Extension of Absolute Frequency Measurements to the cw He-Ne Laser at 88 THz (3.39 μ)

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The highest absolute frequency measurement yet reported is described. The frequency of the 3.39-μ line from a He-Ne laser oscillating at the methane absorption frequency was found to be 88.376245 (55) THz. The frequency was measured by beating the 88-THz radiation with the $R(30)$ line from a cw CO_2 laser and a 48-GHz klystron in a tungsten-on-nickel point-contact diode. The speed of light calculated from this frequency and previous wavelength measurements is in agreement with the accepted value and of comparable accuracy.

This letter describes the highest frequency measurement as yet reported, and completes a chain of known frequencies extending from the National Bureau of Standards cesium beam frequency standard. The frequency of the 3.39-μ He-Ne laser was measured by synthesizing this frequency from the third harmonic of the $R(30)$ line of the CO_2 laser plus 48 GHz from a klystron. The harmonic generation and mixing all occurred in a tungsten-on-nickel diode. The $R(30)$ (10.2-μ) CO_2 frequency is known from our previous measurements[1] on the $P(18)$ and $P(20)$ (10.6-μ) lines and on difference frequency measurements.[2,3] The highest previous frequency measurement[4] was at 5 μ with a pulsed CO laser.

The three sources of radiation necessary were provided by cw He-Ne and CO_2 lasers and a conventional tunable cw 50-GHz klystron. The 8-m He-Ne laser was filled with 0.4 Torr of Ne^{20} and 3.0 Torr of He^3. This pressure was chosen to maximize the laser power and to pressure shift the top of the gain curve toward the CH_4 absorption to which the laser will eventually be stabilized. Mirrors consisted of a 30-m-radius total reflector and a 50% reflecting output flat. A piezoelectric translator was placed on the total reflector. The 13-mm-i.d. tube was sealed with Brewster-angle windows. The laser operated in a single longitudinal mode with 50 to 60 mW of output power. One of the reasons for the success of this experiment lies in the single-mode operation of this laser. The single longitudinal mode apparently results from a pressure width somewhat comparable with the Doppler width and the large degree of saturation of the laser transition due to the extreme length of the laser.

The 1.5-m CO_2 laser was sealed off and had NaCl Brewster windows. The power was reduced to 400 mW with an internal iris diaphragm. A grating was used on one end, and a 95% reflector on the other. A piezoelectric translator on the output mirror provided the fine tuning of the laser. Both lasers used invar rod spacers.

The tungsten-on-nickel harmonic-generator mixer for this experiment was similar to that used to measure the 3.8-THz (78-μ), 10.7-THz (28-μ), and 28-THz (10.6-μ) frequencies.[1,5] The nickel sample used in the experiment was selected from several different purity specimens tested by beating the fourth harmonic of the 0.964-THz (311-μ) HCN laser with the 3.8-THz (78-μ) H_2O laser plus a 35-GHz klystron. This is the same beat note used in comparing the sensitivity of the Josephson junction[6] with that of the tungsten-on-nickel diode. All specimens were tested with the same tungsten catwhisker (which was not repointed between testings). A wide variation was noted which seemed to be independent of purity (ranging from 95 to 99.995%). Repeated measurements on similar specimens were quite reproducible at several different locations on the face of the nickel sample. Tungsten on tungsten produced no signal and the tungsten-on-graphite diode reported by NPL[7] produced a S/N ratio of about 20 dB, while 40 dB was obtained for the chosen nickel sample. The chosen specimen was optically polished and ultrasonically cleaned; the horizontal antenna[8] was a 2.5-μ-diam tungsten wire 0.7 mm long which was etched in a conventional 3N KOH solution with a small Cu ion addition. The 88-THz radiation was focused onto the antenna with a 2.5-cm focal-length lens and a 10-cm focal length was used for the 29-THz radiation. Empirically, it appeared desirable to form the diode with no radiation on the diode. The diode was somewhat unstable; however, it lasted as long as 1 h at a time without the necessity of further adjustment. The same wide-band (10–70-MHz) amplifier and spectrum analyzer were used as in earlier experiments.[1,5]

A single 2-msec/cm trace shows the beat note centered at 40 MHz in Fig. 1. The dispersion was 200 kHz/cm and the bandwidth was 12 kHz. Multiple traces showed the medium term stability (tenths of seconds) to be about 400 kHz (presumably due to mechanical instabilities in the laser cavity). After the lasers and klystron had warmed up for several hours, the beat note drifted only a few megahertz in $\frac{1}{2}$ h. The best signal-to-noise ratio was 28 dB while that illustrated is a little less. It is interesting to note that this signal-to-noise ratio is greater than that obtained from any of our four earlier laser frequency measurements.[1,5] This is presumably due to the lower-order harmonic generation used as well as a somewhat more sensitive diode. However, it is difficult to make comparisons because the harmonic number has been so different in the various experiments and more power is available at the higher frequencies.

In order to make the measurements, the center of the gain curve of each laser needed to be determined. In order to set the CO_2 laser to the top of its gain curve, the piezoelectric translator voltage was varied and the beat note was followed to extinction on the spectrum analyzer. The beat note was then centered between the two extinction points. Centering the He-Ne frequency was slightly more difficult. When this laser was tuned both plus and minus 57 MHz from the presumed center of its gained curve, the laser would jump 18 MHz to the next longitudinal mode closer to the center. It was assumed that the position midway between these two jump

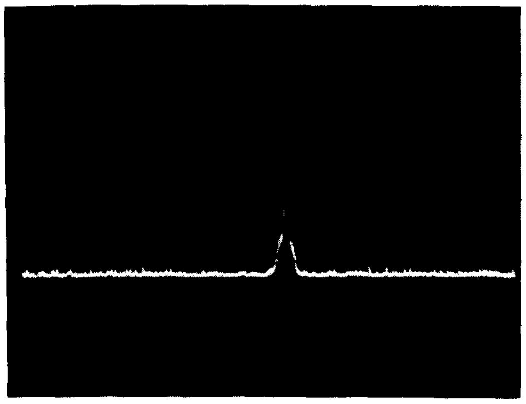

FIG. 1. Beat frequency between the He-Ne laser and the synthesized signal from the CO_2 laser and a klystron. The beat frequency was at 40 MHz and the dispersion was 200 KHz/cm with a 12-KHz bandwidth.

places was the center of the gain curve. The klystron was adjusted so the beat from the two lasers went to zero. Its frequency was then read on a wavemeter, which was checked by a frequency counter and *X*-band klystron.

The frequency of the He-Ne laser is calculated as follows:

$$\nu_{\text{He-Ne}} = 3\times 29.442509 + 0.048673$$
$$= 88.376200\ (50)\ \text{THz}.$$

To obtain the error estimate of ± 50 MHz, the errors listed in the previous CO_2 measurement were analyzed statistically. The analysis resulted in a ± 10-MHz probable error for the *P*(18) and *P*(20) measurement. This resulted in an accuracy of the *R*(30) line listed by Chang[3] of about 15 MHz.

The errors were

frequency of *R*(30)×3	± 45 MHz
centering *R*(30)	± 5 MHz
centering He-Ne	± 10 MHz
klystron frequency	± 5 MHz.

Although the accuracy of this frequency measurement is only 5 parts in 10^7, an accuracy of 1 part in 10^9 is easily obtained with sufficiently stabilized lasers. Frequency measurements in the microwave region have been performed to accuracies better than parts in 10^{12}. The resetability of the methane-stabilized 3.39-μ He-Ne laser was reported[9] to be 1 kHz (1 part in 10^{11}) with a stability of ± 3 Hz (3 parts in 10^{14}) for averaging times of 10–1000 sec. This accuracy contrasts markedly with the 1 part in 10^8 accuracy of the present length standard.

To obtain the frequency of the CH_4 absorption, the frequency difference between our He-Ne laser and a small He-Ne laser with a methane absorption cell was measured by beating the two lasers together. The measured frequency difference is

$$\nu_{CH_4} - \nu_{\text{He-Ne}} = +45\ (5)\ \text{MHz}.$$

Therefore, an adjustment of 45 MHz can be added to our measured frequency giving the result

$$\nu_{CH_4} = 88.376245\ (55)\ \text{THz}.$$

The wavelength of the methane-stabilized He-Ne laser has already been measured to about 1 part in 10^8 by Giacomo[7] and Barger[7] giving a value of 3.3922314 μ. Multiplying this value by our frequency, one obtains

$$c = \lambda\nu$$
$$= 2.9979267\ (20)\times 10^8\ \text{m/sec}.$$

This value is in agreement with the accepted[10] value of 2.9979250 (10)× 10^8 m/sec.

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