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Defining the Speed of Light: A Combination Time, Frequency, and Length Standard: Recent Progress Toward Measuring the Frequency of Visible Light

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The frequencies of the water vapor laser at 3.8 and 10.7 THz (78 μm and 28 μm) and of the P(18) and P(20), 28 THz (10.6 μm) lines of the CO_2 laser have been measured in this laboratory. This was done by generating a beat note between the unknown radiation and combinations of various harmonics from lower frequency laser and klystron radiations impinging on a tungsten catwhisker-on-nickel diode. Efforts are presently underway to measure the frequency and wavelength of the methane-stabilized 88 THz (3.39 μm) He–Ne laser. Current estimations are that the value of c derived from this combined measurement will be better than 1 part in 10^8. It would then be possible to define c as exactly this number, and use the present time and frequency standard as a length standard also.

Key words: Laser; length standard; velocity of light.

Recent progress in the measurement of laser frequencies [1, 2] and in stabilizing lasers to saturated absorptions [3, 4, 5] suggest the possibility of using a single standard for time, frequency, and wavelength [6]. The present length, time and frequency standards are defined as:

$$1m \equiv 1,650,763.73 \text{ wavelengths of the } 2_{p10}-5d_s \text{ transition of } {}^{86}\text{Kr}.$$

$$\left(\begin{matrix} \lambda_{st} = 605.780211 \text{ nm} \\ \nu_{\lambda\ st}{}^{*} = 494.8866 \text{ THz} \end{matrix}\right)$$

$$1 \text{ second} \equiv 9,192,631,770 \text{ oscillations of the } F=4, m_F=0 \text{ to } F=3, m_F=0 \text{ transition of the fundamental state } {}^2S_{1/2} \text{ of } {}^{133}\text{Cs}$$

$$\left(\begin{matrix} \nu_{st} = 0.009,192,631,770 \text{ THz} \\ \lambda_{\nu\ st}{}^{*} = 32,612,260 \text{ nm.} \end{matrix}\right)$$

Wavelength comparisons can generally be made in the visible to a few parts in 10^{10}; however, at about 10 μm, the diffraction and phase shift corrections limit visible to infrared wavelength comparisons to about a part in 10^8. On the other hand, frequency comparisons have limits imposed only by the coherence of the sources and noise limits in the harmonic generator mixers. (These limits seem to be smaller than a part in 10^{11}).

Current measurements [3, 4] on the methane stabilized He–Ne laser at 3.39 μm yield an accuracy of 1 part in 10^{11} and a precision of better than 1 part in 10^{13}; the accuracy [5] of the iodine stabilized 632.8 nm He–Ne laser is better than 2 parts in 10^9. Both of the devices are not only more coherent, but more accurate than the present wavelength standards. Thus, one can immediately switch to either one of these devices and have a better length standard; or, if the frequency of either of these devices can be measured directly, one could obtain an extremely accurate value of c from $\nu\lambda$; c could be defined as exactly this value and then one could use the most stable source, (whether it be the present methane stabilized He–Ne laser, the cesium beam,

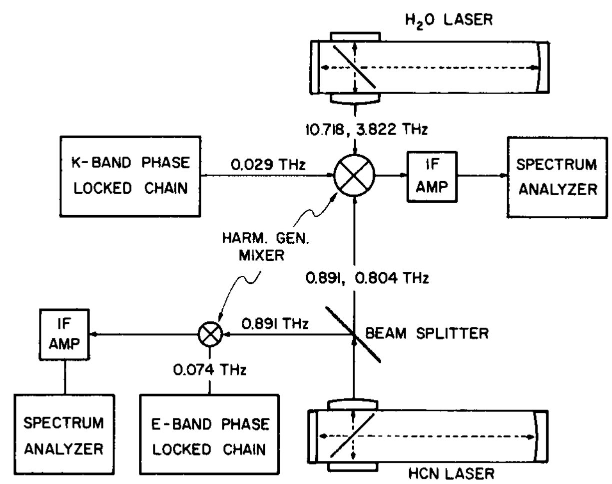

FIGURE 1. *Diagram of 28 μm and 78 μm frequency measuring experiment.*

* Using $c = 2.9979250(10) \times 10^8 \text{m} \cdot \text{s}^{-1}$.

TABLE 1. *Summary of laser frequency measurements*

Frequency ν_x (THz)	Wave-length λ_x (μm)	Power available (mW)	Type of laser	Laser			Laser	Klystron		Ref.
				n	ν_1 (THz)	m	ν_2 (THz)	l	ν_3 (THz)	
0.0106[a]		200								
.0742		100						7	0.0106	
.8907606	337	100	HCN					12	.0742	7, 1
.80475	373		HCN	1	0.891			3	.029	7, 1
3.821775	78	20	H_2O	6	.891	−2	0.805	3	.029	1
10.718073	28	350	H_2O	12	.891			1	.029	1
28.306251	10.6	2000	CO_2	3	10.718	−1	3.821	−1	.027	2
28.359800	10.6	2000	CO_2	3	10.718	−1	3.821	1	.026	2
32.176084	9.3	pulsed	CO_2	3	10.718			1	.022	8
32.134269	9.3	pulsed	CO_2	3	10.718			−1	.020	8
56	5	pulsed	CO	2	26					9
88.37637[b]	3.39	50	He–Ne[a]	8	10.718	3	.891	−1	.040	In progress

[a] X-band klystron—measured in counter.
[b] From wavelength measurements.

or whatever) as a combination length, frequency, and time standard.

It would be conceptually possible to compare the frequency of this primary standard of length, frequency, and time to the frequency of a secondary standard, and thusly, achieve a secondary standard of length, time, and frequency. In practice the only difference between defining λ or defining c is whether one prefers to have only 9 digits (plus zero) in the value of c or in the definition of length. A single standard, of course, would require frequency synthesis up to the visible region of the electromagnetic spectrum, and we would like now to summarize recent progress aimed at this goal.

Since the first laser frequency measurement at 0.89 THz early in 1967, the upper limit to which frequencies have been measured has expanded rapidly to a present value of 55 THz (5 μm).

In order to measure an unknown laser frequency, ν_x, one must add harmonics (n and m) from laser lines with frequencies ν_1 and ν_2, plus harmonics of a klystron to achieve a frequency coincidence; thus:

$$\nu_x = n\nu_1 \pm m\nu_2 \pm l\nu_3.$$

A summary of many of the laser frequencies presently measured, and the one presently in progress is shown in table 1. The work in this laboratory has concentrated on cw lasers, while the work at MIT under the direction of A. Javan has used mainly pulsed lasers.

A block diagram of the experimental arrangement used to measure the water vapor laser frequencies is shown in figure 1. A single diode acts as a combination harmonic generator and mixer for the entire combination of frequencies. A conventional tungsten catwhisker on silicon diode was used up to about 2 THz, while a tungsten on nickel diode was used at higher frequencies (this diode works well at the lower frequencies also). The success of the cw measurements was made possible through the use of three major improvements in increasing the currents on the diode: (1) the use of large lasers (8 m long), (2) variable coupling Michelson lasers for the HCN and H_2O lasers as shown in figure 2, and (3) improved coupling to the catwhisker with the use of long antenna theory [10]. General criterion for the characteristics of a suitable harmonic generator and mixer diode junction have now been established.

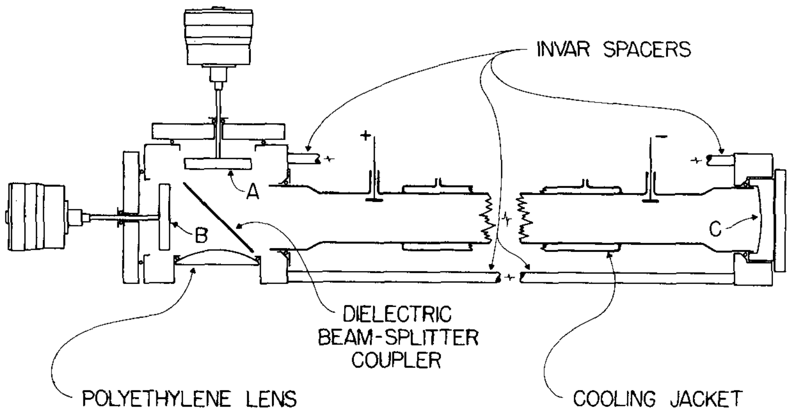

FIGURE 2. *Variable coupling Michelson far infrared laser.*

Currently an attempt is being made to measure the frequency of the He–Ne laser as shown in the last line of the table. This particular scheme is extremely advantageous since only two lasers are used to complete the chain of frequency synthesis to 88 THz. Radiation from all of the various sources is now coupled to the whisker diode, and quite acceptable rectified signals have been obtained which gives encouragement for the eventual success of this measurement. After the free-running-laser's frequency has been measured, a methane stabilized laser will be substituted. A precise measurement of its frequency coupled with current wavelength measurements by R. Barger and J. Hall will yield an extremely accurate value of the speed of light. The initial frequency measurements should be accurate to a few parts in 10^9; meanwhile progress is also underway to stabilize all of the lasers in this chain to yield an even more accurate frequency measurement.

At 28 THz and above, bulk optical second harmonic generation has been used, so that it is quite apparent, that even if the diode is eventually limited in response, that this other method will eventually lead to the measurement of frequencies in the visible.

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DISCUSSION

K. M. Baird: You tempted us with the picture of the Josephson dewar for seeing how high a frequency response you could get, but you didn't say how high it might be.

K. M. Evenson: We have obtained—or I should say Don McDonald in conjunction with us has obtained—responses up to about 6 to 8 terahertz. We have seen the fifth step from the HCN laser, and we have seen the first step of the 118-μm line of the water vapor laser. There are also some possibilities that the Josephson junction will work excellently as a mixer while it may not actually oscillate at this high a frequency. These experiments are also underway.

A. Javan: I'm sorry. Terahertz. I still have difficulty. What wavelength would that be?

K. M. Evenson: Eight terahertz is roughly 50 microns.

A. Javan: Fifty microns? Fine. Very good.

K. M. Evenson: I haven't converted you yet to terahertz?

A. Javan: I haven't developed a feeling for it, so I just don't know what I would be talking about if I used terahertz. This is why I have been staying away from it. As a matter of fact, it's a very good unit to use. It's quite good. This measurement that Dr. Evenson referred to at 5 microns, which is presumably the highest frequency that one has done the mixing, is one that has been submitted for publication to Applied Physics Letters nearly a couple of weeks ago. Maybe I can mention here very quickly, since the speed of light measurement is being discussed so thoroughly here, that ever since the early days at M.I.T. when we attempted the frequency measurements of lasers, we have had an interferometer to measure the wavelength of a far infrared laser and/or infrared laser accurately. The main purpose of it—really I must confess it is not as much measuring the speed of light as it is measuring the wavelength in the infrared or far infrared—is to improve the wavelength measurement all the way to a part in 10^8. Of course, if one does a wavelength measurement to a part in 10^8, then one has the speed of light. But then again the main emphasis is to have some way of measuring wavelength with that high accuracy, and we have an interferometer to do the job. We have a Michelson interferometer. We compare the fringes of an infrared laser with fringes that are simultaneously observed at 6328 A of helium-neon, and in turn we compare the helium-neon laser with the krypton standard. This has been coming along over the years. In fact, a couple of years ago we had a measure of speed of light which was not any improvement over what had been done but one quite in agreement with it to parts in 10^6. Two parts in 10^6 actually. Maybe I could quickly mention that we have now switched the experiment to 10 microns to compare the 10 micron wavelength with the 6328 A wavelength, and I am pretty certain that we will have a part in 10^8 shortly. As a matter of fact, we are not able to make a comparison to a part in 10^7, but the problem is the drift in the laser within a few megacycles. But then we are in the process of stabilizing lasers, and so on and so forth. And at a part in 10^8 we plan to start on the ten microns. The wavelength comparison by itself, despite the fact that the frequency measurement is so important, is going to have its place. And, in fact, in some ways, you know, if you can do a part in 10^7 measurement of wavelength, directly, with the interferometer, you can do it without the need for two lasers or three lasers. So in defense of wavelength measurement, I am all for it, and maybe one can improve the accuracy to a part in 10^8 or even higher, 10^9, or 10^{10} or better. So both of them have their points.