Absolute measurements of IR laser frequencies

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We attained an accuracy of 10^{13} in the absolute measurements of the frequencies of long-wave lasers, including CO_2 lasers. The measurement accuracy is 1×10^{10} in the shorter wavelength region of the IR (to 3.39 μm). The frequency of the CO_2:OsO_4 laser is measured for the first time, 28 464 676 938.5 ± 1 kHz. A much more accurate frequency of the He-Ne:CH_4 laser was obtained: 88 376 181 586 ± 10 kHz.

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To solve the problem of absolute measurements of the laser frequencies, we proposed[1] and partly implemented the following scheme of transferring the standard frequencies from a cesium standard to the optical region of the spectrum:

$$\text{Cesium standard }\overset{1}{—}\text{HCN (337 }\mu\text{m)}\overset{2}{—}D_2O\text{ (84 }\mu\text{m)}\overset{3}{—}$$

$$\overset{3}{—}CO_2 : OsO_4\overset{4}{—}CO_2\text{ (10.18 }\mu\text{m)}\overset{5}{—}\text{He-Ne:}CH_4\text{ (3.39 }\mu\text{m)}$$

Indicated above are the working laser media and the wavelengths. In addition to lasers, each component of the scheme contains SHF sources in the centimeter or millimeter ranges. Frequency conversion was accomplished by using special point-contact, tungsten-silicon diodes in the first component and tungsten-nickel (MOM-diodes) in the other components.

In this paper we report a significant increase in the accuracy of the entire scheme as a whole and the precision frequency measurement of the CO_2:OsO_4 and He-Ne:CH_4 optical standards. These achievements are based largely on the sound structure of the selected measuring system, which has certain advantages over the one developed elsewhere.[2,3] Because of introduction of the D_2O and CO_2:OsO_4 lasers, the multiplication orders were reduced, satisfactory signal-to-noise ratios were obtained in all the components (not less than 20 dB in the 50-kHz band), and the system contains two promising optical standards.

Frequency stabilization of submillimeter lasers can be accomplished by using a narrow-band system of phase synchronization of the D_2O laser according to the frequency standard. Such a system, first advanced and implemented in Ref. 4, was used for the HCN laser. For the standard signal this system issued as a narrow-band servo filter, which attenuates the white phase noise of the standard. The required band of such a filter is ~10 Hz at the D_2O laser frequency. The slow frequency drift of the D_2O laser which is eliminated almost completely in such a system, has no effect on the accuracy of measurements when the averaging time is greater than 10 sec. The system works as follows. The HCN laser and the 74-GHz and 8.2-GHz klystrons are sequentially synchronized with the D_2O laser. The phase of the 8.2-GHz standard signal is compared with the klystron output and the error signal is fed to the frequency control of the D_2O laser. All the foregoing sources in the closed system attain well-defined values of frequencies and, in particular, the HCN and D_2O laser frequencies are equal to 890 760 MHz and 3 557 147.5 MHz, respectively, within the accuracy of the frequency standard. For the first time it was possible to measure frequency of the submillimeter and of the far-infrared laser, including the emission region of the CO_2 lasers, with accuracy of $\sim 10^{13}$ by using the HCN and D_2O lasers and their harmonics. Using the eighth harmonic of the D_2O laser, we can now determine the frequency of the CO_2:OsO_4 standard with the same accuracy.

The CO_2:OsO_4 laser with an external absorption cell was tuned to the most intensive molecular resonance of the OsO_4 molecule, which lies on the *P*(14) line in the laser emission region.[5] The OsO_4 vapor pressure in the cell was $\sim$2.5 Pa. The total width of the resonance was $\sim$200 kHz. Its amplitude was equal to 2% of the reflected power. The estimated stability of the laser was equal to 3×10^{-11}. The measurements of the CO_2:OsO_4 laser frequency were conducted for two weeks at relatively constant parameters of the laser and of the stabilization system. The greatest difficulties were connected with controlling the frequency shifts due to a relatively high level of the parasitic amplitude modulation. Therefore, each series of measurements was carefully compensated for before recording the resultant imbalance, so that corrections could be made. As a result, the following frequency was obtained for CO_2:OsO_4 laser: 28 464 676 938.5 ± 1 kHz; the error was determined almost entirely by the laser instability.

The frequency of the He-Ne:CH_4 laser was measured from the known frequency of the CO_2:OsO_4 laser by using the components 4 and 5. In addition, the frequency of the CO_2 laser at the *R* (30) line was synchronized by using a special system of phase self-tuning with respect to the CO_2:OsO_4 laser. The frequency of the beat signal of the 3rd harmonic of the CO laser, of the 48-GHz klystron, and of the high-power (100 mW) He-Ne laser, which was phase synchronized with the frequency of the He-Ne:CH_4 standard, was measured directly by using the spectrum analyzer.

The He-Ne:CH_4 laser has the following basic characteristics. It is a portable instrument with sealed amplifying and absorbing tubes. The total width of the molecular resonance is $\sim$300 kHz, which is equal to 3% of the output power. The reproducibility of the laser frequency between switching is better than 1×10^{-11} and its instability for several hours is equal to 10^{-12}.

As the result of analyzing several series of measurements, we establish the following frequency of the He-Ne:CH_4 laser: 88 376 181 586 ± 10 kHz. The estimated error of 10 kHz is attributable basically to the instability of the CO_2:OsO_4 laser. In this experiment the additional destabilizing effect on the CO_2:OsO_4 laser was caused by the back reflections from the MOM diode. This effect was reduced by a Fresnel's rhomb and by slight detuning. However, it was not possible to eliminate this effect, which introduced into the frequency of the CO_2:OsO_4 laser an uncertainty of the order of 3 kHz. Note that the obtained value lies within the error range of earlier measurements: 88 376 181 627 ± 50 kHz[2] and 88 376 181 608 ± 43 kHz.[3] This fact deserves special attention, because the frequency of methane transition was used in the exact calculation of the speed of light.[6] Our result, which was obtained by using a radically different system and much more stable intermediate lasers, increases the accuracy and reliability of the accepted value of the speed of light.

This device raised the measuring accuracy of the whole system to the level of the frequency standard. For this reason, it is necessary to build a CO_2:OsO_4 laser with a sufficiently high ($\sim 10^{-13}$), long-term frequency stability. According to Ref. 5, this problem can be solved.

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