PHYSICS OF OUR DAYS

Current state of the problem of the definition of the meter

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Possible ways of increasing the accuracy of definition of the meter in terms of the wavelength of laser radiation are discussed. A review is given of published work on saturated absorption of laser radiation in iodine and methane and on measurements of the wavelength of stabilized lasers in the visible and infrared regions of the spectrum. Values are reproduced for the wavelengths of lasers stabilized by saturated absorption in iodine and methane and for the velocity of light, which have been recommended as standards for measurements of length and wavelength by the Comité Consultatif pour la Définition du Mètre (CCDM) of the Comité international des Poids et Mesures.

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1. INTRODUCTION

a) Definition of Matter

Since 1960, the meter has been defined as 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the $2p_{10}$ and $5d_5$ levels of the krypton-86 atom. In accordance with the specification of the Comité International des Poids et Mesures (CIPM), the uncertainty in the reproduction of the unit of length was adopted as one part in 10^8. The specification demands that the source of light for the primary standard of wavelength should be a hot-cathode discharge lamp containing Kr^{86} of purity not less than 99%, and the amount of this gas must be sufficient for its detection in solid phase at 63°K. The discharge should take place in a capillary with an internal diameter of 2–4 mm and wall thickness of 1 mm. The current density in the discharge should be 0.3 A/cm^2. The radiation should be observed along the capillary so that the light rays travel in the direction from the cathode to the anode. The capillary should be located in a dewar in which the temperature is maintained at the triple point of nitrogen (63°K)[1,2].

The 605.78 021 nm orange line of Kr^{86}, which has a half-width of 1.3 m^{-1}, is sufficiently monochromatic but is not strong.

Historically, it so happened that when the platinum-iridium line standard was adopted for the meter, it became possible to introduce a new definition of the meter in terms of the wavelength of the red line of natural cadmium.

The adoption of the new definition of the meter in 1960 coincided in time with a period of intensive investigations into the properties of continuously-operating gas lasers, which eventually led to the possibility of a replacement of the orange line of Kr^{86}. Metrologists thus had at their disposal a highly monochromatic and exceedingly strong source of light. It was then natural to ask whether the spectral line whose wavelength was used to define the meter should not be reconsidered.

In 1970, the Fourth Session of the Comité Consultatif pour la Definition du Metré (CCDM) of the CIPM reviewed all the existing work on the stabilization and measurement of the wavelengths of helium-neon lasers. By that time, measurements had been carried out of the wavelength of lasers stabilized on the Lamb dip, and these showed that the reproducibility of the wavelength of such lasers lay in the range between 1 in 10^7 and 1 in 10^8, and this could not be improved in view of the width of the Lamb dip itself[3-6]. This meant that further increase in the accuracy with which the laser wavelengths could be reproduced as standards of length would require the development of methods ensuring a higher degree of wavelength stabilization.

A way of producing lasers of highly stable frequency was then suggested in[7]. This was based on narrow optical resonances induced by a coherent light wave, and involved a quantum transition between long-lived levels. The next suggestion was to produce narrow resonances by saturated absorption of laser radiation in a low-pressure gas cell[8-11]. The theory of saturated absorption of laser radiation was considered in detail in the review papers[12,13].

Stabilization of a laser by saturated absorption involves the placing inside the laser cavity of an absorbing cell containing low-pressure gas, the absorption line of which coincides with the laser amplification line.

The fact that a narrow power peak could be generated during saturated absorption of laser radiation was confirmed by Lisitsyn and Chebotaev for a discharge in pure neon.[9] This method was used to produce a peak whose width was of the order of 25 MHz. When the laser frequency was tuned to the generation-peak maximum, it was found that the frequency of the helium-neon laser could be reproduced to within 1 in 10^9. In this experiment, the absorbing cell was filled with Ne^{20} at a pressure of 0.1 Torr, and the excitation was produced by high-frequency discharge. A disadvantage of stabili-

zation by saturated absorption in neon is that an external field has to be applied to the absorbing cell.[14] This leads to the distortion of the absorption-line profile through the Stark and Zeeman effects, and also to heating instability and to a change in the pressure of the absorbing vapor due to the change in temperature. A different situation obtains when resonance absorption is employed. There are then no electric or magnetic fields in the absorbing chamber, and the temperature and pressure of the absorbing material can be accurately determined and reproduced. In the absence of the external field, the position of the absorption-line center is relatively stable.

The presence of resonance absorption lines in the spectra of iodine and methane, which correspond in wavelength to the helium-neon laser generation lines, has led to the use of saturated absorption of laser radiation in iodine and methane without the application of an external exciting field to the absorption cells, and to a considerable increase in wavelength stability.

Reports presented to the Fourth Session of the CCDM indicated that the results obtained in this area were inadequate, and the Session recommended further studies of helium-neon lasers stabilized by saturated absorption in iodine and methane with a view to establishing new ways of increasing the accuracy of reproduction of the standard unit of length.[15]

b) Resonance Absorption in Iodine Vapor

The change from the platinum-iridium bar to the wavelength of light as the standard of length was made in order to have a natural standard related to an atomic constant. The recommendations of the First Session of the CCDM state[16]: "... the meter should be defined in terms of the wavelength of light propagating in vacuum, with the observer and source of radiation at rest relative to each other. The radiation should be determined by two spectral terms of an atom, the spectrum of which has no hyperfine structure, and the terms themselves should not be subject to any external perturbations." It is difficult to imagine the emission of a spectrum by a monochromatic source of light such that the energy levels of the radiating atoms are totally unperturbed and the atoms themselves are at rest relative to the observer. These conditions can be satisfied only in an ideal, unrealizable source of light in which the pressure of the radiating gas, the temperature of the discharge, and the discharge current density are all zero. The task facing metrologists was therefore to select the conditions for the gas discharge so that the excitation of the spectrum was accompanied by minimum additional perturbation of the corresponding energy levels of the radiating atoms.

Even at the very beginning of the investigations of monochromatic sources of light, this was the decisive condition for the choice of the spectral line whose wavelength could serve as the standard of length. Resonance absorption lines are particularly interesting from this point of view. This was why D. S. Rozhdestvenskiĭ drew attention a long time ago to the resonance spectrum of iodine, and suggested that the absorption lines of iodine might be useful in metrology.

The first experimental work on the resonance spectrum of iodine in which narrowed spectral lines were used in an attempt to increase the coherence length in measurements of length, was carried out in 1959.[17] The Rozhdestvenskiĭ interferometer was used to produce absorption line inversion. A chamber containing iodine vapor was placed in one of the arms of the interferometer, and inversion occurred when the path difference in the interferometer was accurately compensated: dark lines became bright and could be used to observe the interference pattern with an analyzing interference instrument. However, their width was determined by the width of the mercury-198 emission lines which formed a background for the absorption observations. This meant that the hyperfine structure of iodine could not be resolved, and a considerable improvement in the coherence limit could not be achieved. Moreover, the complexity of the apparatus and the low intensity of the inversion lines prevented the use of this method for practical purposes. Only the advent of the laser ensured that the absorption phenomenon could really be placed at the service of measurement of length.

Baird[18] was the first to report observations of saturated absorption of laser radiation at 633 nm in I_2^{127} vapor. The possibility of using the hyperfine structure components of the 633-nm absorption line of the iodine molecule as a means of defining the new primary standard of length was suggested in[19]. The absorbing cell containing iodine vapor was placed inside the helium-neon laser cavity and gave rise to inverted Lamb dips on the graph of the output power as a function of wavelength. The absorption was due to the R(127) line of the 11-5 band of the electronic transition $B^3\Pi_{0u}^+ \leftarrow X^1\Sigma_{0g}^+$ in the I_2^{127} molecule. Hanes et al.[19] resolved 14 components, the half-width of which did not exceed 5 MHz when the working pressure in the absorbing cell was 40 mTorr. A relatively unsophisticated servosystem was used to stabilize and measure the wavelength of the laser tuned to the peak of the component i. Comparison with the wavelength of the orange line of Kr^{86} was used to obtain a preliminary value for its wavelength, found to be 632.991 399 nm with short-term stability of 2×10^{-9} and long-term stability of 1×10^{-10}.

The results of a more detailed investigation of the hyperfine structure of iodine were reported in[20]. A study was made of the effect of a magnetic field and of pressure in the absorbing cell on the half-width and position of the peaks, and the frequency difference between the components was determined. The experiments were carried out with the system illustrated schematically in Fig. 1. The cavity length was 2 m, the amplifying cell was 90 cm long and had a diameter of 3.3 mm, and a direct current of 10 mA was employed. The pressure in the 90-cm long absorbing cell was regulated by cooling a side member. The single frequency output was obtained using the Fox-Smith mode selector (see[21]).

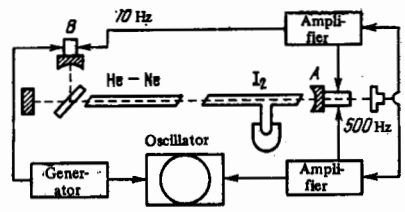

FIG. 1

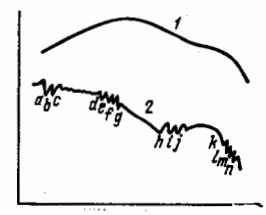

FIG. 2

FIG. 1. Block diagram of apparatus used to investigate the hyperfine structure of iodine during saturated absorption.

FIG. 2. Laser output power (1) and its derivative (2) as functions of wavelength.

TABLE I

Component	ν, MHz	Component	ν, MHz	Component	ν, MHz	Component	ν, MHz
a	297.3	*h*	22.3	*e*	153.6	*m*	−152.3
b	288.5	*j*	−22.0	*f*	139.7	*n*	−162.0
c	280.7	*k*	−129.3	*g*	126.3		
d	166.9	*l*	−137.1				

With a pressure of 40 mTorr in the absorbing cell, 14 components with a width of 4.5 MHz were obtained in a spectral interval of 450 MHz. The disposition of these components relative to the line center is shown in Fig. 2.

Table I lists measurements of the frequency interval between the I_2^{127} components relative to the component i.

When a 500-G magnetic field was applied at right-angles to the 90-cm cell, the components a, b, c, k, *l*, m, and n were found to broaden by a factor of two. At the same time, the broadening of components d, e, f, and g was found to be slight. Components h, j, and i were unaffected by the magnetic field. The same effects were observed when the field was parallel and perpendicular to the plane of polarization of the laser radiation. No wavelength shifts were observed.

To elucidate the effect of pressure in the absorbing cell on the half-width and position of the peaks, an absorbing cell 2 m long was introduced into the resonator cavity and was heated to 40°C to produce a pressure of 1 Torr in the iodine vapor. This was found to result in a broadening of the components by a factor of two, but there was no shift in the wavelength.

These data indicate that the above components can be used as reference points for wavelength stabilization of laser radiation.

If we consider the output power as a function of frequency (see Fig. 2), we find that the resolved hyperfine components of the iodine-127 lines have a low contrast. Knox and Yoh-Han Pao[22,23] used cells filled with iodine I^{127} and I^{129}, and concluded that absorption near 633 nm was stronger in I^{129} than in I^{127} vapor. Moreover, the contrast of the peaks was better, other working conditions being the same. A total of 38 components were resolved in a spectral band of 650 MHz, using the He^3-Ne^{20} laser as a source of light and an absorbing cell filled with I_2^{129}. The position of these components is reproducible to within 10^{-9} or better. The frequency intervals between the components were measured by heterodyning, and are listed in Table II.

Detailed knowledge of the separation between the components gives us considerable freedom in the choice of any particular component for stabilization, and enables us to pass from the wavelength of radiation stabilized on one of the components to the wavelength stabilized on another component, missing complicated comparisons with the orange line of Kr^{86}.

The pressure in the absorbing cell was varied between 30 and 60 mTorr but no systematic changes were found in the position of the components. The reproducibility of the frequency obtained when the laser was tuned to the components m and n was found to be 10^{-9}. When the laser was tuned to components g and m′, which lay near the flat part of the gain curve for neon, the reproducibility was 10^{-10}.

The absorption of He^3-Ne^{20} laser radiation in the

TABLE II

Interval between components, MHz							
a—*b* 16.6	*f*—*g* 11.3	*k*—*l* 18.5	*p*—*a*′ 9.8	*e*′—*f*′ 6.62	*j*′—*k*′ 20.4	*o*′—*p*′ 3.4	*t*′—*u*′ 4.3
b—*c* 5.5	*g*—*h* 8.2	*l*—*m* 24.0	*a*′—*b*′ 20.54	*f*′—*g*′ 7.6	*k*′—*l*′ 5.1	*p*′—*q*′ 15.8	*u*′—*v*′ 15.8
c—*d* 6.4	*h*—*i* 18.9	*m*—*n* 14.01	*b*′—*c*′ 11.96	*g*′—*h*′ 10.65	*l*′—*m*′ 19.7	*q*′—*r*′ 8.8	
d—*e* 17.0	*i*—*j* 3.5	*n*—*o* 23.7	*c*′—*d*′ 7.89	*h*′—*i*′ 3.95	*m*′—*n*′ 28.54	*r*′—*s*′ 18.4	
e—*f* 3.3	*j*—*k* 12.7	*o*—*p* 9.0	*d*′—*e*′ 17.47	*i*′—*j*′ 8.66	*n*′—*o*′ 6.96	*s*′—*t*′ 15.42	

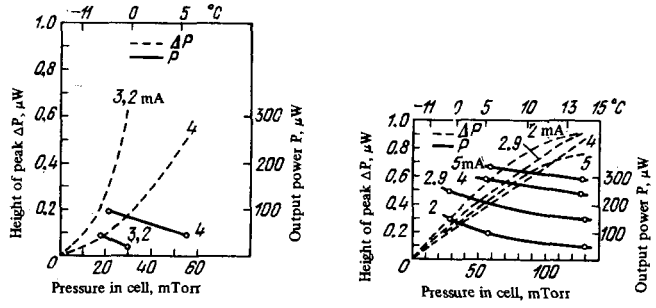

FIG. 3. Laser output power and height of absorption peaks K (a) and B (b) as functions of pressure in the iodine absorbing cell for different values of the discharge current in the amplifying tubes. He^3-Ne^{20}, I_2^{129}.

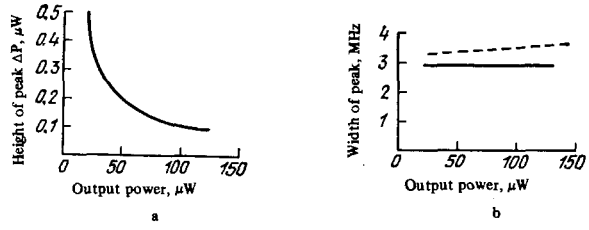

FIG. 4. Height (a) and width (b) of the peak K as functions of the output power of the laser with vapor in the absorbing cell held at 19 mTorr. He^3-Ne^{20}, I_2^{129}.

vapors of the artificial isotope I_2^{129} was investigated in detail in[24]. The profiles of peaks corresponding to the K and B components of iodine were obtained. The output power and the height and width of the peaks were determined as functions of the iodine vapor pressure in the absorbing cell and the discharge current in the amplifying tube.

Figure 3 shows the output power of the laser and height of the absorption peak as functions of pressure in the iodine absorbing cell for different discharge currents in the amplifying tubes filled with Ne^{20} and Ne^{22}. Figure 4 shows the height and width of the K peak as functions of the output power of the laser with the vapor pressure in the absorbing cell held at 19 mTorr. Similar results were obtained for peak B. When the pressure was increased from zero to 180 mTorr, the width of the peak was found to increase by 2.4 MHz, i.e., at the rate of 13 MHz/Torr (the peak width at zero pressure was 2.6 MHz). This is clear from Fig. 5. The data for peaks K and B are practically identical.

Stability and reproducibility were investigated by studying the beat signal obtained by heterodyning two lasers, one tuned to peak n and the other to peak K.

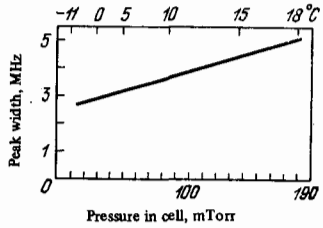

FIG. 5. Peak width as a function of iodine vapor pressure in the absorbing cell.

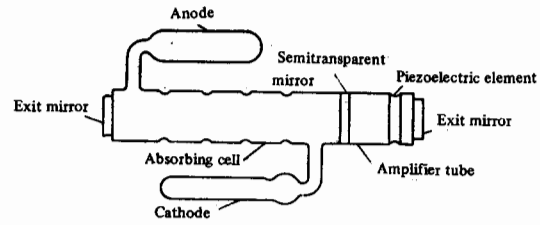

FIG. 6. Integrated design of the laser system.

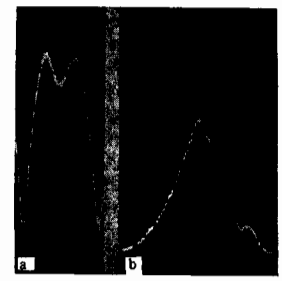

FIG. 7. Output power as a function of generation frequency in the absence of the iodine molecular beam (a) and in the presence of the molecular beam (b).

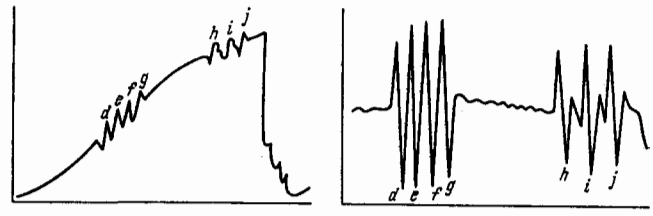

FIG. 8. First (a) and third (b) derivatives of the output voltage of a phase-sensitive detector.

The laser stabilized on peak n was operated at constant power and constant temperature in the iodine cell, whereas the parameters of the laser stabilized on peak K was subjected to systematic variation. The frequency stability over a period of 10 sec was found to be 2×10^{-12} and frequencies reproducibility 1×10^{-10}.

In all these experiments, the amplifying tube and the absorbing cell were not in contact with one another, and the mirrors were adjusted with the aid of mechanical attachments. An original integrated design of the laser system was proposed in[25,26]. All the component parts of the system, namely, the amplifying tube, the absorbing cell, and the resonator mirrors were coupled through an optical contact.

This design (Fig. 6) can be used to reduce energy losses, provide high mechanical stability, isolate the optical path from the atmosphere, and prevent the appearance of extraneous chemical impurities which are usually introduced when the windows of the amplifying tubes and absorbing cells are attached with the aid of adhesives. A channel about 100 mm long and 1 mm in diameter, which forms the capillary of a discharge tube, is drilled through fused quartz cylinder, the ends of which are polished and are plane parallel. Plane-parallel quartz mirrors are in optical contact with the ends of the cylinder. One of these mirrors has a high reflection coefficient and the other is semitransparent and acts as the entrance window for the cylindric quartz cell filled with I_2^{129}. The exit window of the absorbing cell is the high-reflectance second flat mirror of the resonator. Side members, sealed into the cylinder, contain the electrodes of the discharge tube. It was found that the optimum conditions for saturated absorption could be achieved when the reflectance of the semitransparent mirror was 20% and the temperature of the side member of the cell was 4°C. The hyperfine structure components of I_2^{129} were resolved under these conditions.

Studies of the absorption of laser radiation by molecular beams were carried out in parallel with the above work on saturated absorption in the more conventional absorbing chambers.[27-29] An iodine molecular beam was used in[27,28]. Crystalline iodine was placed in the lower[27] or upper[28] side members of the chamber to produce the beam. A collimated beam was obtained by passing the iodine vapor through slits, and the resulting beam was intercepted by a trap located in the upper[27] or lower[28] parts of the chamber. The trap walls were cooled down to a temperature ensuring that a directed molecular beam was produced at right-angles to the helium-neon laser beam[27] or the argon laser beam.[28] The cell containing the iodine was placed inside the cavity in[27]. In the absence of the molecular beam, the output power as a function of generation frequency is represented by a symmetric curve (curve 1 in Fig. 7). Curve 2 was obtained for a helium-neon laser beam passing through an iodine molecular beam at right-angles to the direction of the latter. This curve has a sharp peak corresponding to absorption in the molecular beam. The observed half-width of the peak is of the order of 12—14 mHz (without taking into account the instrumental function). In[28], the cell containing the iodine was located outside the cavity. The hyperfine structure of I_2 with component half-width not greater than 5 MHz was resolved at the wavelength of 514.5 nm.

It is clear from these results that the molecular beam has no advantages for the resolution of the structure as compared with saturated absorption in ordinary chambers. At the same time, a molecular beam is a difficult object to work with. A special pumping system has to be used for the iodine, since the life of the beam is no more than 20 min.

As already noted, although the contrast of the I_2^{129} components is better than that of the I_2^{127} components, it is still insufficient for the achievement of ultrahigh stability by the use of automatic frequency control.

The method of triple differentiation (third derivative) was proposed in[30]. This method completely eliminates the effect of the background curve and can now be regarded as the classic method of stabilization. It is used in practically all the work on the investigation and stabilization of laser sources by saturated absorption in iodine.[24,31-33]

Figure 8 shows the curve observed on the oscillograph screen when the third-derivative method is used. It shows the first and third derivatives of the output voltage of a phase-sensitive detector. The first deriva-

tive, which corresponds to phase-sensitive detection at fundamental frequency, gives the well-known dispersion curve superimposed on the background curve. The second derivative is a symmetric function of frequency and, therefore, cannot give rise to a change in the polarity of the voltage generated by the phase-sensitive detector relative to the center of the absorption line. This derivative is therefore unsuitable for frequency stabilization. The third derivative eliminates all the background effects and ensures that the zero of the phase-sensitive detector output cuts the absorption spectrum at the line center.

Lasers stabilized against iodine components isolated by the third-derivative method had a long-term stability and reproducibility of better than 10^{-10}.

The fact that there is a large number of published papers on the absorption of 633-nm He-Ne laser radiation by iodine vapor is not accidental. The availability of a highly stable spectral line in the visible part of the spectrum is particularly important for measurements of length in which all the measuring systems are designed for the visible region. However, a single spectral line is insufficient for the method of exact fractions widely used in measurements of length. The use of ion lasers (argon, xenon, and krypton) offers a way of producing a number of stabilized lines in the spectrum of a single source. These lasers generate a number of lines. Studies of the absorption of this radiation by iodine-127 and 129 vapor are within the "field of view" of metrology, but are only just beginning.[34-36] However, metrologists are interested not only in producing several highly stable lines in a single source in the visible region, but also in increasing the stabilization precision independently of the spectral region employed. Studies have now begun of CO_2 lines in fluorescence radiation at 4.3 μ wavelength,[37] using a stabilization system based on the Lamb dip, and of the hyperfine structure of iodine lines in fluorescence.[38,39] The method of saturated fluorescence has been used to resolve the hyperfine structure of iodine lines at different wavelengths (5682-5017 Å) at pressures less than a millitorr, and a study has been carried out of the linewidth of the hyperfine components as a function of pressure and intensity. As an example, Fig. 9 shows the hyperfine splitting of the R(78)40-0 line of iodine-127.[38] These peaks have half-widths of the order of 3 MHz, which is a little less than the half-widths of peaks obtained by saturated absorption of laser radiation in I_2^{127} vapor, using an internal absorbing tube.

The method of saturated fluorescence is advantageous as compared with the method of saturated absorption of laser radiation when very low pressures, very weak transitions, or weakly populated lower levels have to be used. So far, it is only at an initial stage of development, and studies are being carried out with a view to ascertaining whether it can be used for the stabilization of laser radiation wavelength.

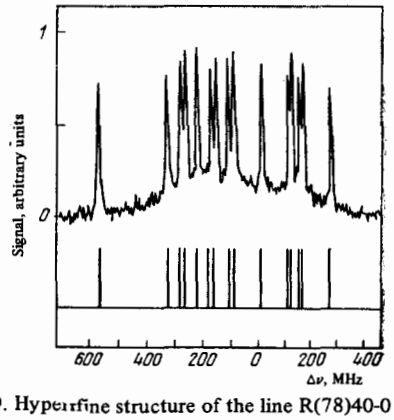

FIG. 9. Hyperfine structure of the line R(78)40-0 of I_2^{127}.

Very high stability and reproducibility of laser wavelengths have been achieved when the helium-neon laser lines were stabilized by saturated absorption in methane.

c) Absorption of Laser Radiation in Methane

The use of methane as a nonlinear absorber of helium-neon laser radiation at 3.39 μ was proposed as a method of frequency stabilization, based on the power peak at the frequency of the vibration-rotation transition ν_3P(7) of the CH_4 molecule.[40-49] The vibration-rotation absorption line P(7) of the ν_3 band of methane is separated from the 3.39-μ line of the helium-neon laser by 50—80 MHz. Precision of coincidence is achieved by increasing helium pressure in the amplifying medium,[40] or by using Ne^{22}.[50] The most favorable conditions for a narrow peak occur when the methane pressure is between 10 and 100 mTorr and the helium-neon mixture is at 2.9—7.5 Torr. The generation and absorption lines coincide when the helium-neon mixture is at 5.4 Torr. The dependence of output power on the generation frequency at this pressure is symmetric in form, and the peak is located at the power maximum. The width of the peak is 100—300 kHz. The inverted Lamb dip observed at the top of the output-power curve is shown in Fig. 10a. Figure 10b shows the first derivative of the inverted Lamb dip.[51] When the helium-neon laser radiation is stabilized on this peak, the resulting stability is found to be of the order of 10^{-13} and the reproducibility 10^{-11}. The reproducibility of the frequency of the helium-neon laser is restricted by the unresolved fine structure of the CH_4 line used to stabilize the frequency of the laser. The line consists of three components. They are separated by 10 kHz from one another and have different intensities.[52]

Higher stability and reproducibility can be achieved by using methane at a pressure of 1 mTorr. In this pressure region, line shifts in methane are smaller than the separations between the hyperfine structure components and reach values of the order of 10 Hz/mTorr.[49]

The advantage of using the 3.39-μ line of methane is that its half-width is independent of the electric field, and depends only slightly on the magnetic field, which offers a possibility of producing a narrow peak.

2. MEASUREMENT OF THE WAVELENGTHS OF STABILIZED LASER SOURCES

Precise measurements of spectral-line wavelengths are based on comparisons with a standard wavelength by an interference method. This principle remains valid for wavelength measurements in the case of lines generated by stabilized lasers. To ensure the continuity and unity of such measurements, the wavelengths of stabilized-laser lines in the visible part of the spectrum are compared by classical interference methods with the wavelength of the 605-78021-nm line of Kr^{86}. When the 1960 definition of the meter was introduced, a considerable amount of time was spent on studies of the symmetry, half-width, and reproducibility of the maxi-

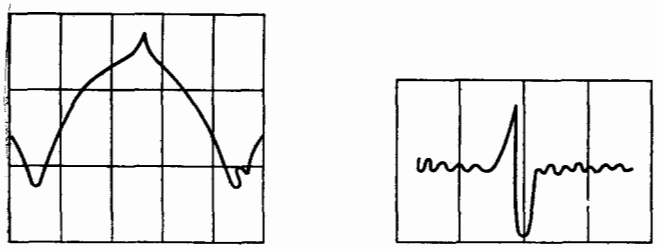

FIG. 10. Laser output power (a) and its derivative (b) as functions of frequency.

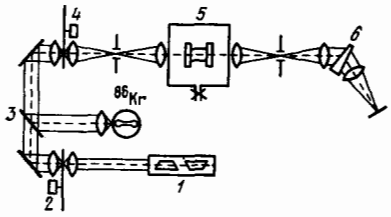

FIG. 11. Block diagram of a spectro-interferometer for absolute measurements of wavelength: 1—iodine stabilized laser; 2, 4—scattering plates; 3—semitransparent plate; Fabry-Perot interferometer; 6—spectrograph.

mum on the profile of the orange line of Kr^{86} emitted by lamps constructed in accordance with the recommendation of the CIPM.[53-60] All these studies were reviewed by the Fifth Session of the CCDM (in 1973) and the actual uncertainty in the reproduction of the wavelength defining the standard length was established. This uncertainty, 4×10^{-9}, characterizes the accuracy of the practical realization of the modern standard meter and the continuity of transition to the new definition of the standard unit of length.

a) Method of Measuring Laser Wavelengths in the Visible Part of the Spectrum

The classic instruments used to measure wavelengths in the visible part of the spectrum are the photoelectric spectro-interferometers. The optical system of most of these instruments is based on scanning Fabry-Perot etalons with different dividers, or Michelson interferometers with different path differences. It is well known that, since the time of Fabry, Perot, and Benoit, the method of exact fractions has been used to compare different wavelengths using a number of auxiliary spectral lines.[61] These lines are usually secondary standard wavelengths in the visible part of the spectra of Kr^{86}, Hg^{198}, and Cd^{114}.[62]

The main function of the spectro-interferometers is to determine the fractional parts of the interference orders with the lowest possible uncertainty. Spectro-interferometers with Fabry-Perot etalons differ from one another only by the method of scanning and of determining the fractional parts of the interference orders. The most widely used scanning method so far is the optical method based on the variation of the refractive index in the vacuum chamber of the Fabry-Perot etalon. This method was used as far back as 1947 to vary the interference order with a view to isolating the single-isotope radiation of mercury-198.[63] In 1948, the method was used as a basis for the photoelectric detection of the hyperfine structure of spectral lines.[64] There was an associated development of methods for the determination of the fractional parts of interference orders,[55-67] which were then perfected and used to determine the wavelengths of laser sources in the visible part of the spectrum. Thus, in the spectro-interferometer used in[68], scanning was achieved by varying the refractive index in the vacuum chamber of a Fabry-Perot etalon either by pumping out air or by introducing gas into the system with the aid of a small pump using a piston with a linear excursion. These measurements were therefore carried out in air, and the refractive index was determined at the same time. The etalon mirrors were silver-coated. The fractional part was read off a digital voltmeter and was printed out.

Conversion of the wavelength from air to vacuum always introduces an additional systematic uncertainty into the refractive index, and it is therefore better to measure the wavelength directly in vacuum.[24,33]

Figure 11 shows the optical system of a spectro-interferometer using air scanning and photographic recording of the interference orders.[33] Scanning was achieved by leaking an ultrasonic current of air into the vacuum chamber and, at the same time, subjecting the photographic plate to a linear displacement. The scanning linearity was 0.001 of a fringe. The fractional part of the interference order was measured to within 0.002 of a fringe by examining the photographic plate on a microdensitometer. The measurements were performed with aluminized mirrors and invar dividers, using two path differences. The dispersion of the phase change was taken into account in the usual way.[69]

Another variant of the spectro-interferometer is described in[24]. In this instrument, the fractional parts were read off during the scanning of the interference pattern by a linear leak of nitrogen into the vacuum chamber through an ultrasonic nozzle, and the fractional part of the interference orders was calculated by a computer. The initial reading of the fractional part was obtained at a pressure of about 0.025 Torr in the vacuum chamber of the Fabry-Perot etalon. Analysis of the krypton line profile confirmed the presence of a small asymmetry which was of the same order as that observed by other workers.[70] In view of this, the wavelength of the orange line of Kr^{86} was assigned to the center of gravity of the profile constructed on the basis of the data in[71]. In addition to the orange line of Kr^{86}, the fractional parts were also found for the 565 line of this isotope in order to determine the integral orders.

An improved method of scanning based on the piezoelectric effect has been widely used in recent times. A Fabry-Perot etalon with piezoelectric scanning elements is used for wavelength measurements in the spectro-interferometer of the Soviet standard of length for spectroscopy.[72] The fractional parts of the interference orders are determined by a modulation method of measuring small phase shifts during the measurement of the output signal by a digital voltmeter.[73] The root mean square deviation of the fractional part of the interference order is 0.001 of a fringe.[74] The spectro-interferometer is based on the vertical design. The optical system is similar to that used in the French instrument[75] but differs from it by the illuminating and interference elements.

Spectro-interferometers in which the interference element is a Michelson interferometer also differ from

one another by the method used to scan the interference pattern. In the classic interferometer system,[58] scanning is carried out by turning a compensating plate, and the fractional part of the interference order is related to the reading of a precision angle-measuring device.

Another variant of this system is the well-known horizontal Kösters interferometer.[76]

A third arrangement of the Michelson interferometer (the Möbius system) is described in[77] and is convenient for the measurement of wavelengths in the visible and infrared parts of the spectrum. The fractional part of interference orders is determined by measuring the change in intensity during scanning of the interference pattern by varying the pressure in an air-filled chamber, which is recorded by a manometer. Signals from the manometer and the receiver are applied to the x and y inputs of a two-coordinate recorder, respectively, and the recorded data are analyzed by a computer.

In view of the foregoing, it is important to emphasize that the two methods of measuring wavelengths involving scanning Fabry-Perot etalons and Michelson interferometers result in comparable accuracy.

b) Methods of Measuring Laser Wavelengths in the Infrared

One of the main systematic errors in wavelength measurement is connected with the dispersion in the phase change on reflection from the interferometer mirrors. As a rule, this error is eliminated by introducing the appropriate correction. To determine the correction, the wavelength measurement is always carried out for a number of path differences and the corrections are calculated from the Meissner formulas.[69] However, when the measured wavelength lies too far away from the standard wavelength in the spectrum, the uncertainty in the correction itself becomes appreciable and reduces somewhat the precision of measurement. This is why the method of direct comparison and the method of transfer through an intermediate secondary standard of wavelength are equivalent. This is so when the wavelength of the 3.39 μ laser radiation is observed. In this case, the transfer of the wavelength from the standard is carried out through the wavelength of a stabilized laser generating the 633 nm radiation and using saturated absorption in iodine.

One of the possible variants of this transfer was realized in[78]. An $LiNbO_3$ crystal was used to mix the frequencies of laser radiations at 3.39 μ and 0.633 μ, and the latter was compared with the wavelength of 0.533 μ corresponding to the frequency sum. The precise value of the wavelength at 3.39 μ was calculated from the result. The recording and analysis of the data were performed in the same way as in the case of wavelength comparisons in the visible. The uncertainty in the dispersion of the phase change on reflection was reduced to 0.001 of a fringe and the uncertainty in the fractional part to 0.001 of the order. The uncertainty in the wavelength is connected with the stabilization of the lasers and amounts to 1 in 10^9.

A somewhat different method of measuring wavelength at 3.39 μ is outlined in[79]. As in the last paper, the wavelength of the stabilized iodine laser is used as a secondary standard. A functional diagram of this system is shown in Fig. 12. For the sake of simplicity, the figure shows a single confocal dichroic resonator.

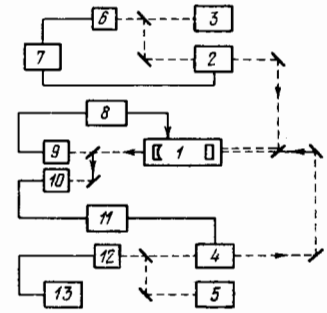

FIG. 12. Functional diagram of the dichroic interferometer: 1—passive dichroic resonator; 2—local generator working at 3.39 μ; 3—methane stabilized laser; 4—local generator (0.633 μ); 5—iodine stabilized laser; 6, 9—infrared receivers; 7—frequency tuning; 8, 11—tuning to the transmission of the signal maximum; 10, 12—receivers for the red region; 13—counter.

In actual fact, there were two such resonators, replacing one another, with lengths of 62 and 250 cm. The frequency of the local 3.39 μ generator was tuned to the frequency of a laser stabilized by saturated absorption in methane. The length of the passive resonator is tuned so that it contains a whole number of wavelengths of the local 3.39-μ generator. A slight adjustment of the local 0.633-μ laser is used to fit a whole number of wavelengths of the 0.633-μ radiation in the resonator. The wavelength of the local 0.633-μ laser is controlled throughout by beats against an iodine laser. In the case of infrared radiation, a coefficient of sharpness of the order of 80 is sufficient for the observation of transmission bands of reasonable contrast, and $\Delta\nu$ can be determined from the difference between the neighboring modes.

In the visible, even when the sharpness coefficient is of the order of 180, the contrast of the bands is insufficient for the determination of $\Delta\nu$. In this case, the frequency of the local 0.633-μ resonator is modulated with a frequency of the order of 10 GHz so that, in addition to the fundamental frequency, the resonator transmits two side bands at $\nu_0 + \Delta\nu$ and $\nu_0 - \Delta\nu$, where $2\Delta\nu$ is equal to 100 orders for the short resonator and 400 orders for the long resonator. The precision with which the microwave frequency is determined is of the order of 10^6 for the short and 4×10^6 for the long resonator, and is entirely sufficient for the determination of a whole order. Such measurements ensure that the final uncertainty is of the order of 1 in 10^{11}.

An improved interferometric procedure is described in[80] where it was used to carry out a direct comparison of the wavelength of the 3.39-μ line of the methane laser with the 0.605-μ line of Kr^{86} with a somewhat reduced accuracy (1 in 10^9) as compared with previous work (1 in 10^{11}). The measuring system incorporates a Fabry-Perot etalon, the mirror separation of which is accurately adjusted by an automatic feedback system so that it contains a whole number of wavelengths of the radiation emitted by a local 3.39-μ laser tuned to the frequency of a methane laser. The frequency of this laser and the length of the interferometer are scanned with an uncertainty approaching the uncertainty of stabilization of the methane laser. The relative error of alignment to the maximum of the band at 3.39-μ is 2×10^{-5}.

Figure 13 shows a frequency-controlled interference system for wavelength measurements at 3.39 μ. The frequency-controlled interferometer was used to reexamine the profile of the orange line of Kr^{86}, including its symmetry and the Doppler shift along the axis of the capillary of the lamp. A wavelength shift between mutually perpendicular directions in the capillary of

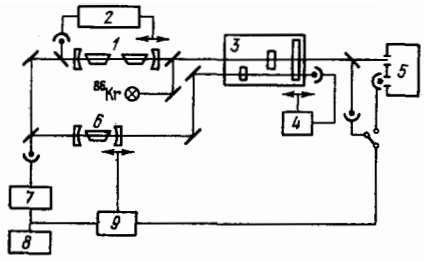

FIG. 13. Block diagram of a frequency-controlled interference system: 1—methane stabilized laser; 2—servosystem for tuning to the center of the CH_4 line; 3—Fabry-Perot interferometer; 4—servosystem for displacing the mirror of the Fabry-Perot etalon to the line center; 5—spectrometer; 6—local generator (3.39 μ); 7—computing unit; 8—multichannel analyzer; 9—servosystem for varying the frequency of the local generator.

the lamp was found right at the start of the investigations reported in[71,81]. However, this shift can hardly be connected with the Doppler effect, and is more likely to be due to the temperature effect of the pressure difference between the anode and cathode in the discharge tube. When the 3.39-μ wavelength was calculated, corrections were included for the asymmetry of the profile and for the Doppler shift (1.31×10^{-4} cm^{-1}), the size of which lay at the limit of precision of the measurements.

The wavelength of the 3.39-μ laser was measured to a still lower accuracy with the Michelson interferometer, using fringe counting by reversing counters.[82] This method was subsequently improved somewhat, and has been used to measure wavelengths at 1.15 μ.[83]

3. MEASUREMENTS OF THE WAVELENGTH OF LASERS STABILIZED BY SATURATED ABSORPTION IN IODINE AND METHANE AND RECOMMENDATIONS OF THE CCDM (JUNE 1973)

The results of the investigations described briefly in this paper were presented to the Fifth Session of the CCDM which was set up by the CIPM to look into scientific problems in this field.

Monochromatic light sources are now available for the visible and infrared parts of the spectrum and can be used for precision interference measurements of length and wavelength. Their high intensity and small linewidths ensure that they have almost ideal metrologic properties. Wavelength reproducibility determined by the method of beats between two lasers of different design and stabilized by saturated absorption is of the order of 1 in 10^{10}. On the other hand, there has been considerable progress in the measurement of frequencies in the optical band: comparison of frequencies with the transition frequency in cesium-133, which defines the second, is now possible up to 88 GHz (3.39 μ) with a relative uncertainty of the order of 6×10^{-10}. The velocity of light should therefore be known to an uncertainty of 6×10^{-10} if the existing meter were defined to better than 1×10^{-8} ($c = \lambda\nu$).

The CCDM was presented with two questions in connection with the modern definition of the meter:

1) What is the extent to which the wavelength radiated by the Kr^{86} lamp defined by the specification differs from the wavelength emitted by an atom free from perturbations as demanded in the definition of the meter?

2) If the profile of the Kr^{86} line is asymmetric, should the wavelength be referred to the peak of the profile or to its center of gravity?

As already noted, having reviewed once again all the investigations into the profile of the orange line of krypton, carried out previously and repeated during measurements on the wavelength of laser sources, the members of the CCDM agreed to assign an uncertainty of $\pm 4 \times 10^{-9}$ to the contemporary meter. This figure represents the possible discrepancy between different laboratories. When the profile is constructed in accordance with its previously determined components, the shift of the maximum is found to be small. Repeated measurements using path differences most commonly employed in interferometer measurements, have shown that the bands are distributed as if this were the ideal monochromatic source with the maximum of the line profile lying between the center of gravity and the maximum of the asymmetric profile obtained experimentally. This is the point to which the wavelength of the orange line of Kr^{86} should be referred. However, the most recent data have shown that the asymmetry of the line lies at the limit of accuracy.

The wavelength of the laser stabilized by saturated absorption in I^{127} has been measured at six laboratories by independent methods. After investigations into the hyperfine structure of the 11-5 band of iodine, which is determined by R(127) transitions, component i was selected as the best, although direct measurements were performed for different components of I^{127} and I^{129} and all these were referred to component i by measuring the frequency interval between the components by the method of beats. The fact that all these measurements are in good agreement is clear from the data listed in Table III.

The mean of all these results is 632.99 139 nm. The largest departure from the mean is less than 3×10^{-9}.

In addition to this table, it is interesting to consider the table of frequency and wavelength intervals for the components of the hyperfine structure in I_2^{127}. These data are given in Table IV.

TABLE III

Laboratory, country	Vacuum wavelength, nm	Laboratory, country	Vacuum, wavelenth, nm
National Bureau of Standards, USA	632.9913998	Physicotechnical Institute, West Germany	632.991397
National Research Council, Canada	632.991398	National Physical Laboratory, England	632.991399
National Laboratory of Standards, Australia	632.991398	Bureau of International des Poids et Mesures, France	632.9913994

TABLE IV

Method used (with reference)		Components a	b	c	d	e	f	g
20, 33, 68	Δf, MHz	297.3	288.5	280.7	166.9 165.060 165.107	153.6 152.214 152.225	139.7 138.845 138.865	126.3 125.690 125.677
	$\Delta\lambda$, F	—397	—386	—375	—220.6	—203.4	—185.6	—168.0

Method used (with reference)		Components h	i	j	k	l	m	n
20, 33, 68	Δf, MHz	22.3 21.919 21.938	0 0 0	—22.0 —21.572	—129.3	—137.1	—152.3	—162.0
	$\Delta\lambda$, F	—29.3	0	28.8	173	—183	204	217

TABLE V

Laboratory, Country	Vacuum wavelength, nm	Laboratory, Country	Vacuum wavelength, nm
National Bureau of Standards (Section V), USA	3392.23140	National Research Council, Canada	3392.23140
National Bureau of Standards (Section D), USA	3392.23139	Bureau International des Poids et Mesures, France	3392.23139

The wavelength of the laser stabilized by saturated absorption in methane has been measured at four major laboratories. The corresponding data are summarized in Table V.

The rounded mean is $\lambda(CH_4) = 3392.23\ 140$ nm.

The mean wavelengths listed in Tables III and V were recommended by the Fifth Session of the CCDM as standard values for measurements of length and wavelength.

In the USA, measurements at the National Bureau of Standards have yielded $\nu(CH_4) = 88\ 376\ 181\ 627 \pm 50$ kHz (an uncertainty of 1×10^{-10}). Using the above mean value of $\lambda(CH_4)$, we find that the velocity of light is

$$c = \nu(CH_4)\,\lambda(CH_4) = 299792458 \text{ m/sec}.$$

This value is based on measurements of $\lambda(CH_4)$ performed at four laboratories and has been confirmed by measurements carried out at the National Physical Laboratory in England,[84] at the National Bureau of Standards in the USA,[85] and the Canadian Science Research Center.[86]

The velocity of light obtained at the National Bureau of Standards in the USA is

$$c = 299792462 \text{ m/sec}$$

with a relative uncertainty of 6×10^{-9} and the value obtained at the Science Research Center of Canada is

$$c = 299792457 \text{ m/sec}$$

with a relative uncertainty of 2×10^{-9}.

Their precision is greater than that achieved by Froome (3×10^{-7}) but is still substantially inferior as compared with the value for $\nu(CH_4)$, which is 6×10^{-10}.[87,88]

Having discussed in detail the possibility of defining a unit of length in terms of a world constant, the members of the CCDM came to the conclusion that the adoption of this definition was at present somewhat premature in view of the difficulties of transferring this measure to artificial measures. However, the CCDM has recommended c = 299 792 458 m/sec as the constant for use in astronomy, geodesy, and range measurements.

In conclusion, we reproduce the recommendations of the fifth session of the CCDM (June 1973) adopted by the CIPM (October 1973).

RECOMMENDATIONS OF THE CCDM APPROVED BY CIPM IN OCTOBER 1973

Recommendation M1 (1973)

The CCDM

CONFORMING to Recommendation M2(1970) concerning the study of the radiations of lasers stabilized by saturated absorption of iodine or methane, and measurements of their wavelengths,

HAVING EXAMINED the results of wavelength intercomparisons of these radiations with that by which the metre is defined, and after discussion of the agreement between different laboratories,

AFFIRMS that the practical realization of the metre as shown by these comparisons is better than one part in one hundred million (10^{-8}),

RECOMMENDS the use of the following values for the vacuum wavelengths of the radiations of helium-neon lasers stabilized by saturated absorption

Line	Vacuum Wavelength
Methane, P(7), band ν_3	$3\ 392\ 231.40 \times 10^{-12}$ m
Iodine-127, R(127), band 11-5, component i	$632\ 991.399 \times 10^{-12}$ m

ESTIMATES that the wavelengths of these radiations have the values indicated with proportional uncertainties of $\pm 4 \times 10^{-9}$, and that this uncertainty is essentially due to the present uncertainty in the practical realization of the metre, and

NOTES that other components of the line R(127) of the 11-5 band of iodine-127 or the components of iodine-129 can be used without loss of accuracy by taking into account the frequency separations; for example, the frequency difference of the B component of $^{129}I_2$ leads to a wavelength value shorter than that of i of $^{127}I_2$ by $1.321\ 16 \times 10^{-12}$ m, so that its wavelength value is $632\ 990.078 \times 10^{-12}$ m. The notation of these components is given in Appl. Phys. Lett. **18**, 360 (1971); J. Phys. **E5**, 926 (1972); Appl. Opt. **12**, 2927 (1973).

Recommendation M2 (1973)

The CCDM

CONSIDERING the methane line with a recommended vacuum wavelength of $3\ 392\ 231.40 \times 10^{-12}$ m, which is estimated to be correct to $\pm 4 \times 10^{-9}$, and the value (88 376 181 627 ± 50) kilohertz for the frequency of this same line determined at the NBS using intermediate standards of which the frequency has been confirmed by independent measurements in other laboratories,

AFFIRMS that the resultant value for the speed of light in vacuum is 299 792 458 metres per second with an uncertainty of $\pm 4 \times 10^{-9}$ which is due to the uncertainty of the practical realization of the metre, and

NOTES that this value is in agreement, within the limits of the estimated uncertainties, with two other very recent and independent measurements which were communicated to the CCDM at this meeting.

Recommendation M3 (1973)

The CCDM

CONFIRMS the earlier recommendation M4 (1970) underlining the need for new research towards a future redefinition of the metre more precise than the present definition, particularly regarding new measurements of optical frequencies and new wavelength intercomparisons of the radiations of stabilized lasers.

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