LASER FREQUENCY MEASUREMENTS AND THE REDEFINITION OF THE METER

The extension of absolute frequency measurements to the visible has led to a proposed new definition of the meter

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Measuring the speed of light, an activity which has challenged scientists for over 300 years, may be a thing of the past if a recently proposed redefinition of the meter is adopted. This proposal[1] states: "The meter is the length equal to the distance traveled in a time interval of 1/299,792,458 of a second by plane electromagnetic waves in vacuum." With this redefinition, c will be fixed and the meter will be realized via a frequency measurement of any stabilized laser which is maintained at a fixed value. It is the advent of the absolute frequency measurement of visible light, with the inherently high accuracy of frequency measurements, which has made this redefinition possible.

Two fundamental standards, time (the second) and length (the meter) are defined in terms of electromagnetic radiation, and the electromagnetic spectrum can be characterized by either frequency or wavelength. However, it is only recently[2] that visible radiation has been measured with the more accurate technique of direct frequency measurement. Wavelengths are measured with grating or prism spectrometers and interferometers, and the accuracy is limited by mechanical and optical properties of the devices themselves. State-of-the-art wavelength measurements in the visible are presently made with a fractional uncertainty of about $\pm 1 \times 10^{-10}$. In comparison, frequency measurements are limited only by the stabilities of the oscillators used. The cesium time standard has a fractional stability and reproducibility of better than $\pm 1 \times 10^{-13}$, and some lasers are now approaching this value.[3]

Frequency measurements are man's most accurate measurements. Electronic counters directly count frequencies up to about 500 megahertz in the radio-frequency regime; measurement of higher frequencies requires harmonic generation and heterodyning techniques. Harmonics of a known frequency are generated by illuminating a nonlinear device which produces radiation at a frequency $n\nu_0$ (where n is an integer) when the input is at ν_0. The $n\nu_0$ radiation is then subtracted from an unknown, higher frequency near $n\nu_0$ to produce a much lower difference or "beat" frequency ν_B, which is usually at a directly countable radio frequency. Thus

$$\nu = n\nu_0 + \nu_B$$

where ν_0 is the known frequency, ν_B is directly counted and ν is the unknown frequency. In the infrared region of 0.5 to 200 terahertz, a tungsten-nickel point-contact diode performs both the harmonic generation and mixing functions. Since the diodes generally have harmonic numbers less than 12, a whole series of measurements must be made to reach the visible region, which occupies frequencies some 57,000 times that of the cesium time standard. (At frequencies above 200 THz, the MIM diode is less sensitive, and bulk mixing in crystals is generally used.) To reach a visible frequency, an entire chain of frequency measurements starting from the fundamental frequency standard (the 9.3-gigahertz oscillation of the cesium atom) was used, as shown in Fig. 1. The final link in this chain — the measurement of the frequency of visible light[2] — was the result of a joint effort of the U.S. National Bureau of Standards and Canada's National Research Council.

Normally, a laser's output frequency wanders over its entire emission line; thus some way to stabilize its frequency is needed to make it useful for precision experiments.[3] Fortunately, this can be accomplished with sub-Doppler saturated absorption spectroscopy, which permits the "locking" of the frequency of the radiation to very narrow spectral features so that the frequency remains fixed. A number of different laser wavelengths have been stabilized and thus can serve as precise frequency and wavelength sources. For example: the helium-neon laser at 3.39 μm, stabilized with a saturated absorption in methane; the 10-μm carbon-dioxide laser, stabilized with a saturated fluorescence in CO_2; the common red He-Ne laser at 0.6328 μm, stabilized to an iodine saturated absorption; and the yellow 0.57-μm light produced by frequency doubling a 1.15-μm He-Ne laser, also stabilized to iodine.

Presently, the unit of length — the meter — is defined

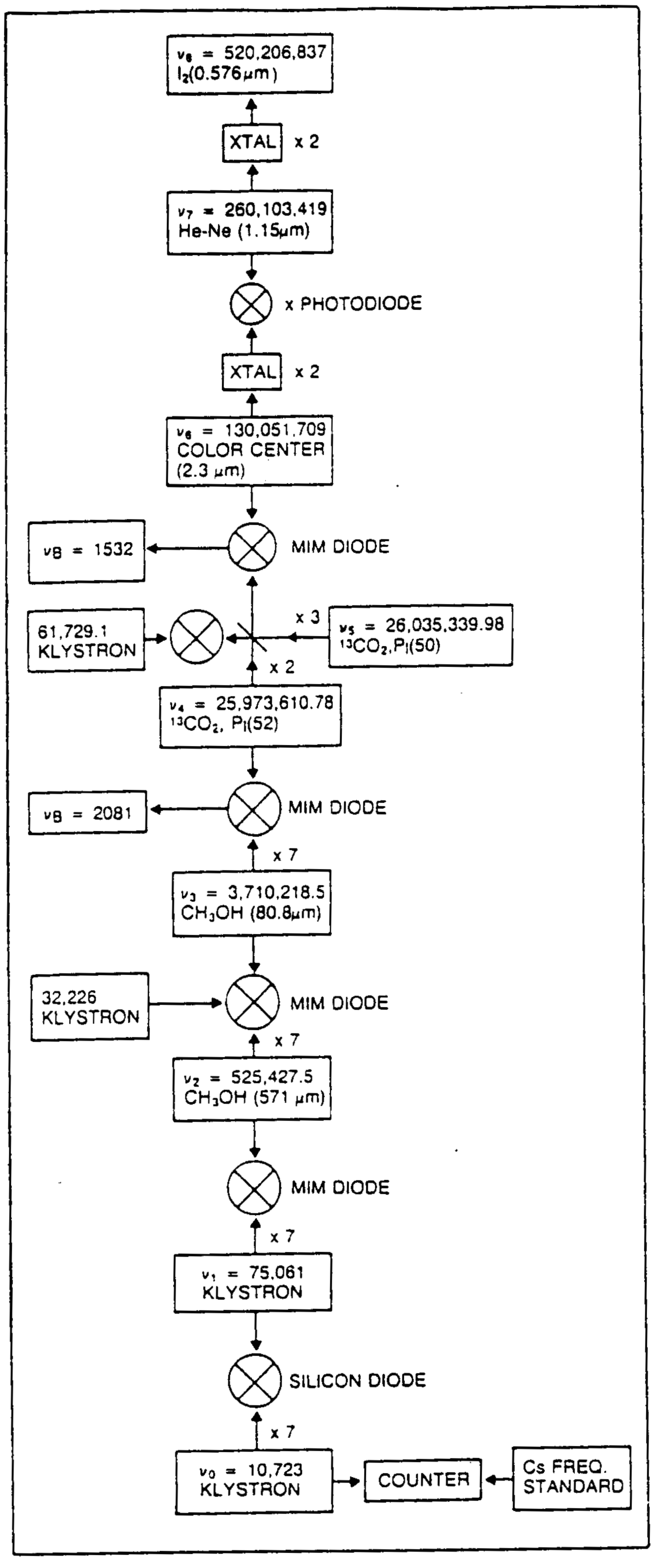

Fig 1 *Laser frequency-synthesis chain, starting from the cesium standard and extending upward to the 1.15-μm He-Ne laser. All frequencies are in terahertz*

as 1,650,763.73 times the vacuum wavelength of an orange-red spectral line of krypton-86. Wavelengths can be compared with high precision in a Fabry-Perot interferometer, but ultimately, one runs up against the accuracy limitation imposed by the spectral width of the krypton emission, leading to an uncertainty in all length measurements of about 3 parts in 10^9.

In 1972, the highest frequency measurement in history was accomplished: that of a methane-stabilized, He-Ne laser (3.39 μm).[4] This was a very significant measurement because this laser's wavelength could be measured some hundred times more accurately than wavelengths in the microwave region.[5] And since the product of the frequency and wavelength of an electromagnetic wave is the speed of light, a 100-times more accurate value of c was obtained.

The present definition of the meter, tied as it is to incoherent radiation, is obviously archaic and the use of laser radiation would significantly improve our standard of length. This has been proposed by a recent meeting of the Consultative Committee on the Definition of the Meter as was mentioned earlier. With such a definition, any suitable stabilized laser whose frequency has been measured could be used to establish the meter. Its vacuum wavelength would be

$$\lambda_{vac} = \frac{c_0}{\nu}$$

where ν is the measured frequency of the laser, and c_0 would be the defined value of the speed of light. Thus, the meter is ν/c_0 vacuum wavelengths of this radiation, and c_0 (299,792,458 m/s) would be the value chosen to maintain continuity in the realization of the meter.

If a laser-based definition of the meter is adopted, the era of speed-of-light measurements would be at an end

There would be no loss in the accuracy of realizing the meter this way compared with defining the meter in terms of the wavelength of a single stabilized laser because frequencies can be measured a hundred to a thousand times more accurately than wavelengths. Well-characterized, stabilized lasers are sufficiently stable so that their frequency need be measured only once; then, any other similarly stabilized laser would also emit this standard wavelength and could be used as a standard of length without further measurements. Thus, if this new definition is adopted, one of our fundamental units (the meter) would be defined in terms of another (the second), and the era of speed-of-light measurements would be at an end.

References

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