Measurement of the frequency of a He–Ne/CH_4 laser

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All-Union Scientific Research of Physicotechnical and Radiotechnical Measurements

(Submitted 18 June 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 4, 175–178 (20 August 1981)

The frequency of a He–Ne laser stabilized through the F_2^2 component of methane has been measured in the most accurate measurements reported to date. A completely phase-locked chain of lasers was used for the measurements. The frequency of the He–Ne/CH_4 laser is 88 376 181 603.4 ± 1.4 kHz.

PACS numbers: 42.55.Fn

The He-Ne laser stabilized through the F_2^2 component plays an important role in optical frequency standards. The potential applications of this laser have been expanded by the development of methods for measuring laser frequencies. Independent measurements of the frequency and wavelength of the He-Ne/CH_4 laser have made it possible to refine the value of velocity of light by two orders of magnitude.[1] The next step is to redefine the meter and to use the optical standard as a common standard of time, frequency, and length. It is therefore important to determine the frequency of the He-Ne/CH_4 laser accurately.

In this letter we are reporting the most accurate measurements to date of the frequency of the He-Ne/CH_4 laser. The relative error of the measurements is no greater than 1.6×10^{-11}.

Figure 1 shows a simplified diagram of the multiplying laser chain developed for these measurements. The most important point to be noted is that the submillimeter lasers are phase-locked with the standard, while the infrared lasers are phase-locked with the He-Ne/CH_4 laser. The multiplying chain is thus completely phase-locked, and the measurements are carried out at only a single point.

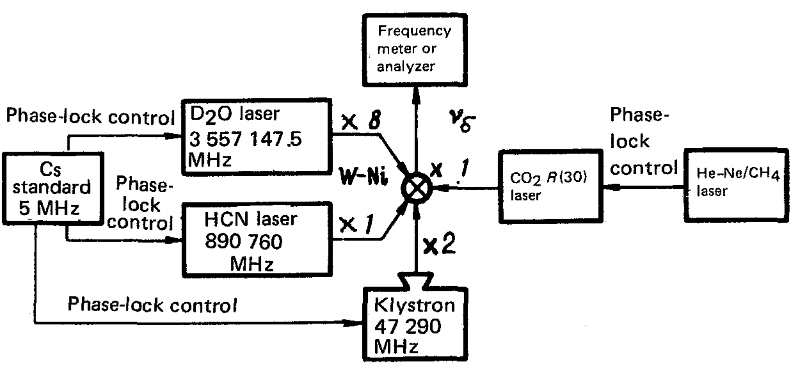

FIG. 1. Simplified diagram of the multiplying laser chain.

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The concept underlying the phase locking of the CO_2 laser at the $R(30)$ line with the He-Ne/CH_4 standard is the same as in Ref. 2, where a system is described for locking a CO_2 laser at the $R(30)$ line with a CO_2/OsO_4 standard. The system for phase locking of HCN and D_2O lasers is described quite thoroughly in Ref. 3.

The typical beat signal at the measured frequency ν_6 has a signal-to-noise ratio of 10–12 dB in a 100-kHz band and a signal spectral width of 70–120 kHz. Because of the low signal-to-noise ratio, the frequency measurements were first carried out with a spectrum analyzer. Many of these measurements were rejected when a comparison revealed a large uncontrollable error, attributable to the spectrum analyzer. It turned out that the analyzer introduced a frequency shift whose direction and magnitude depended on the operating conditions of the analyzer, but the actual presence of the shift was a consequence of the broad spectrum of the measured signal.

For all those measurement runs with the spectrum analyzer which were used to determine the frequency of the He-Ne/CH_4 laser we measured the corresponding correction to the analyzer readings and made appropriate corrections to the measurement results. To determine the correction, we simulated a beat signal by modulating the frequency from an rf oscillator with a low-frequency Gaussian noise. This simulated signal was then converted with the help of a local oscillator whose frequency was higher than the signal frequency in one case and lower in another. An analyzer was used to measure the intermediate frequency. Since the sum of the analyzer readings is equal to the difference between the local-oscillator frequencies, we determined the correction for the analyzer from it.

Some of the measurements were carried out with a frequency meter. Since the signal-to-noise ratio was too low for a direct reading of the signal frequency by the frequency meter, we used an auxiliary tracking rf oscillator. The beat signal was used to arrange phase locking of this oscillator, and a frequency meter was used to read its frequency. The cutoff frequency of this phase-locking loop was 27 kHz. Under these conditions there was a satisfactory locking at a signal-to-noise ratio of 10 dB at the input in a 100-kHz band and with a spectral width of no more than 80 kHz for the beat signal.

Six measurement runs were carried out over a three-month period starting in February and ending in May of 1981. Five of the runs (487 readings) were made with the spectrum analyzer, under various operating conditions, and in one of these runs we used a preliminary amplitude clipping of the measured signal. The corrections for the analyzer ranged from 7.8 ± 2.1 to -2.2 ± 0.9 kHz under the various operating conditions. In the first run the standard deviation was 11.7 kHz, and the average deviation was 0.94 kHz; the corresponding figures for the last run were 5.1 and 0.66 kHz, respectively. The longest run (322 readings) was carried out with the frequency meter. In this case the standard deviation was 8.7 kHz and the average deviation 0.48 kHz.

Figure 2 shows histograms of four runs, after corrections for the analyzer. These histograms show that the spread in the measured values corresponds satisfactorily to a normal distribution law. There are no excursions beyond 3σ. The mean values found for the frequency of the He-Ne/CH_4 laser were approximately the same for all experimental runs, agreeing within the random errors.

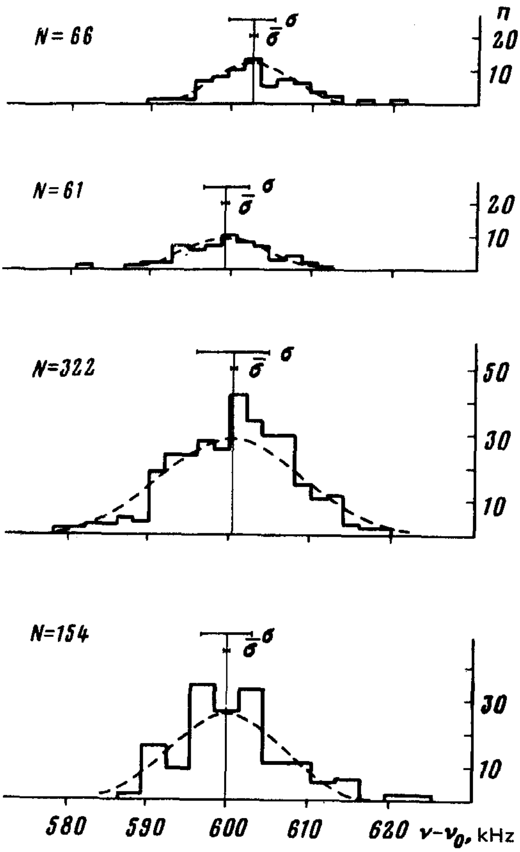

FIG. 2. Histograms of the corrected measurements. The dashed curves show a normal distribution.

Since each run has its own advantages and disadvantages, we incorporated all six of the runs, with equal weights, in the final analysis. As a result, we found the following value for the frequency of the portable He-Ne/CH_4 laser, for which these measurements were carried out: $\nu_p = 88\ 376\ 181\ 599.9 \pm 1.2$ kHz. The error of 1.2 kHz is due primarily to the uncertainty in the corrections for the analyzer. The random error of the direct frequency readings is much smaller in the case of the frequency meter: 0.48 kHz or a relative error of $\sim 5 \times 10^{-12}$.

During the time intervals between successive measurement runs we compared the frequency of the portable He-Ne/CH_4 laser used in the measurements with that of a stationary He-Ne/CH_4 laser. It was found that the frequency of the portable laser is 3.5 ± 0.7 kHz lower than that of the stationary laser. When all the corrections are taken into account, therefore, the frequency of the He-Ne/CH_4 laser turns out to be $88\ 376\ 603.4 \pm 1.4$ kHz.

This frequency agrees with the data reported by Clairon *et al.*[4] (. . . 618 ± 13.8 kHz) but not with the more accurate measurements of Knight *et al.*[5] (. . . 616 ± 3

kHz) or with our own preliminary measurements.[2] Our previous measurements, we should point out, were afflicted by a systematic error attributable to the spectrum analyzer. This error is estimated to be no less than 10.4 kHz, and when it is taken into account the results of the two series of measurements agree.

In summary, this study has essentially achieved the limiting accuracy of absolute frequency measurements for the He-Ne/CH_4 laser stabilized through the F_2^2 component of methane, since the reproducibility of the portable lasers used in the comparisons was limited to $\sim 10^{-11}$. In 1979, our stationary laser was compared with portable lasers of the International Bureau of Weights of Measures,[6] and the difference between the frequencies of the best IBWM laser (BICH-4.6) and that of our stationary laser was 1.26 ± 0.66 kHz.

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Translated by Dave Parsons
Edited by S. J. Amoretty