Reproducibility of Helium-Neon laser wavelengths at 633 nm

Reproducibility of Helium—Neon Laser Wavelengths at 633 nm

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Measurements, performed at NBS, NPL, and PTB, on helium–neon lasers stabilized on the Lamb dip, have shown that the wavelengths of these lasers fell within approximately 1 part in 10^7. Beyond this limit, different lasers were found to emit different wavelengths. In addition, the wavelength of a given laser may vary during the life of its discharge tube. Pressure shifts appear to be a major cause of these variations.

I. Introduction

During the summer of 1965, the wavelengths of two helium–neon lasers operating at 633 nm were measured by Mielenz et al.[1] Each laser* contained nine parts of ^{3}He and one part of ^{20}Ne at an approximate total pressure of 4 torr in a cold cathode, dc excited plasma tube enclosed in a temperature-controlled, 10-cm hemispherical resonant cavity. The wavelength of each laser was controlled by automatic adjustment of the cavity length such that the resonant frequency was locked to the center of the Lamb dip of the gain curve. By comparison with a standard ^{86}Kr lamp, using a Fabry–Perot étalon crossed with a prism spectrograph, both lasers were found to emit the same vacuum wavelength, within the imprecision of the measurement:†

$$\lambda_{vac} = (632.99147 \pm 0.00003) \text{ nm}. \tag{1a}$$

At approximately the same time, an independent measurement of laser wavelengths was carried out by Rowley and Wilson.[2] Using a pressure-scanned recording Fabry–Perot interferometer, these authors obtained

$$\lambda_{vac} = (632.991380 \pm 0.000006) \text{ nm}, \tag{1b}$$

* Model 119 Gas Laser, Spectra-Physics Inc., Mountain View, California.

† The uncertainties quoted throughout this paper are standard deviations of the mean (standard errors). As such, they reflect the random errors associated with the measurements. They do not necessarily indicate the accuracy of these measurements which may be affected by systematic errors of larger magnitude. In particular, an uncertainty of approximately 1 part in 10^8 is associated with the ^{86}Kr standard wavelength upon which all observations are based[4].

from eleven observations on two lasers of the same type and manufacture as those used at NBS,* and

$$\lambda_{vac} = (632.99145 \pm 0.00001) \text{ nm} \tag{2a}$$

from fourteen observations on a prototype laser of different manufacture.‡ This laser contained ten parts of ^{4}He and one part of ^{20}Ne at a total pressure of 3.3 torr in a hot cathode, dc excited discharge tube. It had a 140-mm hemispherical resonant cavity, mounted with the discharge tube vertical, and piezoelectric control. Its wavelength was locked automatically to the Lamb dip in the resonance curve.

A third series of measurements was reported by Engelhard.[3] In this case, a visual technique employing a Michelson type interferometer was used to compare one laser of the same type and manufacture as those tested at NBS and NPL (Spectra-Physics model 119 gas laser) with the ^{86}Kr standard. The laser wavelength was measured in regular time intervals throughout the 2000-h lifetime of the laser; the results obtained are plotted vs time in Fig. 1. The initial wavelength was

$$\lambda_{vac} = (632.991381 \pm 0.000003) \text{ nm}, \tag{1c}$$

and the laser was found to maintain this wavelength, to within 2 parts in 10^8, during the first 800 h of continuous lasing. After this time, a significant deterioration of wavelength stability was observed, and the mean wavelength of emission decreased as operating time increased. After 1500 lasing hours, when the mean wavelength was about 6 parts in 10^8 lower than the initial value given in Eq. (1a), locking on the Lamb dip was no longer possible, and lasing stopped altogether after about 2000 h.

Of the results quoted above for five samples of one laser from the same manufacturer [Eqs. (1a), (1b), (1c)], those obtained at NPL and PTB are in mutual agree-

‡ Model 727 HNL 6, Mark II gas laser, Elliott Brothers (London) Ltd., Frimley, Camberley, Surrey, U.K.
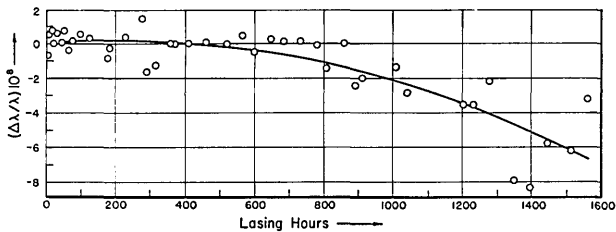
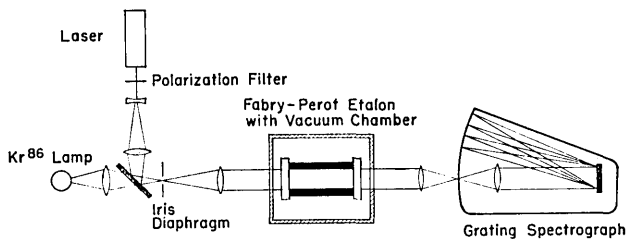Fig. 1. Variation of laser wavelength with time, observed at PTB.

Fig. 2. Fabry-Perot etalon and grating spectrograph used at NBS.

ment but differ by about 1.4 parts in 10^7 from the NBS value. To decide whether this discrepancy was real or due to measurement error, the three laboratories agreed to measure the wavelength of the same laser. This laser, of the same type and manufacture as the five previous ones, was acquired during the summer of 1966 and started its European trip to NPL and PTB shortly after its wavelength had been measured at NBS.

On the other hand, the discrepancy of about 1.1 parts in 10^7 between the results obtained at NPL for two lasers of different manufacture indicated that different lasers may, indeed, emit different wavelengths. In order to investigate this point further, still other samples of wavelength-stabilized helium–neon lasers were measured at all three participating laboratories.

II. Work at the National Bureau of Standards

A. Wavelength Intercomparison

The wavelength of the laser selected for comparison of measurement techniques was measured at NBS using the apparatus shown schematically in Fig. 2. An uncoated glass plate tilted 45° with respect to the optical axes was used to combine the light from the laser with that from the standard ^{86}Kr lamp operated as recommended.[4] Both beams were brought to a common focus with approximately the same angle of convergence at a small iris diaphragm, and then recollimated to illuminate a 75-mm Fabry-Perot etalon with aluminized plates, which was kept in vacuum at $(20 \pm 0.01)°C$. A polarization filter was used to match the laser light intensity to that of the krypton lamp. All optical elements near the laser were slightly tilted to prevent pulling of the laser wavelength caused by intense reflection of light back into the resonant cavity. The Haidinger ring pattern produced by the etalon was imaged on the slit of a stigmatic plane grating spectro-

graph of approximately 1.5 nm/mm linear dispersion. The photographic plates containing the channeled spectra thus produced were evaluated with a photoelectric scanning microscope comparator. A computer program, based on a least-square fit of squared ring diameters vs ring number and wavelength, was used to calculate the laser wavelength relative to that of the primary standard line of ^{86}Kr at 606 nm.

A first series of measurements gave $\lambda_{vac} = 632.99141_3$ nm. Subsequently, a discharge tube failure occurred, so that the laser had to be equipped with a new tube and remeasured. The result of that measurement was

$$\lambda_{vac} = (632.99142_0 \pm 0.00001_1) \text{ nm}, \qquad (1d)$$

which is the mean of ten observations.

B. Studies of Other Lasers

In addition to the above measurements, the wavelengths of two samples of another U.S.-made laser* were determined at NBS during the summer of 1967. These lasers contained 4 torr of a 7:1 mixture of ^{3}He and ^{20}Ne in a dc excited, hot cathode discharge tube enclosed in a 12-cm longradius cavity, with the resonant frequency automatically locked to the Lamb dip by piezoelectric tuning. The wavelengths obtained for these two lasers were

$$\lambda_{vac} = (632.991398 \pm 0.000002) \text{ nm} \qquad (3a)$$

from eleven individual measurements, and

$$\lambda_{vac} = (632.991389 \pm 0.000004) \text{ nm} \qquad (3b)$$

from ten individual measurements.

III. Work at the National Physical Laboratory

A. Wavelength Intercomparison

The apparatus used for wavelength intercomparisons at NPL is shown in Fig. 3. The two light sources illuminate separate collimators through a rotating shutter disk which transmits each beam alternately at 325 Hz. The twin optical channels have filters and prisms to isolate the radiations of interest, and are combined at a semireflector before passing through the 84-mm Fabry-Perot etalon. The Fabry-Perot ring pattern is focused onto a diaphragm which has a small hole accurately centered on the pattern. Light passing through this hole is detected by a photomultiplier, and the signals are passed to an amplifying and digital recording system. The etalon is enclosed in a pressure vessel connected to a motor-driven piston. This steadily changes the pressure of the dried air around and inside the etalon through a range of approximately 50 mb from atmospheric pressure in about 10 min, causing the Fabry-Perot patterns to change through three orders of interference, and enabling the patterns due to both sources to be recorded in sampled form on punched

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* Model 5800 gas laser, Perkin-Elmer, Electronics Products Division, Wilton, Connecticut.
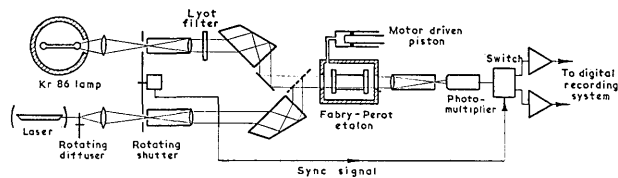
Fig. 3. Pressure-scanned, Fabry-Perot system used at NPL.

paper tape. Subsequently, these records are analyzed by a computer which determines the relative positions of the fringes and calculates the unknown wavelength, taking into account the dispersion of the air and the slight nonlinearity of the scanning arrangement. Information is also derived concerning any asymmetry of the interference patterns.

A [86]Kr lamp conforming to the standard recommended specification[4] was used as the reference source. The laser light was passed through a rotating diffusing screen which was then regarded as a secondary source to be imaged on the entrance slit in the normal manner. In this way the uniphase wavefront of the laser radiation is broken up lest it cause confusing interference patterns, and the laser is decoupled from the light reflected back from the rest of the optical system. The diffusing screen also gives an effective source of finite size so that even illumination can be achieved simultaneously across the aperture of the etalon and in the plane of its ring pattern. It is very important that the etalon is evenly illuminated by both sources. A wavelength comparison to ±0.00003 nm requires subdivision to one hundredth of the fringe spacing, and etalon plates are seldom flat and parallel to this limit over their whole area. To check upon the systematic error arising from lack of uniform illumination, and to reduce its effect, the two sources are interchanged and the measurements repeated. The average difference in measured wavelength is normally less than 0.000003 nm.

For the laser undergoing international wavelength measurement the result obtained was

$$\lambda_{vac} = (632.9914146 \pm 0.0000008) \text{ nm}, \quad (1e)$$

this value being the mean of twenty observations.

B. Studies of Other Lasers

As mentioned in the introduction, the wavelength of a stabilized helium-neon laser from a British manufacturer (Elliott Brothers model 727 HNL 6, Mark II gas laser) was measured at NPL during the summer of 1965.[2] Subsequently, four more production samples of this model have been measured. The wavelength values obtained are shown in Table I. From these observations the most probable value for the wavelength of this model of laser is

$$\lambda_{vac} = 632.991441 \text{ nm}, \quad (2)$$

but there is clearly a variation between samples giving rise to an uncertainty of at least 4 parts in 10^8.

IV. Work at the Physikalisch–Technische Bundesanstalt

A. Wavelength Intercomparison

The PTB interferometer used for wavelength measurements, which is described elsewhere[5,6] in greater detail, is shown schematically in Fig. 4. Monochromatic light illuminating the interferometer from the upper right corner of the figure is divided into two beams by the Koesters double prism K. One of these beams returns after reflection from the reference mirror R. Some of the other is reflected from the front surface M of a gauge block B, and some from a mirror M' wrung to the rear surface of the gauge block. As a result, the two sets of Fizeau fringes F shown in the insert are formed in the left-hand field of view of the interferometer. The interferometer is enclosed in an airtight housing connected to a piston P permitting the variation of the air pressure inside it until the two sets of fringes coincide. In this case, which is shown in the figure, the length L of the gauge block is equal to an integral number N' of half wavelengths in air, $N' = 2Ln/\lambda$, λ being the vacuum wavelength and n the refractive index of the air inside the interferometer.

In addition, the lower arm of the interferometer contains an evacuated chamber C, consisting of a 1-m iron tube sealed at both ends with plane parallel glass plates G, G' extending into the other interferometer arm. The difference between the air and vacuum paths in the interferometer is $2(n - 1) L'' = (M + \mu)\lambda$, where $L'' = 1$ m is the length of the chamber C, where M is an integer of the order of 1000 which can be read from a calibrated scale S attached to the piston P, and where

Table I. Wavelength Measurements of British Lasers[a] Performed at NPL.

Serial No.	Date	λ_{vac} (nm)	Standard deviation of mean	Number of observations
Prototype	July 65	632.991448	0.000012	14
XEB 1018	March 67	632.991445	0.000001	12
XEB 1069	July 67	632.991440	0.000001	7
XEB 1065	July 67	632.991444	0.000002	8
XEB 1070	July 67	632.991421	0.000004	8

[a] Model 727 HNL 6, Mark II gas laser, Elliott Brothers (London) Ltd., Frimley, Camberly, Surrey, U.K.
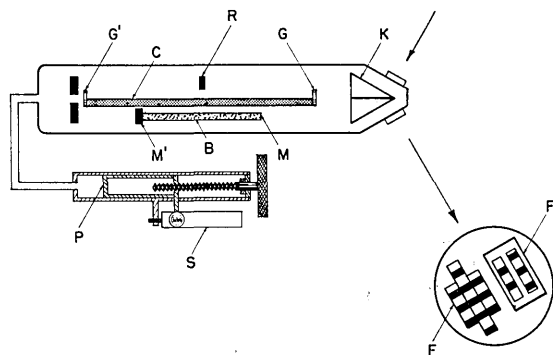

Fig. 4. Interference comparator used at PTB.

the fraction μ is the mutual displacement of the two fringe patterns F' appearing in the right-hand field of view of the interferometer.

The order of interference that would be obtained if the gauge block were in vacuum is

$$N + \epsilon = 2L/\lambda = 2Ln/\lambda - 2L(n-1)/\lambda = N' - (M + \mu)L/L'',$$

which may be approximated, to within ± 0.001 fringe, by $N + \epsilon = N' - (M + \mu)L'/L''$, where L' is an approximate value within ± 1 μ of L. Since L'' is known, and since N' is an integer, this last equation gives the fraction ϵ, while the integer N is obtained in the usual manner from the fractions ϵ measured at different wavelengths λ.

This method has the advantage of measuring the length of a gauge block in vacuum wavelengths without actually putting it in vacuum. Conversely, it may be used to compare vacuum wavelengths in air, with the gauge block serving as a transfer standard. For the measurement of laser wavelengths described here, the interferometer was illuminated, alternately, by the ^{86}Kr standard lamp and the laser, the light from the latter being diffused in a manner similar to that employed at NPL. A 40-cm gauge block was used.

The average wavelength obtained for the laser selected for international comparison was

$$\lambda_{\text{vac}} = (632.991418 \pm 0.00003) \text{ nm.} \tag{1f}$$

B. Studies of Other Lasers

Additional wavelength determinations were undertaken at PTB using a laser of the same design and manufacture (Spectra-Physics model 119 gas laser) as the previous ones, but with a discharge tube filled with a mixture of 90% ^{3}He and 10% ^{20}Ne at 3-torr instead of 4-torr total pressure. The average wavelength obtained was

$$\lambda_{\text{vac}} = (632.991373 \pm 0.000003) \text{nm,} \tag{1g}$$

which is smaller than either of the two values [Eqs. (1c) and (1f)] measured at PTB for lasers filled at the higher pressure of 4 torr.

V. Conclusions

The results quoted in Eqs. (1d), (1e), and (1f) for the laser wavelength measured in the three participating laboratories are in satisfactory agreement, and are all well within the associated limits of imprecision. The mean wavelength is

$$\lambda_{\text{vac}} = 632.991418 \text{ nm,} \tag{1}$$

from which none of the three individual values differs by more than 5 parts in 10^9. Since three different and independent measurement techniques were involved in this intercomparison it is concluded that there are no significant systematic errors in any of these techniques, and that Eq. (1) gives the correct wavelength of this particular laser at the time it was measured. Furthermore, it is concluded that all other wavelengths quoted in this paper, too, are without serious bias.

There is, however, a discrepancy between any of the former values [Eqs. (1a), (1b), and (1c)] and the new value [Eq. (1)] now obtained for a laser of the same type and manufacture. The results for lasers from other manufacturers, as given in Eqs. (2a) and (2) or Table I, and in Eqs. (3a) and (3b), are different again. It follows that different samples of lasers have in fact different wavelengths. Thus, unless a laser has its wavelength individually measured, all that can be said is that the wavelength probably lies somewhere between 632.99147 and 632.99134 nm, due allowance being made for the decrease in wavelength, shown in Fig. 1, during the life of the discharge tube.

Hence, an uncertainty of at least ± 1 part in 10^7 must be associated with the wavelength of a typical frequency-stabilized helium–neon laser of the kind studied, a likely value for this wavelength being

$$\lambda_{\text{vac}} = 632.9914 \text{ nm.} \tag{4}$$

It is interesting to note that the published wavelengths[1,7,8] of lasers containing helium and neon of natural isotopic abundance, and stabilized to their peak intensity, also, fall within 1 part in 10^7 of this value.

At this point it should be remembered that uncertainties of 5 and 8 parts in 10^8, respectively, are associated with the wavelengths of internationally accepted secondary standard sources such as ^{198}Hg and ^{114}Cd lamps. The laser wavelength given in Eq. (4), although still somewhat more uncertain than these secondary standard wavelengths, should be sufficiently accurate for many industrial applications of laser interferometry.

On the other hand, the variations of laser wavelengths reported in this paper should be compared with the wavelength reproducibility of better than 1 part in 10^8 of the primary standard line of ^{86}Kr. The agreement of the results quoted in Eqs. (1d), (1e), and (1f) is, in fact, further evidence of the reproducibility of the primary standard. To this high accuracy it is impossible to specify the wavelength of a laser without measuring it. In addition, Fig. 1 shows that in such cases the laser should be recalibrated from time to time.

The measurements at PTB (Fig. 1 and Sec. IV.B) indicate a dependence of laser wavelength on discharge tube gas pressure. If the variation shown in Fig. 1 is attributed to gas losses during prolonged laser action,[9] both measurements give a red shift with increasing pressure. In the range between 2 torr and 4 torr, this is in agreement with the results of Bloom and Wright[10]; it also agrees with measurements by Fadl[11] of the spontaneous emission line of Ne obtained from He–Ne mixtures. On the other hand, White[12] and Lee and Skolnick[13] reported blue shifts of the wavelength with increasing pressure, which agrees with unpublished measurements by Birky.[14]

Unless a satisfactory explanation can be found for these discrepancies, it appears that laser wavelengths may be affected by still other and yet unexplored parameters. Since a modern wavelength standard should produce the unperturbed radiation of the emitting atoms rather than reflect its own excitation parameters, these effects must be investigated thoroughly before lasers may become standard sources.

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K. D. Mielenz of the National Bureau of Standards, the editor of the feature on Optics in Germany in this February issue.

Molecular Structure and Spectroscopy
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The 23rd annual Symposium on Molecular Structure and Spectroscopy will be held at the Department of Physics, The Ohio State University, 3–7 September 1968. The program will include **D. A. Ramsay,** National Research Council, Canada, and **I. G. Ross,** University of Sydney, Australia, speaking on the electronic spectra of larger molecules, and **Ali Javan,** MIT, discussing molecular problems studied with gas lasers. Specially arranged seminars on specific topics such as computer techniques in spectroscopy and Fourier transform spectroscopy will also be featured. Some instrument companies will exhibit their latest products during the Symposium. Air-conditioned dormitory accommodations will be available for those who wish to reside on the campus during the meetings; it will be possible to accommodate married couples in these dormitories. If you are not already on the Symposium mailing list, write to K. Narahari Rao, Molecular Spectroscopy Symposium, Department of Physics, The Ohio State University, 174 West 18th Avenue, Columbus, Ohio 43210, for further information or for a copy of the program when it becomes available.