the relative stability of the frequency of a rubidium standard (3×10^{-11}), as its frequency characteristics are considerably worse than those of a He-Ne/CH_4 laser.

Measurements

With the known factor of division, the measurement of the frequency of a SHF oscillator synchronized to a He-Ne/CH_4 laser permits one to obtain an absolute value of laser frequency. The measurements were performed in [6, 8]. New measurements are of interest, as the frequency values obtained with a high accuracy in [7, 8] are different. Our measuring system is shown in Fig. 3. It uses the same chain of oscillators as that shown in Fig. 1. The 11th harmonic of the frequency ν_{k5} (65 GHz) of the klystron synchronized to a rubidium standard was compared to the frequency of 716 GHz of an HCOOH laser synchronized to that of a He-Ne/CH_4 laser. The frequency synthesis was performed in such a way that the condition $11 f_{k5} - \nu_{\mathrm{HCOOH}} = f_x \simeq 10$ MHz is fulfilled. The measured signal of an intermediate frequency f_x was fed to the MCS.

The frequency of a He-Ne/CH_4 laser was measured in two synthesis schemes and calculated by

$$\begin{aligned}\nu_{1\,\mathrm{CH_4}} &= +126 f_x + 1386 f'_{k5} - 21 f_{k4} \\ &\quad + 3 f_{k3} - 15 f_{k2} + f_{k1} + 106\,[\mathrm{MHz}]\,, \\ \nu_{2\,\mathrm{CH_4}} &= -126 f_x + 1386 f''_{k5} - 21 f_{k4} \\ &\quad + 3 f_{k3} - 15 f_{k2} + f_{k1} + 106\,[\mathrm{MHz}]\,.\end{aligned}$$

The desired value of the frequency was found as a halfsum of these values. At first $\nu_{\mathrm{CH_4}}$ was obtained as an arithmetic average for the series of 20 measurements, then the mathematical treatment of these re-

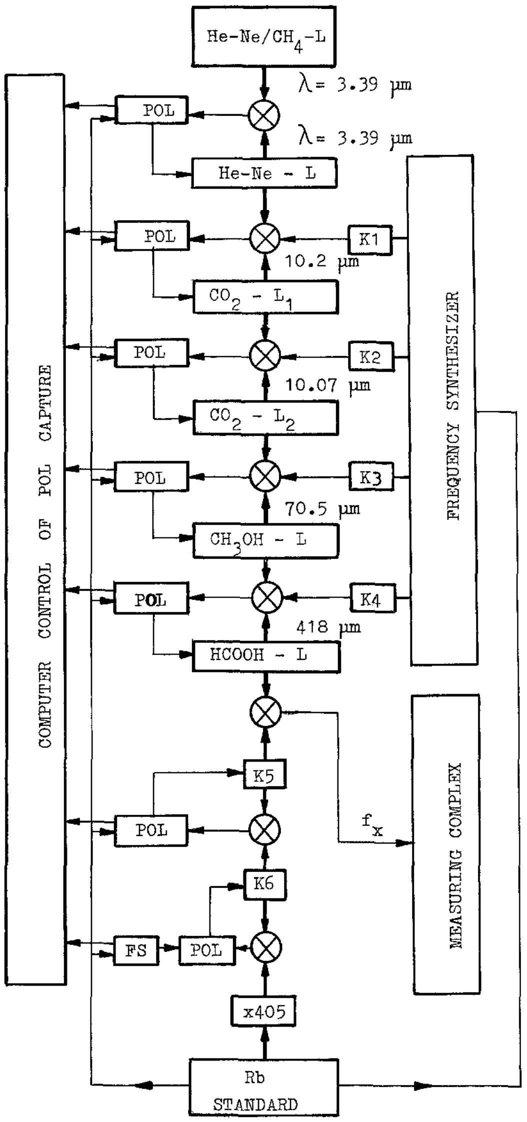

Fig. 3. Schematic of the installation for measuring the frequency of a He-Ne/CH$_4$ laser

sults was performed. 28 series were obtained for each calculation of $\nu_{1\,\mathrm{CH}_4}$ and $\nu_{2\,\mathrm{CH}_4}$. The time of one measurement was 0.05 s. The measurements were performed in April and June, 1981 and gave the same results according to which $\nu_{\mathrm{CH}_4} = 88376181.603 \pm 3$ MHz. The rubidium standard we used was tested and certificated at the Siberian Institute of Metrology. This result differs from those of [7, 8] and agrees with the recent communication [9]. As has been already noted, the precision of our measurements is due to the frequency characteristics of the rubidium standard and to an error of measurement of frequency f_x.

Outlook

An increase of the time standard frequency permits a shortening of the time of measurements and an increasing of accuracy. The simplification of the scheme of frequency synthesis in combination with the use of a high stable laser will enable one, even in the nearest future, to proceed toward the creation of a united time and length standard, that in its characteristics may be superior to the available time and length standards.

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