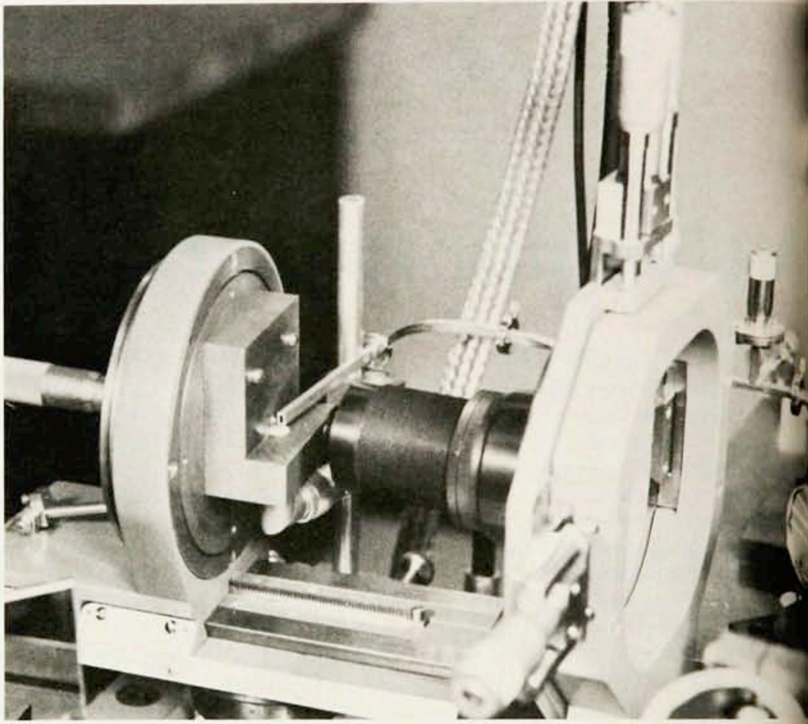
Frequency measurement of optical radiation



By using nonlinear devices to mix signals and comparing the resulting beats with microwave signals whose frequency is known, one can count directly the oscillations of visible light.

Kenneth M. Baird

Among the remarkable facts of modern technology, one of the most striking is that the possibility is at hand of making an exact count of cyclical events that occur at a rate of over 500 million in a microsecond; this will be the likely result of present work on the measurement of the frequency of optical radiation and the use of optical resonances at frequency standards. The actual counting of the exact frequency of optical radiation or locking its oscillations to microwave standards is still very much in the development stage; however, its feasibility has already been demonstrated in experiments such as a recent measurement of the frequency of a visible laser emission, a feat that gained a recognition not often accorded scientists: mention in the *Guinness Book of Records* for the highest frequency measured! A number of laboratories are actively engaged in setting up systems for precisely relating optical and microwave standards. The Institute for Semiconductor Physics in Novosibirsk, for example, has announced the first "optical clock," in which microwaves were locked to the 3.39-micron absorption line in methane.

A major part of the motivation for this work has been associated with the efforts to establish a more precise basis for defining the international meter, a program that may also produce a new standard of time and frequency. Another important motive has been the improvement in the knowledge of the speed of light. Because very-high-resolution spectroscopy involves closely related techniques, these measurements will also affect our knowledge of other important physical constants, such as the Rydberg.

Wavelength standards

The development of the laser gave rise to a new set of wavelength standards markedly superior to the traditional thermal sources of radiation, not because laser emissions themselves have such precisely given wavelengths, but because it is possible to control the very monochromatic laser radiation so as to be centered on sharp, virtually unperturbed absorption lines, using clever techniques to eliminate Doppler broadening. (See the article by Arthur L. Schawlow, PHYSICS TODAY, December, page 46 and reference 1.) This has resulted in wavelength reference standards that are a factor of 10^3 to 10^5 narrower and less subject to perturbations than those produced by sources such as the Kr^{86} discharge lamp now used in realizing the international standard meter. A number of such standards, using lasers stabilized on certain lines in the spectra of CH_4 and I_2, have been listed, together with their wavelengths, by the International Committee of Weights and Measures (CIPM). These sources have been shown to emit light having a sufficiently reproducible wavelength to allow the adoption of one of them as a primary standard of length, orders of magnitude more precise than the present international meter standard. However, the coherence of these sources and the recent development of very-high-speed, nonlinear optical devices has offered a much more attractive alternative I describe below, involving the measurement of the frequency of radiation in the optical region of the spectrum.

The measurement of optical frequencies produced a dramatic turn in the long and interesting history of the measurement of the speed of light, *c*.

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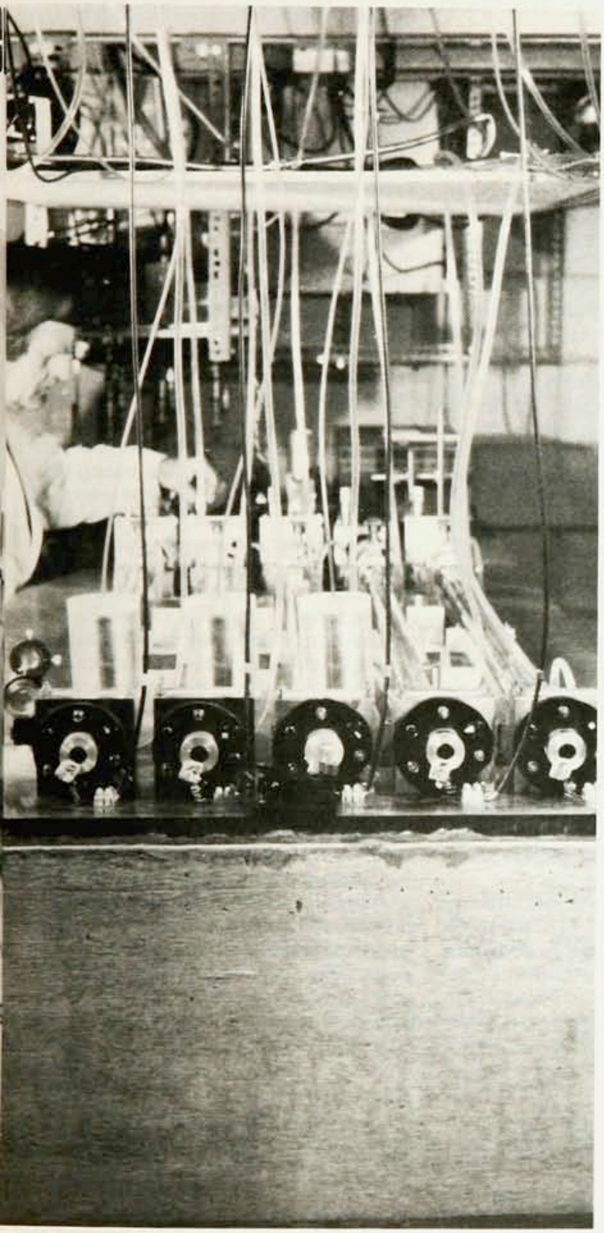


Mixing optical and microwave frequencies in a metal-oxide–metal diode (photo on opposite page). The diode is immediately in front of the open end of the waveguide, just left of center, from which it receives the microwave signal; it also receives light from a CO_2 laser via the lens at right and microwaves from a klystron via the waveguide. Its output, consisting of beats between the two signals, is carried by the coaxial cable at the base of the diode. **Frequency chain** at NRC for locking the oscillations of a CO_2 laser at 30 THz (10 microns) to those of a Cs primary frequency standard at 9 GHz (photo at left). The array of CO_2 laser tubes shown in the foreground is mounted on a vibration-isolating table inside a heavy masonry structure that provides thermal and acoustic isolation. The frequency-mixing and detection components of the apparatus are in the background. The photo is by Brad Whittford, who is responsible for setting up the experiments.

For several centuries after Galileo and his assistant tried to measure c by successively uncovering their lanterns on opposite sides of a valley in Italy, the measurement of c was limited by the difficulty of accurately determining the time and distance corresponding to the separation of a single pair or a few pulses of light. A considerable improvement resulted in modern times when it became possible to produce electromagnetic waves short enough that their length could be measured by the techniques of interferometry, and whose frequency could be measured directly. Nevertheless, the waves were still so long that the corrections for diffraction, necessary for comparison with physical lengths or spectroscopic wavelengths, remained difficult, and the uncertainty in c was little better than 10^{-6}. A real breakthrough occurred with the extension of frequency measurement to the optical region where certain wavelengths were known to an accuracy limited by the international meter as now defined with reference to a thermal source. While this limitation could be removed by redefining the meter in terms of one of the new stabilized laser emissions, a more attractive alternative presented itself, as I have mentioned, namely the adoption by convention of an exact value (in meters/second) for c, from which the relationship $c = f\lambda$ would automatically yield the wavelength of a radiation whose frequency was known. Similarly the frequency would follow if the wavelength were known, but at present frequencies can be compared more precisely than lengths or wavelengths.

Steps are now underway to redefine the international meter, in the way described, in a program coordinated under the auspices of the CIPM. It is of course very important to have suitably confirmed evidence to ensure that the newly defined meter will result in a real improvement and that there be no significant discontinuity in its value. It is expected that a new definition will be adopted in October 1983 by the General Conference on Weights and Measures (CGPM), and that it will be of the form:

> The meter is the length of the distance traveled in vacuum by light during a time 1/299 792 458 of a second.

The proposed definition is obviously suited to the sort of measurements used in geodesy and in satellite and planetary ranging, in which very precise measurements of the propagation times of light pulses are utilized to measure distances. In addition, for those spectral lines for which the frequency can be measured directly, the new definition assigns a wavelength whose value is as precise as the frequency measurement. These wavelengths can then be used for measuring other wavelengths by interferometry or other methods. One can then relate other measurements of length to these wavelengths, as is now the practice with the meter defined in terms of a standard wavelength. One does hear that using the speed of light is not a practical way to measure yard goods or lumber supplies, but a few years ago one would have said the same about surveying, and there are now on the market surveying transits that carry pulsed lasers for measuring distances by the pulse transit time. In any case, most common measurements of length have always depended on secondary standards such as scales, gauge blocks or yardsticks, whose calibration is traceable to the primary standard; the nature of the primary standard—the distance from King John's nose to his finger, or the transit time for a pulse of light—has no effect on how the secondary standards are used.

The new definition of the meter will

provide an exact and enduring value for c and will provide a vastly improved standard for the measurement of lengths and wavelengths. There are already a number of measurements in astronomy, spectroscopy and the Earth sciences that are more precise than the present standard for the meter; their precision, however, is still far short of the part in 10^{13} that the new definition, taken together with the cesium frequency standard, will allow. New techniques of frequency measurement and alternative atomic resonances are being studied that promise several orders of magnitude greater precision than the cesium standard, and they may make possible significant tests in basic physics—related to the theory of relativity, and the constancy of c with time, among others.[2]

Measurement of optical frequencies

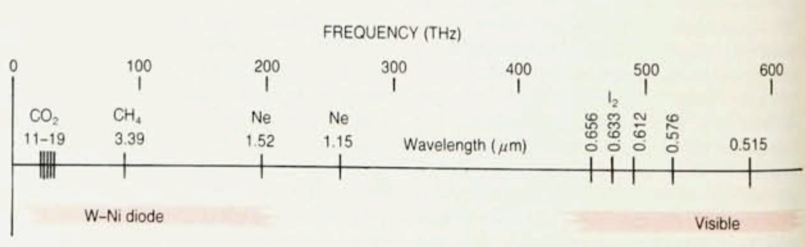
Frequencies of electromagnetic oscillations up to about 500 MHz can be counted directly electronically, but the measurement of higher frequencies requires the use of harmonic generation and heterodyning techniques. The principle is as follows: a device that has a nonlinear response will convert a sinusoidal signal into a distorted output, which contains harmonics of the original signal. Such a device will also convert a mixture of two sinusoidal signals of slightly different frequencies, into an output that contains a signal corresponding to the difference in the frequencies between the two original signals. A count of these beats over a period of time yields exactly the difference in the number of cycles of the original signals. Clearly, if two signals, one of which is nearly equal to a harmonic of the other, are impressed upon a suitable nonlinear device, the rather complicated output will contain a signal at a frequency equal to the difference between the one and the harmonic of the other. A measurement of the frequency of a beat, f_b, will yield the value of the higher frequency f_2 in terms of the lower f_1: $f_2 = Nf_1 + f_b$. Thus one can measure even very high frequencies, provided the beat frequency is low enough for to be measured and counted by convenient electric circuits. The only technical requirement is that the nonlinear device used for the harmonic generation and mixing have a very fast response. Of course, it is important that the oscillations be sufficiently coherent (that is, they must suffer frequency changes sufficiently slowly) to allow observation of enough beat oscillations to make a significant measurement. When suitably applied, the method makes it possible to measure the number of oscillations of the higher-frequency signal during a given number of periods of the lower without missing one. Alternatively the beat signal can be used in a feedback loop to control one of the frequencies, forcing it to maintain a given relationship with the other to within a fraction of one cycle—such signals are said to be phase-locked.

These techniques are well known in the radiofrequency and microwave range. Two major developments have made it possible to apply them to measure frequencies in the optical region of the spectrum: The first was the invention of the laser, which satisfied the coherence requirement and provided very precise reference standards with the development of Doppler-free spectroscopy and techniques for stabilization; the second was the development of suitable very-high-speed nonlinear devices.

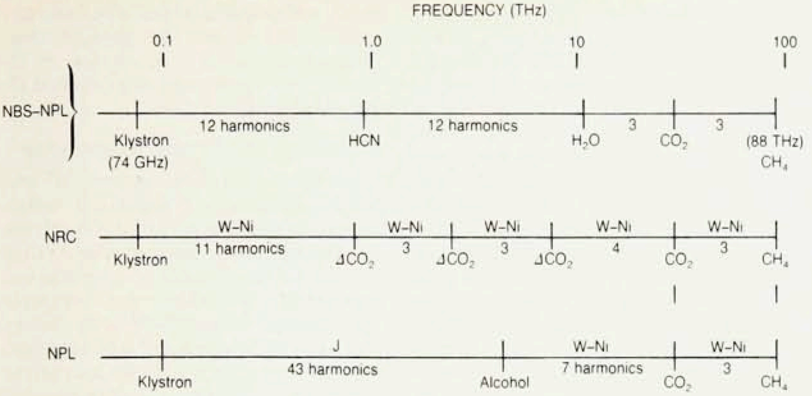
For the present discussion, the most important of the nonlinear devices is the point-contact metal-oxide–metal diode, made at present by bringing the very fine tip of an etched tungsten wire into contact with an oxidized nickel post. These diodes achieve an extremely high speed of response because of their small, low-resistance, low-capacitance junctions. The contact area can be on the order of 10^{-11} cm^2 giving a very low capacitance; the high-speed electrical response is thought to be due to electron tunneling through the nickel-oxide layer, which is about 8–10 Å thick. These diodes can mix and generate sum and difference signals from dc up to about 200 THz (a wavelength of 1.5 μm). Focusing infrared radiations on such a device in an electric circuit, generates currents in the circuit at the desired beat frequency, f_b.

A second type of nonlinear device, useful in the range from about 30 THz (10 μm) up to frequencies of radiation in the visible and ultraviolet, is provided by nonlinear optical crystals.[3] Monochromatic light traveling through such crystals generates accompanying waves of higher harmonics. These crystals can be used for harmonic generation and signal mixing in the same way as other nonlinear devices, but because they do not themselves produce a usable electric signal they must be coupled to a suitable detector. There are important limitations in the use of crystals. First, they have limited ranges of transparency and thus limited ranges of usability. Second, they have extremely small coefficients of nonlinearity, so, to get usable outputs, the signals generated along a considerable path length must add up coherently, that is, the harmonic generated "downstream" must be in phase with the harmonic that has come from "upstream." However, the phase velocities of the generating beam and the harmonic will normally differ, because of dispersion, and the two beams will not remain in phase for the required distance. In some crystals this difficulty can be overcome by careful tuning of the birefringence, through changes in temperature or angle of propagation.

Although these developments have made possible direct comparisons of optical with microwave frequencies, actually making such comparisons is far from simple, and a great deal remains to be done to attain the promised goal of very precise measurements of optical frequencies with respect to microwave standards. Problems arise from the fact that the frequencies involved are extremely high, so that very small relative differences result in beat frequencies that are high compared to those that can be handled in convenient state-of-the-art circuitry.



Electromagnetic spectrum from microwaves to the visible. The marked frequencies indicate some of the important laser lines used as intermediates in extending direct measurement of frequencies to the visible. The linear scale (lower graph) shows clearly the large frequency gaps that have to be bridged in going from the cesium frequency standard to the visible.



Microwave-to-infrared frequency chains used at the National Bureau of Standards, the National Physical Laboratory and the Canadian National Research Council. The radiation of the indicated lines is mixed in W–Si, W–Ni and Josephson-junction diodes. In this way klystron (Kl) frequencies are related through intermediate lasers to a He–Ne laser stabilized on CH_4; "ΔCO_2" indicates an intermediate frequency generated by the difference between two CO_2 laser transitions.

This causes difficulties in two ways. First, small frequency instabilities in the laser cause very large excursions in the beat. For example, a jitter of $10^{-6}f$ at 100 THz (or 3 μm) is 100 MHz; if the sought-for beat signal is of this order, measuring it becomes very difficult, to say the least. Second, matching the harmonic of one source sufficiently closely to the frequency of another source to produce low-frequency beats is not easy, because of the limited choice of reference lasers and their limited tuning range. This situation is illustrated in the graph on the opposite page. The top half shows on a logarithmic scale the five decades in frequency from the cesium standard at 10 GHz to the visible. The ranges of klystrons and the range of operation of the W–Ni MOM diode are indicated, as well as important benchmark frequencies of Cs, HCN, H_2O, CO_2, CH_4 and Ne, up to the I_2 lines on which He–Ne and argon lasers can be stabilized by saturated absorption. Because frequency comparison depends to a considerable extent on the simple addition of frequencies, particularly at the higher ranges and because it yields output signals that correspond to differences, the difficulties are more appropriately illustrated by a linear scale, as in the bottom half of the figure. On this scale the total range of frequency comparison and measurement from sub-kHz, through the GHz microwave band that have been made possible with recent commerical equipment development, and to the infrared region opened up by the pioneering experiments done during the 1960s at MIT and elsewhere, covers only a very small part at the left of the scale. The enormous range yet to be bridged to reach the visible, as well as the large gaps between available lasers to provide intermediate steps, is evident.

A major problem in the strategy of setting up a chain for frequency comparison is the discovery of a suitable set of stable lasers such that the harmonics or sums of lower frequencies match the higher frequency closely enough that the beat frequency can be handled in electrical circuits. Even in an apparently crowded region such as the familiar 10-μm band of CO_2, the Doppler width of about 75 MHz over which the laser can be tuned at each line represents only about one one-thousandth of the separation between the lines, so that the chance of finding a harmonic of a lower frequency close enough to a higher one to produce beats of a usably low frequency is rather small.

In the visible part of the spectrum the problem is greatly increased because there are no such convenient bands of laser lines and the frequency gaps are very much wider. The scarcity of benchmark laser lines can be alleviated by the use of tunable dye lasers in the visible, and, recently, of color-center lasers (in which amplification is provided by a crystal containing color centers) in the range from about 2.5 μm to 1 μm, but problems associated with their inconvenience and instability are not trivial.

Linking microwaves and infrared

It is evident from the foregoing that, despite the simplicity of the basic principle, the extension of exact frequency measurement to the optical region of the spectrum is far from easy. Nevertheless, several accurate measurements of infrared frequency standards have been made; these, taken in conjunction with accurate wavelength measurements, have given the speed of light to an accuracy limited by the uncertainty in the Kr^{86} primary standard of length, and led to the present moves to redefine the international meter.

The frequency measurements were made in several stages, using intermediate frequencies to construct a complete chain of exact frequency comparisons from the microwave to the infrared. The graph on page 55 diagrams three such chains. In 1972 Kenneth Evenson and his colleagues at NBS in Boulder measured the frequency of the 3-μm radiation from a CH_4-stabilized He–Ne laser by following up the pioneering work at MIT and elsewhere on W–Ni diodes in the far infrared, gradually extending their use to shorter wavelengths.[4] At about the same time, a group at the National Physical Laboratory in London set up a similar chain, obtaining results in very good agreement with the NBS result.[5] At about this time, my colleagues and I at NRC had been making very precise measurements of the CO_2-laser wavelengths, using a method involving nonlinear mixing. Consequently, when Evenson's group published values for the frequencies of these lines, we were able to announce[6] (at the Quantum Electronics Conference in Montreal in 1972) the first of the "new generation" of values of c: 299 792 460 m/sec.

In the NBS and NPL chains, the output of a 74-GHz klystron was compared with the HCN laser by generation of the 12th harmonic and mixing in a conventional tungsten–silicon microwave diode. The HCN-laser output was in turn compared to the H_2O-laser line at about 10 THz by generation of its 12th harmonic and mixing in a W–Ni diode. The H_2O line was multiplied by three and compared with CO_2-laser radiation at 30 THz, again in a W–Ni diode, and finally, the 30 THz radiation was multiplied by three and compared with a CH_4-stabilized He–Ne laser at 88 THz. As I mentioned, this description is very much simplified; for example, at nearly all the stages above the first klystron stage, additional klystron frequencies had to be added or subtracted in the diode to reduce the output beat signal frequency to the MHz range so as to be convenient for measuring; also the CO_2 line used for comparison to the H_2O laser was not the same line that was used in the comparison with CH_4, and the difference had to be measured against a klystron-generated frequency. At NPL a different pair of CO_2 lines was used in this stage. These early experiments suffered loss of accuracy in the transfer from one stage to the next, but more refined repetitions of the experiments produced frequency values for the CH_4 and CO_2 lines of accuracy better than one part in 10^9. These values, taken together with wavelength measurements at NBS, NPL and several other national laboratories, led to the recommendation in 1975 by the CGPM of 299 792 458 m/sec as the best value for the speed of light. At the National Research Council in Ottawa we replaced the HCN and H_2O laser stages with difference frequencies generated in W–Ni diodes by simultaneous input from two CO_2 lasers operating on appropriately chosen transitions. A considerable advantage in the simplicity of the laser is partially offset by the low signal strengths of the difference frequencies. This required the addition of an extra stage to reduce the harmonic numbers to 3, 3 and 4. The major source of error resulted from independent operation of the separate stages; this was also the case, but to a lesser extent, at NBS and NPL. We are currently setting up a new system at NRC that uses simultaneous phase locking of the CO_2 lasers. We have already produced phase locking of one of the stages, and we have every indication that a CO_2 line, phase-locked to the cesium standard and therefore accurate to about 1 part in 10^{13}, can be realized.[7] The system is shown in the photo on page 53.

In a revised version of the NPL chain, David Knight's group was able to reduce the number of stages by comparing in a Josephson junction the 43rd harmonic of klystron radiation to the light from a CO_2-pumped alcohol laser at 4.25 THz; from there two stages of $7\times$ and $3\times$ were used to go via a CO_2 laser to the CH_4-stabilized He–Ne laser at 88 THz. In this measurement the stages were operated simultaneously, and the use of phase locking or beat-frequency counting at all points gave a much higher precision (3 parts in 10^{11}) than the first experiment.

Frequency comparison chains up to the 88-THz, CH_4-stabilized laser line have now also been set up in France, Germany, Japan and the USSR, and improvements are proposed or being tested. V. P. Chebotaev at ISP in Novosibirsk recently reported[8] phase-locking microwaves to the CH_4-stabilized laser.

Chains to the visible

The graph on page 57 diagrams three chains of comparison to extend direct frequency measurements to the visible. The first of these[9] was a joint effort by NBS and NRC in 1979, which yielded the frequency of an I_2 absorption line in the visible. While Chebotayev's group demonstrated in 1976 that the ISP system does in fact work, the component frequencies were not measured. The third system is being developed at NBS and has recently been operated.[9] Some details of these systems follow.

In the NBS–NRC experiments, the frequency of a Xe laser at 150 THz (2.02 μm) was first measured by comparison in a W–Ni diode with the sum frequency of a He–Ne laser at 88 THz (3.39 μm) and two 30-THz CO_2 lines (10 μm). The sum of this Xe line and a CO line at 50 THz was used to measure the 196-THz (1.5-μm) He–Ne laser line, again in a W–Ni diode. In the final part of the experiment done at NBS, the He–Ne 196-THz line was added in a proustite crystal to the sum of two CO_2 lines (produced by addition in a $CdGeAs_2$ crystal) resulting in a sum frequency very near 260 THz (1.15 μm). This was compared in a Schottky diode with the output of a pure-Ne laser at 260 THz. The neon laser, which was stabilized on its Lamb dip (a narrow dip on the gain curve due to saturation), was taken to NRC, where Gary Hanes had succeeded in stabilizing 1.15-μm He–Ne laser by doubling its frequency to 520 THz (0.58 μm) and locking it to a green I_2 line by saturated absorption. Comparison of the two lasers, completed in 1979, yielded the frequency of the I_2 line and demonstrated for the first time a direct measurement of a frequency in the visible;[9] it also resulted in the entry in the *Guinness Book of Records* that I mentioned earlier.

The ISP system used three Ne transitions, at 3.39, 2.29 and 1.15 μm, excited simultaneously in a He–Ne plasma; nonlinear interactions in the plasma itself produced a sum frequency at 474 THz (0.633 μm). Although the scheme is in principle very elegant, it has not been widely adopted because of apparent difficulties in measurement and control of the three component frequencies. However, a group at NBS have recently demonstrated the technique in a more practical form, by using a color-center laser instead of the He–Ne plasma for the 2.39-μm line and using a separate plasma tube for the nonlinear mixing.

The third chain shown, also demonstrated at NBS, starts with CO_2 lines whose sum frequency, generated in a W–Ni diode, is used to control a color-center laser at a known frequency at 130 THz. This frequency is doubled to 260 THz in a $LiNbO_3$ crystal, and compared to a He–Ne laser operating at 260 THz (1.15 μm). The frequency of the latter is doubled in a second $LiNbO_3$ crystal for reference to the I_2 line at 520 THz as in the NBS–NRC experiment. The results of this work were described at the Conference on Precision Electromagnetic Measurements at Boulder in June 1982 and will be published in the March issue of *Optics Letters*.

A number of other frequency comparisons are being considered at other laboratories, and some are currently being developed. The apparently simple schematic diagrams I have used to represent such systems notwithstanding, the experiments involved are still very difficult. The problems associated with phase matching, small signals, laser instability and large frequency differences all require a great deal of effort to resolve. But these experiments, including those that are only in their preliminary stages, are making it clear that we will be able to make measurements of frequencies in the visible that are almost as precise as the standard of time itself.

Standards for optical frequencies

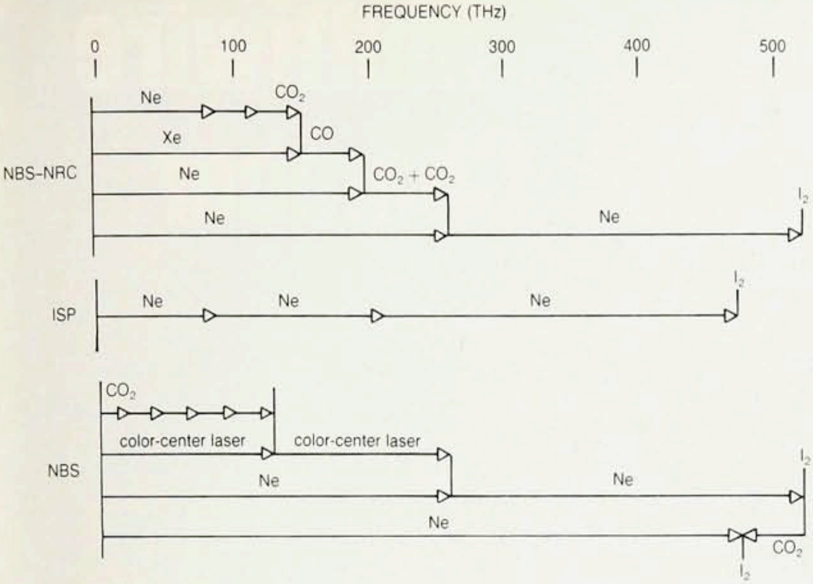
In view of the extension of very precise frequency comparison techniques to the visible part of the spectrum, one might well wonder about their impact on the system of spectroscopic standards: whether, for example, wavelength comparison will be replaced by the convenient sort of technology now used in the radio and microwave region for tuning, comparing and counting frequencies. There is, in fact, already a sort of "new look" for some spectroscopic standards, measured by frequency instead of wavelength methods; this is especially the case in the far infrared. However, there are very important limitations and qualifications to any general application of frequency standards.

In the first place, frequency comparison is very difficult and is rarely used in cases involving incoherent radiation—that is, essentially, any radiation not from a laser. In the second place, there is still a major difficulty caused by the enormous frequency gaps involved in comparisons in the near infrared and shorter wavelengths where detectors and broadband frequency mixers having the necessary high speed do not yet exist.

The realization of laser frequency standards very precisely calibrated against the standard cesium frequency will be achieved either by using completely phase-locked systems or by a simultaneous counting of beats at some of the stages. However, these procedures will likely be practical in the visible for only a few benchmarks, such as the I_2 lines at 0.515 μm, 0.576 μm, 0.633 μm and 0.612 μm, and possibly the I_2 line near the Hα Balmer line at 0.656 μm, which is important for measuring the Rydberg constant. Once such benchmarks are established in a given part of the spectrum, either in the form of a precisely reproducible absorption line or a laser locked to a frequency chain, one can measure other lines or benchmarks by reference to them either by wavelength interferometry or by frequency comparison.

Although, as we have seen, frequency comparison is inherently more precise than wavelength comparison at this time, the measurements are extremely difficult and the comparison of the secondary lines with the primary benchmarks may involve a number of intermediate steps, particularly for large frequency differences.

In the region where point-contact metal-oxide–metal diodes have a nonlinear electrical response, that is up to



Infrared-to-visible frequency chains used at the National Bureau of Standards, the National Research Council and the Institute of Semiconductor Physics. Infrared lasers of known frequency are compared to visible light from I_2 lasers via the intermediate steps shown.

about 200 THz or 1.5 μm, the process of measuring a laser frequency has become relatively straightforward. One can measure differences of up to a few tens of GHz directly in the diode output; for greater separations, up to about 100 GHz, one can mix klystron radiation with the two signals in the diode to produce differences in the MHz range. For yet greater separations, up to about 7 THz, one can use two CO_2 lasers having the appropriate frequency difference; and finally, one can use harmonics and sums of the radiation from CO_2 or other appropriate lasers to measure frequencies or frequency separations upwards of 25 THz.

The measurement of large frequency differences gets considerably more difficult above the electrical response limit of the MOM diodes at about 1.5 μm. For measuring frequency differences up to several GHz of radiations in the region from 3 μm through the visible one can use photoelectric detectors. Some experiments, such as the NBS measurement of the neon laser that contributed to the NBS–NRC measurement of the 520-THz I_2 line, have used Schottky diodes to measure frequency differences as high as about 100 GHz by mixing the signals with klystron-generated frequencies. In the region above 200 THz one must generally use nonlinear crystals to generate harmonics or to mix frequencies to produce beats that are slow enough to measure with detectors sensitive in this region. However, Robert Drullinger and his colleagues at NBS have recently shown[10] that metal-oxide–metal diodes can be used to measure THz frequency differences in the visible.

As I have mentioned, nonlinear crystals have serious limitations in their usefulness for frequency comparisons: small coefficients of nonlinearity, limited ranges of transparency and problems of phase matching. It has also not been possible to mix klystron frequencies with the signals in nonlinear crystals to produce countable beats. One must hope that the number of special combinations of suitable crystals and laser lines will increase with further developments in crystal growing and in tunable dye and color-center lasers. One experiment has already, in effect, transferred the 7-THz grid of CO_2-laser frequencies into the red part of the visible spectrum by mixing in proustite crystals.

This brief discussion shows that while the direct measurement of frequencies in the visible region is possible, it is at present still difficult. We may, however, hope that developments of new devices, perhaps a broad-band nonlinear reflector, will make possible in the optical region "day-to-day" use of the inherently accurate methods of frequency comparison. Another scheme has been proposed[12] by a group at NBS. This involves locking the revolutions of a trapped electron to the oscillations of a laser: An electron in the static electric and magnetic fields of an evacuated trap (a "Penning trap") orbits with a well-defined frequency locked to a microwave source; a laser beam is focussed at one point of the electron's orbit, and if its oscillations are in phase with the orbiting electron—like the field in the cavities of a synchrotron—one expects to see a resonance.

For some time to come, however, the best means for comparing optical frequencies—particularly if the required precision is no more than one part in 10^8—will continue to be wavelength interferometry. In fact, a number of important recent improvements[11] in the technique of wavelength comparison allow a precision of about one part in 10^{10}.

While the developments I have described may appear to have only limited applications, in a specialized area of physics, they are likely in the long run to have a far wider impact. Not only do these techniques bring to spectroscopy an improvement in precision from one part in 10^8 or 10^{10} to one part in 10^{12} or 10^{13}, they may also find engineering applications as light waves realize their full potential as carriers of information. The precise measurements of time and distance will have clear applications in tests of special relativity. As yet our understanding of the mechanisms of high-speed detectors is largely empirical and incomplete; an improvement in our understanding of these processes may also affect our knowledge of solid-state and surface physics involving oscillations of conduction electrons at frequencies of 10^{13} to 10^{14} Hz and amplitudes of a few angstroms.

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