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ABSOLUTE FREQUENCY MEASUREMENTS OF THE CO_2 cw LASER AT 28 THz (10.6 μm)

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The two highest cw absolute frequency measurements as yet reported are described. Frequencies of the $P(18)$ and $P(20)$ 10.6-μm lines from a cw CO_2 laser were found to be 28.359800 THz and 28.306251 THz ± 0.000025 THz, respectively. The frequencies were measured by beating each of these lines with 3.8-THz (78 μm) and 10.7-THz (28 μm) radiation from a water vapor laser and a 26- to 28-GHz klystron in a tungsten-on-nickel point contact diode.

This letter describes the two highest cw frequency measurements as yet reported. The frequencies of the two strongest lines, $P(18)$ and $P(20)$, of the 28-THz (10.6 μ) branch of the CO_2 laser were measured by comparing each line with combinations of harmonics from the 10.7- and 3.8-THz water vapor laser, previously measured by the same technique,[1] and a 26- to 28-GHz klystron.

The relation between the various frequencies of the laser line, $\nu_{CO_2} = 3\times\nu_{28\,\mu m} - \nu_{78\,\mu m} \pm \nu_{klystron} + \nu_{beat}$, requires three sources of radiation in the experiment. A conventional 0.5-m flowing CO_2-He-N_2 laser produced 2 or 3 W of radiation in a single line. One laser and end mirror was tuned with a piezoelectric driver, and a grating monochromator was utilized to indicate proper tuning of the laser to either the $P(18)$ or $P(20)$ lines which were to be measured. A single 8 m long, compound beam-splitter water vapor laser provided both 10 mW of 3.8-THz and 350 mW of 10.7-THz radiation as in the previous experiment.[1] The small difference frequency radiation came from a conventional klystron which provided about 50 mW of power between 26 and 28 GHz. The microwave frequency was measured by a wavemeter calibrated by the National Bureau Standards.

The same tungsten-on-nickel harmonic generator-mixer that was used to measure the 3.8- and 10.7-THz frequencies was used again. Upon progressing to higher frequency measurements, additional diode instabilities were encountered, which might possibly be due to larger thermal-expansion effects caused by much higher power levels than in the previous lower frequency measurements. Necessary conditions for the observation of the desired beat note were a 4 to 5 mV detected dc voltage and a strong 18.7-MHz intermode beat note from the 10.7-THz line. The diode was so unstable that any appreciable change in either the 10.7- or 28-THz power levels destroyed the operational contact. Due to this instability, it was necessary to form the contact while the radiation was present on the cat-whisker diode.

In the previous experiment 50 mW of power at 0.89-THz radiation produced 40 mV of detected signal, while presently 350 mW of 10.7-THz radiation yielded only 5 mV of detected signal; this decrease might be explained by an increasing capacitive shunting of the diode with higher frequency. A 10-60 MHz video amplifier and spectrum analyzer were used for a video display of the beat note. The frequencies of the water vapor laser were not measured at this time, rather the values from the earlier measurements[1] were used.

The $P(18)$ beat note is shown in Fig. 1. The signal is centered at 98 MHz (somewhat above the

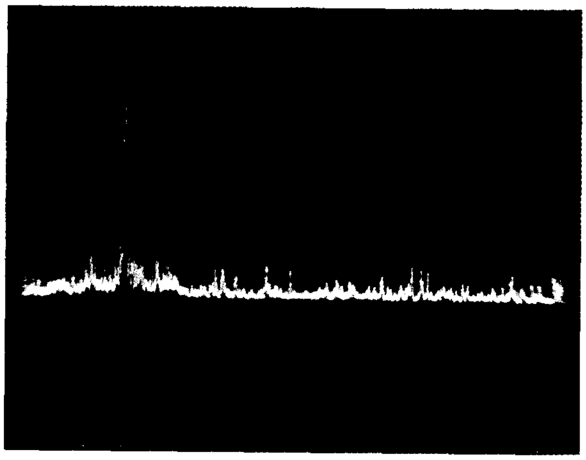

FIG. 1. $P(18)$ beat note, single trace, $(28.359800 = 3\times 10.710873 - 3.821775 + 0.027454 - \nu_{\text{beat}})$, $\nu_0 = 98$ MHz, trace width = 500 kHz, sweep time = 20 msec.

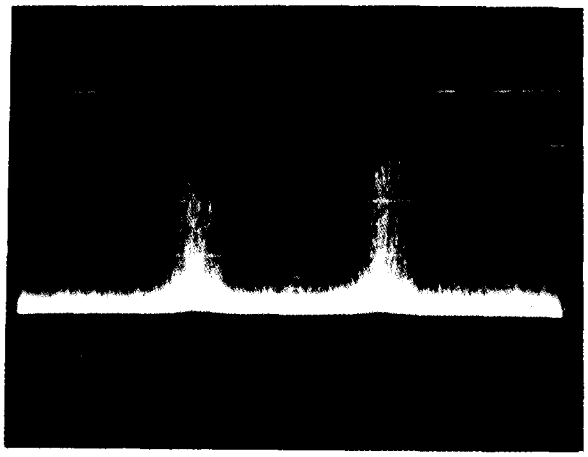

FIG. 2. $P(18)$ beat note + side band, multiple trace, $\nu_0 = 9.3$ MHz, trace width = 1 MHz, sweep time 20 msec/trace, 100 traces.

specified 10–60 MHz pass band of our amplifier), and the entire trace is 500 kHz wide and represents a single sweep of the spectrum analyzer. The klystron was unlocked, and this may have produced a narrowing effect on a single trace as it did in the earlier experiments; therefore, a multiple trace photo is presented in Fig. 2, which shows two beat notes with the entire scan representing 1 MHz. The klystron and spectrum analyzer were tuned so that the center of the scan was at 9.35 MHz, and the main beat note (the larger one on the right) was at about 9.2 MHz. The one at the left is produced by the subtraction of the large intermode water vapor beat note at 18.7 MHz from the main beat note at 9.2 MHz yielding a beat at 9.5 MHz on this scan. All in all, six or seven sidebands on each side of the large center beat note could be seen. These sidebands resulted from the addition and subtraction of multiples of the 18.7-MHz intermode beat note to and from the main beat. By tuning the klystron and observing pairs of signals, it was easy to discern the large central fundamental beat. The $P(20)$ signal was 20% larger than this, but was otherwise very comparable.

In order to determine the top of the gain curve the beat signal was "chased" on the spectrum analyzer while each of the lasers was tuned across its respective gain curve. This technique allowed a placement of each laser to its respective center of its gain curve to within about 10% (about 3 MHz).

The zero beats from the $P(18)$ and $P(20)$ lines came from mixing the frequencies in the following way:

$$\nu_{P(18)} = 3\times 10.718073 - 3.821775 + 0.027356$$

$$= 28.359800 \text{ THz},$$

and

$$\nu_{P(20)} = 3\times 10.718073 - 3.821775 - 0.026193$$

$$= 28.306251 \text{ THz}.$$

These values are in excellent agreement with frequencies obtained from McCubbin's wavelength measurements of the CO_2 lines.[2] Error limits of ± 25 MHz resulted from an addition of the following sources of error:

Centering the CO_2 laser on its gain curve	± 4 MHz
Accuracy of 10.7-THz line[1] 3×(± 2)	± 6
Accuracy of 3.8-THz line[1] 1×(± 3)	± 3
Centering 10.7-THz laser on its gain curve	± 6
Centering 3.8-THz laser on its gain curve	± 3
Accuracy of wavemeter	± 2
Accuracy of spectrum analyzer	± 0.5
Total accuracy limits	± 25 MHz

The listed errors are believed to be independent of each other. The difference between $P(18)$ and $P(20)$ has been previously measured,[3,4] and the values of 53 548 ± 1 MHz and 53 548.16 ± 0.1 MHz are in excellent agreement with our difference value of 53 549 MHz.

In addition to providing a measurement of the absolute frequency of these lines of the CO_2 laser and hence all other lines in this branch[3,4] with an order of magnitude more accuracy than wavelength measurements provide, the 100-kHz spread of the beat note indicates that the output of a simple, free running CO_2 laser can be monitored to better than 3 parts in 10^9 by using a chain of harmonic generators and lasers extending upwards from an X-band klystron, a frequency counter, and a standard of frequency. The frequency of the 9.3-μm branch of a pulsed CO_2 laser has already been compared[4] with the third harmonic of the 10.7-THz line.

This experiment represents another step in the chain through which it may shortly be possible to measure frequencies in the visible. One of the next higher frequency lasers in the chain is the 88-THz (3.39 μm) He-Ne laser. Measurements on the saturated absorption methane device[5-7] (which serves that laser to the methane frequency) have indicated an accuracy of 1 part in 10^{11} and a stability of better than 5 parts in 10^{14} for averaging times of 1000 sec. An accurate measurement of the methane frequency (in terms of Cs^{133}) and wavelength (in terms of K_r^{86}) will yield an extremely good value of c. Also the saturated absorption methane device is a good candidate for a single standard of time, frequency, and length.[8] It will at least provide a secondary single standard for extremely accurate length and frequency measurements.

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[1] K. M. Evenson, J. S. Wells, L. M. Matarrese, and L. B. Elwell, Appl. Phys. Letters 16, 159 (1970).

[2] T. K. McCubbin, Jr., Air Force Cambridge Research Laboratories Report, AFCRL67-0437, 1967 (unpublished).

[3] L. O. Hocker, D. R. Sokoloff, V. Daneu, A. Szoke, and A. Javan, Appl. Phys. Letters 12, 401 (1968).

[4] V. Daneu, D. Sokoloff, A. Sanchez, and A. Javan, Appl. Phys. Letters 15, 398 (1970).

[5] T. J. Bridges and T. Y. Chang, Phys. Rev. Letters 22, 811 (1969).

[6] R. L. Barger and J. L. Hall, Phys. Rev. Letters 22, 4 (1969).

[7] R. Barger and J. L. Hall, in Proceedings of the 23rd Annual Symposium on Frequency Control, Fort Monmouth, New Jersey, May 1969, p. 306 (unpublished).

[8] R. Barger and J. L. Hall (private communication).