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SPEED OF LIGHT FROM DIRECT LASER FREQUENCY AND WAVELENGTH MEASUREMENTS: EMERGENCE OF A LASER STANDARD OF LENGTH

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Abstract

Recent frequency and wavelength measurements of a methane stabilized laser yield a value of the speed of light 100 times less uncertain than the previously accepted value. Various possibilities using lasers as radiation sources for a new length standard are discussed. One possibility is to fix the value of the speed of light in the redefinition of the meter.

The speed of light is one of the most interesting and important of the fundamental (dimensioned) constants of nature.[1] It enters naturally into ranging experiments, such as geophysical distance measurements which use modulated electromagnetic radiation, and astronomical measurements such as microwave planetary radar and laser lunar ranging. Basically, very accurately measured delay times for electromagnetic waves are dimensionally converted to distance by use of the light propagation speed. Recent experiments have set very restrictive limits on any possible speed dependence on direction[2] or frequency.[3] Another interesting class of applications involves the speed of propagating waves in a less obvious manner. For example, the conversion between electrostatic and electromagnetic units involves the constant, c, as does the relativistic relationship between the atomic mass scale and particle energies.

With the perfection of highly reproducible and stable lasers, their wavelength-frequency duality becomes of wider interest. We begin to think of lasers as frequency references for certain kinds of problems such as optical heterodyne spectroscopy.[4] At the same time, we use the wavelength aspect of the radiation, for example, in precision long-path interferometry.[5] Also since the fractional uncertainty in the frequency of these lasers is approximately one part in 10^{11}, the duality implies that the radiation must have a similar wavelength characteristic, i. e., $\Delta\lambda/\lambda \approx 10^{-11}$ or about 100 times better than the current length standard. Hence, the stabilized laser must be considered to have tremendous potential in wavelength as well as frequency standards applications and perhaps in both.[6]

It has been clear since the early days of lasers that this wavelength-frequency duality could form the basis of a powerful method to measure the speed of light. However, the laser's optical frequency was much too high for conventional frequency measurement methods. This fact led to the invention of a variety of modulation or differential schemes, basically conceived to preserve the small interferometric errors associated with the short optical wavelength, while utilizing microwave frequencies which were still readily manipulated and measured. These microwave frequencies were to be modulated onto the laser output or realized as a difference frequency[7] between two separate laser transitions. Indeed, a proposed major long-path interferometric experiment[8] based on the latter idea has been made obsolete by the recent high-precision direct frequency measurement.[9] An ingenious modulation scheme, generally applicable to any laser transition, has recently successfully produced an improved value for the speed of light.[10] While this method can undoubtedly be perfected further, its differential nature leads to limitations which are not operative in direct frequency measurements.

The product of the frequency and wavelength of an electromagnetic wave is the speed of propagation of that wave. For an accurate determination of both of these quantities, the source should be stable and monochromatic and should be at as short a wavelength as possible. At shorter optical wavelengths the accuracy of the wavelength measurement increases. A suitable source of such radiation is the methane-stabilized He-Ne laser[11] at 3.39 μm (88THz). Direct frequency measurements were recently extended to this frequency[12] and subsequently refined[9] to the present accuracy of 6 parts in 10^{10}. The wavelength of this stabilized laser has been compared[13-16] with the krypton-86 length standard to the limit of the usefulness of the length standard (approximately 4 parts in 10^9). The product of the measured frequency and the wavelength yields a new, definitive value for the speed of light, c.

The previously accepted value[17] of c was similarly determined by measuring the frequency and wavelength of a stable electromagnetic oscillator; however, it oscillated at 72 GHz (more than 1000 times lower in frequency than in the case of the present measurements). The 100-fold improvement in the presently reported measurement comes from the increased accuracy possible in the measurement[13] of the shorter wavelength.

A block diagram in figure 1 illustrates the entire cesium to methane frequency chain. The three saturated-absorption-stabilized lasers are shown in the upper right-hand section, the transfer chain oscillators are in the center column, and the cesium frequency standard is in the lower right-hand corner. The He-Ne and CO_2 lasers in the transfer chain were offset locked,[11] that is, they were locked at a frequency a few megahertz different from the stabilized lasers. This offset-locking procedure produced He-Ne and CO_2 transfer oscillators without the frequency modulation used in the molecular-stabilized lasers. The measurements of the frequencies in the entire chain were made in three steps shown on the right-hand side, by using standard heterodyne techniques previously described.[12, 18-20]

Conventional silicon point-contact harmonic generator-mixers were used up to the frequency of the HCN laser. Above this frequency, tungsten-on-nickel diodes were used as harmonic generator-mixers. These metal-metal diodes required 50 or more mW of power from the lasers to obtain optimum signals. The 2-mm-long, 25 μm-diam tungsten antenna, with a sharpened tip which lightly contacted the nickel surface, seemed to couple to the radiation in two separate manners. At 0.89 and 10.7 THz it acted like a long wire antenna,[21, 22] while at 29-88 THz its conical tip behaved like one-half of a biconical antenna.[22] Conventional detectors were used in the offset-locking steps.

The methane-stabilized He-Ne laser used in these experiments is quite similar in size and construction to the device described by Hall.[23] The gain tube was dc excited, and slightly higher reflectivity mirrors were employed. The latter resulted in a higher energy density inside the resonator and consequently a somewhat broader saturated absorption. Pressure in the internal methane absorption cell was about 0.01 Torr (1 Torr = 133.3N/m^2).

The two 1.2-m-long CO_2 lasers used in the experiments contained internal absorption cells and dc-excited sealed gain tubes. A grating was used on one end for line selection, and frequency modulation was achieved by dithering the 4-m-radius-of-curvature mirror on the opposite end. CO_2 pressure in the internal absorption cell was 0.020 Torr. The laser frequency was locked to the zero-slope point on the dip in the 4.3 μm fluorescent radiation.[24] The 0.89-, 10.7-, and 88-THz transfer lasers were 8-m-long linearly polarized cw oscillators with single-mode output power greater than 50 mW. The Michelson HCN laser has been described.[25] The H_2O laser used a double-silicon-disk partially transmitting end mirror, and a 0.5-mil polyethylene internal Brewster-angle membrane polarized the laser beam. The 8-m He-Ne laser oscillated in a single mode without any mode selectors because of a 4-Torr pressure with a 7:1 ratio of helium to neon. This resulted in a pressure width approximately equal to the Doppler width, and the high degree of saturation allowed only one mode to oscillate.

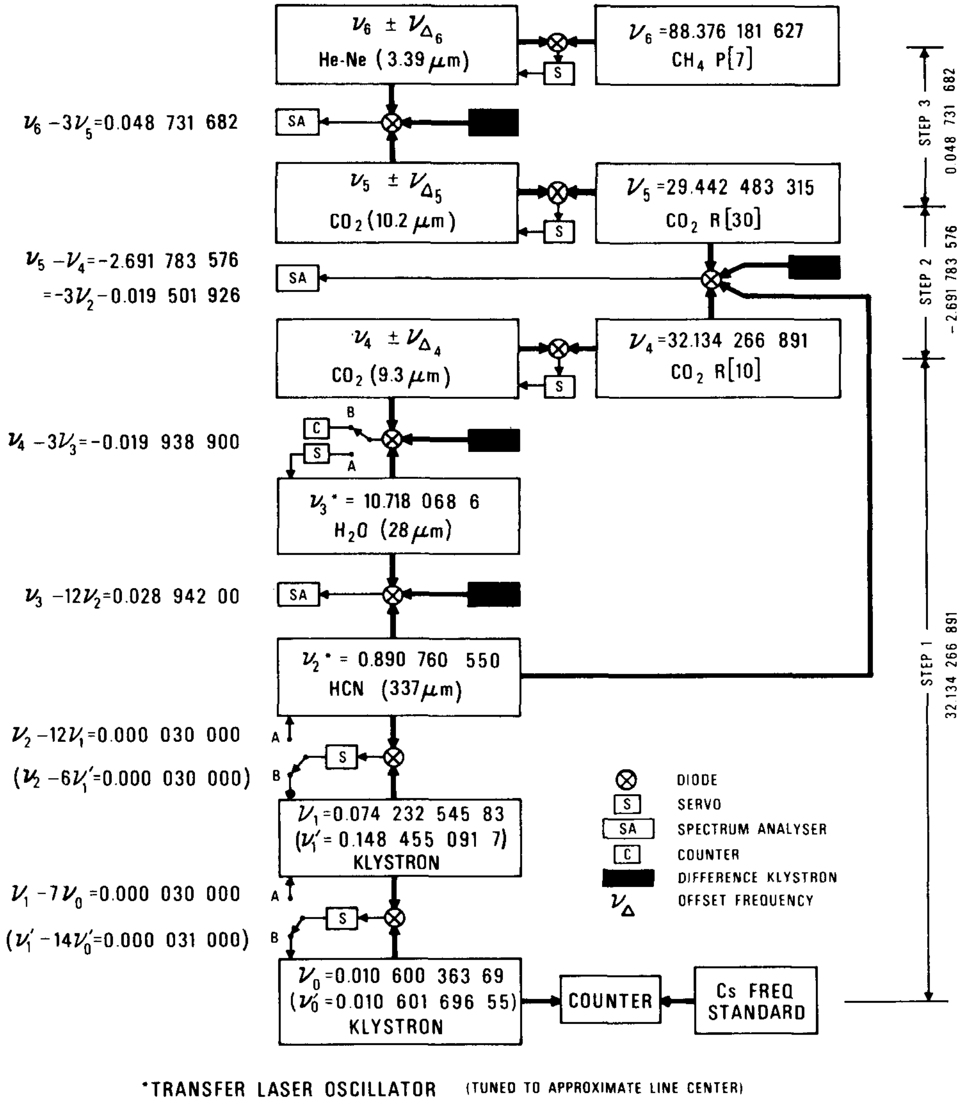

Figure 1. Stabilized Laser Frequency Synthesis Chain. All frequencies are given in THz; those marked with an asterisk were measured with a transfer laser oscillator tuned to approximate line center.

Conventional klystrons used to generate the four difference frequencies between the lasers were all stabilized by standard phase-lock-techniques, and their frequencies were determined by cycle counting at X-band.

An interpolating counter controlled by a cesium frequency standard, the AT (NBS) time scale[26, 27] in the NBS Time and Frequency Division, counted the 10.6-GHz klystron in the transfer chain. This same standard was used to calibrate the other counters and the spectrum-analyzer tracking-generator.

In step 1, a frequency synthesis chain was completed from the cesium standard to the stabilized R(10) CO_2 laser. All difference frequencies in this chain were either measured simultaneously or held constant. Each main chain oscillator had its radiation divided so that all beat notes in the chain could be measured simultaneously. For example, a silicon-disk beam splitter divided the 10.7-THz beam into two parts: one part was focused on the diode which generated the 12th harmonic of the HCN laser frequency, the remaining part irradiated another diode which mixed the third harmonic of 10.7-THz with the output from the 9.3 μm CO_2 laser and the 20-GHz klystron.

Figure 1 shows the two different ways in which the experiment was carried out. In the first scheme (output from mixers in position A), the HCN laser was frequency locked to a quartz crystal oscillator via the 148- and 10.6-GHz klystrons, and the frequency of the 10.6-GHz klystron was counted. The H_2O laser was frequency locked to the stabilized CO_2 laser, and the beat frequency between the H_2O and HCN lasers was measured on the spectrum analyzer. In the second scheme (output from mixers in position B), the 10.6-GHz klystron was phase locked to the 74-GHz klystron, which in turn was phase locked to the free-running HCN laser. The 10.6-GHz klystron frequency was again counted. The free-running H_2O laser frequency was monitored relative to the stabilized CO_2 laser frequency. The beat frequency between the H_2O and HCN lasers was measured as before on the spectrum analyzer.

In step 2, the difference between the two CO_2 lines was measured. The HCN laser remained focused on the diode used in step 1, which now also had two CO_2 laser beams focused on it.

The sum of the third harmonic of the HCN frequency, plus a microwave frequency, plus the measured rf beat signal is the difference frequency between these two CO_2 lines. The two molecular-absorption-stabilized CO_2 lasers were used directly, and the relative phase and amplitudes of the modulating voltages were adjusted to minimize the width of the beat note. The beat note was again measured on a combination spectrum analyzer and tracking-generator-counter. The roles of the CO_2 lasers were interchanged to detect possible systematic differences in the two laser-stabilization systems.

In step 3, the frequency of the P(7) line in methane was measured relative to the 10.18 μm R(30) line of CO_2. Both the 8-m 3.39 μm laser and the CO_2 laser were offset locked from saturated-absorption-stabilized lasers and thereby not modulated. The 10- to 100-MHz beat note was again measured either on a spectrum analyzer and tracking generator, or in the final measurement when the S/N ratio of the beat note was large enough (about 100), directly on a counter.

The measurements were chronologically divided into four runs, and values for each of the steps and for ν_4, ν_5, and ν_6 were obtained by weighting the results of all runs inversely proportional to the square of the standard deviations. The largest uncertainty came from step 1; a recent measurement by NPL[28] gave a value of the R(12) line which was only 2×10^{-10} (7kHz) different from the number obtained by adding the R(12) - R(10) difference[29] to the present R(10) value. Thus, the first step of the experiment has been verified.

The final result is:

Molecule	Line	λ	Frequency
$^{12}C^{16}O_2$	R(30)	10.18 μm	29.442 483 315 (25) THz
$^{12}C^{16}O_2$	R(10)	9.33	32.134 266 891 (24)
$^{12}CH_4$	P(7)	3.39	88.376 181 627 (50)

The numbers in parentheses are 1-standard-deviation-type errors indicating uncertainties in the last two digits.

In a coordinated effort, the wavelength of the 3.39 μm line of methane was measured with respect to the ^{86}Kr 6057 Å primary standard of length by R. L. Barger and J. L. Hall.[13] Using a frequency-controlled Fabry-Perot interferometer with a pointing precision of about 2×10^{-5} orders, a detailed search for systematic offsets inherent in the experiment, including effects due to the asymmetry of the Kr standard line, was made. Offsets due to various experimental effects (such as beam misalignments, mirror curvatures and phase shifts, phase shift over the exit aperature, diffraction, etc.) were carefully measured and then removed from the data with an uncertainty of about 2 parts in 10^9. This reproducibility for a single wavelength measurement illustrates the high precision which is available using the frequency-controlled interferometer.

At the 5th session of the consultative committee on the definition of the meter (CCDM)[30], results of Barger and Hall as well as measurements made at the International Bureau of Weights and Measures[15], the National Research Council[16], and the National Bureau of Standards at Gaithersburg[14] were all combined to give "recommended" values for the wavelengths of this transition of methane and the transition of iodine used to stabilize the visible He-Ne laser. The recommended values are:

$$\lambda_{CH_4}\left(P(7),\ \text{band}\ \nu_3\right) = 3\ 392\ 231.\ 40 \times 10^{-12}\ \text{m},$$

$$\lambda_{I_2}\ 127\left(\begin{array}{l}R(127),\ \text{band}\ 11\text{-}5,\\ \text{i component}\end{array}\right) = 632\ 991.399 \times 10^{-12}\ \text{m}.$$

These "recommended" values are in agreement with wavelength measurements to the limits possible with the krypton length standard (that is, about $\pm 4 \times 10^{-9}$). It is "recommended" that either of these values be used to make length measurements using these stabilized lasers in the interim before the meter is redefined.

Multiplying this recommended wavelength of methane by the measured frequency yields the value for the speed of light:

$$c = 299\ 792\ 458 \text{ m/s}$$

which was also recommended by the CCDM. This value of c is one which should be used in distance measurements where time of flight is converted to length and for converting frequency to wavelength and vice versa.

The fractional uncertainty in this value for the speed of light, $\pm 4 \times 10^{-9}$, arises from the interferometric measurements with the incoherent krypton radiation which operationally defines the international meter. This limitation is indicative of the remarkable growth in optical physics in recent years; the present krypton-based length definition was adopted only in 1960!

This result is in agreement with the previously accepted value of c = 299 792 500 (100) m/s and is about 100 times more accurate. As mentioned above, a recent differential measurement of the speed of light has been made by Bay, Luther, and White;[10] their value is 299 792 462 (18) m/s, which is also in agreement with the presently determined value.

As a result of the recommendations made by CCDM, two different definitions of a new length standard must be considered. First, we can continue as before with separate standards for the second and meter but with the meter defined as the length equal to $1/\lambda$ wavelengths in vacuum of the radiation from a stabilized laser instead of from a ^{86}Kr lamp. Either the methane-stabilized[11, 23] He-Ne laser at 3.39 μm (88 THz) or the I_2-stabilized[31] He-Ne laser at 0.633 μm (474 THz) appear to be suitable candidates. The 3.39 μm laser is already a secondary frequency standard in the infrared, and hopefully direct measurements of the frequency of the 0.633 μm radiation will give the latter laser the same status in the visible. The 3.39 μm laser frequency is presently known to within 6 parts in 10^{10}, and the reproducibility and long term stability have been demonstrated to be better by more than two orders of magnitude. Hence, frequency measurements with improved apparatus in the next year or two are expected to reduce this uncertainty to a few parts in 10^{11}. A new value of the speed of light with this accuracy would thus be achievable if the standard of length were redefined to be this laser.

Alternately, one can consider defining the meter as a specified fraction of the distance light travels in one second in vacuum (that is, one can fix the value of the speed of light). The meter would thus be defined in terms of the second and, hence, a single unified standard would be used for frequency, time, and length. What at first sounds like a rather radical and new approach to defining the meter is actually nearly one hundred years old. It was first proposed by Lord Kelvin in 1879.[32] With this definition, the wavelength of all stabilized lasers would be known to the same accuracy with which their frequencies can be measured. Stabilized lasers would thus provide secondary standards of both frequency and length for laboratory measurements with the accuracy being limited only by the frequency reproducibility and measurability and the long term frequency stability. It should be noted that an adopted nominal value for the speed of light is already in use for high-accuracy astronomical measurements; thus, now there are two different standards of length in existence: one for terrestrial measurement and one for astronomical measurements. A definition which fixes c and unites these two values of c would certainly be desirable from a philosophical point of view.

Independent of which type of definition is chosen we believe that research on simplified frequency synthesis chains bridging the microwave-optical gap will be of great interest, as will refined experiments directed toward an understanding of the factors that limit laser optical frequency reproducibility. No matter how such research may turn out, it is clear that ultraprecise physical measurements made in the interim can be preserved through wavelength or frequency comparison with a suitably stabilized laser such as the 3. 39 μm methane device.

Frequencies are currently measurable to parts in 10^{13}, and hence the over-all error of about six parts in 10^{10} for the frequency measurement represents a result which can be improved upon. The experiment was done fairly quickly to obtain frequency measurements of better accuracy than the wavelength measurements; this was easily done. It should be possible to obtain considerably more accuracy by using tighter locks on the laser. For example, the 8-m HCN laser has recently been phase locked[33] to a multiplied microwave reference which currently determines the HCN laser line widths. An improved microwave reference could be a superconducting cavity stabilized oscillator[34] for best stability in short term (narrowest line width) coupled with a primary cesium beam standard for good long term stability.

The relative ease with which these laser harmonic signals were obtained in the second round of frequency measurements indicates that the measurement of the frequencies of visible radiation now appears very near at hand. Such measurements should greatly facilitate one's ability to accurately utilize the visible and infrared portion of the electromagnetic spectrum.

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