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Wavelength Stability of He-Ne Lasers Used in Interferometry: Limitations and Traceability

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Summary: After a short discussion on the main sources of long and short term inaccuracy of the wavelength of He-Ne lasers some attention is paid to the I_2-stabilized He-Ne laser as a wavelength reference: the accuracy and the numerical value of the wavelength as stated by CCDM. The principle of calibration of commercial He-Ne lasers against an I_2-stabilized laser is described and a number of wavelengths of He-Ne lasers as determined by this method are given.
From the results we conclude the reproducibility of the measured lasers is better than 10^{-7} and only one check of wavelength is necessary for usual measurements.
Final we give some remarks on the problem of legal traceability of commercial lasers as measuring tools.

INTRODUCTION

Many kinds of lasers exist; for the measurement of length by interferometry only low power helium neon lasers are used. Such a laser consists of a gas discharge tube mounted in an optical resonator. The resonator consists of two mirrors held in a well-defined position and at a well defined distance (Fabry Perot resonator).
Under certain conditions of gas pressure, current density and low resonator loss, laser operation takes place and a monochromatic light beam, suitable for interferometric length measurement, is emitted. Of utmost importance is the wavelength of the emitted light. This is determined by two conditions. The wavelength must be one of the several possible modes of the resonator, given by

$$\lambda_k = \frac{2l}{k} \qquad \text{or} \qquad f_k = \frac{c\,k}{2l\,n}$$

(l = distance between mirrors, C = velocity of light in vacuum, n = coefficient of refraction of the medium in the resonator, k = a whole number) and the wavelength must lie within that part of the neon spectral line which is above a certain threshold value (the threshold value is, among others, dependent upon the losses in the resonator), (see fig. 1). Dependent upon the distance between modes a laser can emit light of one wavelength (single mode laser) or of more modes.

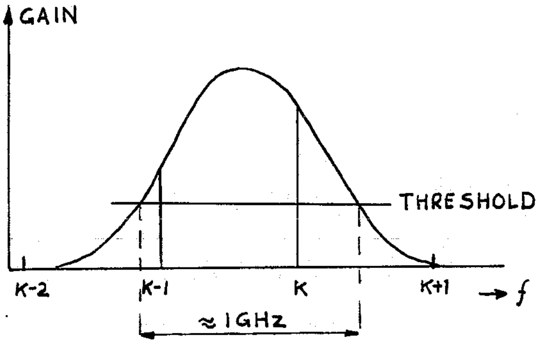

Fig. 1. Gain profile of He-Ne laser with possible modes k-1, k.

The distance between modes follows from the resonator equation given above:

$$\Delta f = \frac{c}{2l\,n}$$

As will be clear later on, it is much more convenient to discuss laser performance in terms of frequency than in terms of wavelength. If desired, wavelength performance can be judged by the relation

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta f}{f}$$

As it is generally necessary to have only one wavelength or frequency, the mode distance Δf must preferably be larger than the width of the spectral line on the threshold. Therefore a short resonator must be used, resulting in a low-power laser.
The frequency of a so called free-running laser is, according to the discussion given above, somewhere within the profile of the spectral line, that is within a range of about 1 GHz *).
As the frequency of the spectral line is about 470 THz*), the accuracy of such a laser does not even reach 10^{-6}, therefore some means of stabilization is necessary. Stabilization is effected by changing the length of the resonator (generally by piëzoelectric means or - less common - by temperature control) in such a way that the laser frequency coincides with a suitable feature of the neon spectral line. Three common methods of stabilization will be described, and the properties of such lasers evaluated by measurement of the resulting frequency. The exact frequency of a spectral line, however, depends on gas pressure, on the electrical conditions within the gas discharge, and on the isotope chosen. If a mixture of isotopes is used, the frequency may depend on the composition of the mixture. Therefore a fourth type of a stabilized laser will be described where these drawbacks are eliminated.

STABILIZATION OF LASER FREQUENCY

1. The center of the neon spectral line would seem to be a convenient feature for stabilization. However, the shape of the top of the profile is not always well defined and is, among others, influenced by the isotopic composition of the neon gas used. Under certain conditions a well defined dip in the top of the profile exists, the Lamb-dip (fig. 2) which can be used as a reference for locking the laser frequency. The frequency of the laser then coincides with the lowest part of the dip. A so-called Lamb-dip-stabilized laser was supplied by a well known manufacturer of lasers and is used to some extent in laboratory measurements.

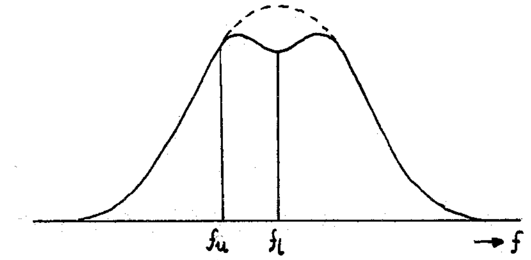

Fig. 2. Gain profile of He-Ne Lamb-dip laser.
f_u: Frequency of unlocked laser,
f_l: Frequency of locked laser.

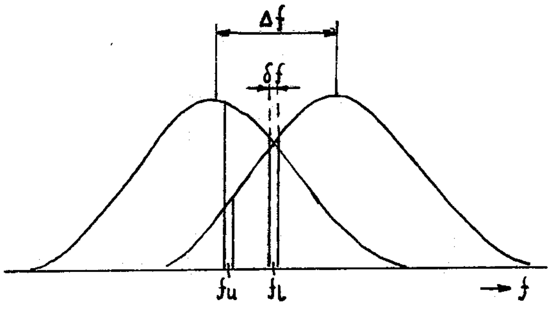

Fig. 3. Frequency splitting of neon line Δf.
f_u: Frequency of unlocked laser,
f_l: Frequency of locked laser,
δf: Frequency difference of splitted laser line (Highly exaggerated, δf ≈ 2MHz).

2. A further stabilization scheme uses the so called Zeeman-splitting of the neon spectral line by a weak axial magnetic field (fig. 3). When this is done, the laser emits two modes of almost exactly the same frequency, but belonging to the two

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*) 1 GHz = 10^9 Hz; 1 THz = 10^{12} Hz.

spectral line profiles, and thus having different intensity, except when the laser frequency is that of the intercept of the two profiles, which coincides with the central frequency of the original spectral line. Stabilization is - of course - effected by changing the resonator length until the intensity of the two modes is equal. Although this stabilization scheme in reality depends upon the slope of the flanks of the profile, the frequency is that of the profile center. This kind of laser is used by a well known manufacturer of complete laser-interferometer systems often used in practical length measurements.

3.

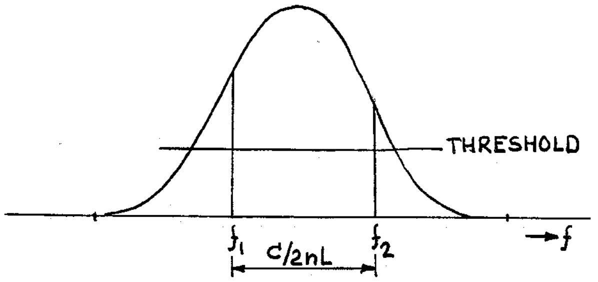

Fig. 4. Frequency situation in a two-mode laser (unlocked).

A third method of stabilization uses a somewhat longer resonator, resulting in two-mode operation (fig. 4). If the length of the laser is changed, these two modes move along opposite flanks of the profile and thus change intensity in opposite sense. As the two modes have different polarisation properties, the intensities can be measured separately, and their difference used to effect frequency locking. Of course, only one of the modes must be used for actual length measurement. This stabilization method is used in a laser measuring system more recently put on the market.

RESULTING ACCURACY OF WAVELENGTH

From the foregoing it might seem that a very stable frequency - or wavelength source is now available. Such, however, is not the case. Short time variations are caused by the inherent limitations of the electronic stabilization circuits, and the disturbance of resonator length by mechanical vibrations. The wavelength in air, which is used in practical measurements, depends on the coefficient of refraction of the air, and thus on pressure, temperature,moisture content and on possible contaminations. This influence can normally be taken into account by Edlén's relation [1] and suitable corrections can be applied by the operator or by an automatic compensation system, provided temperature and pressure are known accurately enough. More dangerous is the dependence of the frequency upon gas pressure, gas composition and discharge current within the gas discharge. In practice these parameters are not well known, pressure generally changes with time, and the resulting change in frequency can well reach 10^{-7} [2].
This effect has the well known property of systematic errors that there are no means *within* the system to detect this error; therefore the error can only be measured by comparison with other - more stable - standards and in practice the operator might well be unaware that such an error exists. It is for this reason that the measurements described in the latter part of this paper were undertaken.

I_2-STABILIZED LASER

Although it is possible to measure the wavelength of a laser by comparison with a conventional wavelength standard - preferably with the primary Krypton lamp - such a measurement is tedious and much more accurate results can be achieved by comparison with a stable laser. The only laser suitable for this purpose is the so called iodine stabilized laser. (A similar laser, the methane-stabilized laser, emits infra-red radiation and is therefore not convenient for the present problem.) The principle of stabilization is somewhat similar to the Lamb-dip stabilization mentioned above. If iodine gas, placed in a suitable absorption tube, is placed in the resonator - as it were in series with the normal gas discharge tube - very minute, but narrow and well defined pikes appear on the output-versus-frequency curve. These pips arise from an effect called saturated absorption, the frequency of the pikes depends slightly upon the iodine pressure, but the pressure can be easily controlled by cooling a part of the absorption tube because the iodine is at a solid-gas equilibrium.
If the laser is locked to one of these pikes a very stable frequency results: short time stability is a few parts in 10^{11}, lasers built in different laboratories give the same frequency within 10^{-10}. The wavelength of one of the pikes is measured by a number of laboratories against the primary standard and these measurements agree within 5×10^{-9}, which represents the accuracy of the primary standard. Such lasers are therefore ideally suited for the calibration of commercial lasers. A few practical drawbacks remain: these lasers are not available commercially, the electronic setup is rather elaborate, and some extra precautions are necessary to realise the accuracy mentioned above.
As a consequence the use of such lasers is at present practically restricted to special laboratories.

METHOD OF COMPARISON

The frequency difference between two lasers can easily be measured by a heterodyning technique, provided that the frequency difference is not greater than a few hundred MHz. The two laser beams are brought together on a single photodetector by means of a semi-reflecting mirror. If certain conditions of equal shape of wavefront are met and if the response of the photodetector is sufficiently fast (this response time is related to the maximum usable frequency difference), the difference frequency appears as an electrical signal of the same frequency, which can be counted by a conventional electronic counter. The heterodyne phenomenon can be understood by considering that a photodetector responds reasonable linear to light intensity and that intensity is proportional to the square of the amplitude. In this case the output is proportional to the square of the sum of the E-vectors of both electro-magnetic waves. It can be seen easily that this gives rise among others to the difference frequencies.

PRACTICAL RESULTS

In our laboratory three I_2-stabilized lasers are available. By measuring the frequency difference of these lasers their reproducibility is easily checked (see fig. 5).

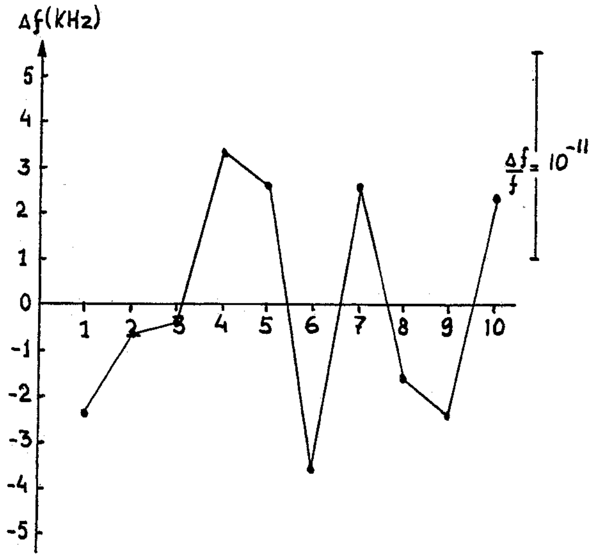

Fig. 5. Reproducibility of frequency difference between two J_2-stabilized He-Ne lasers (THE). Measuring period: 10 days.

Against these lasers were measured 2 different Lamb-dip-stabilized lasers, 5 different Zeeman-stabilized lasers, and 2 two-mode-stabilized lasers of different manufacture. In general measurements were performed by punching the frequency in tape at regular intervals during a few days. A sample of such a measurement is given in graphical form in fig. 6.
Then, some of the lasers were measured from a cold start. In general the lasers settled down within 1 hour, and different lasers behaved roughly in the same way. A sample graph is given in fig. 7. As a consequence, the frequency during the first hour, if measured, was not taken into account in calculating the average.
Further, a number of the lasers were measured a few times after having been switched off during some hours. These measurements are given in fig. 8. Mean wavelengths of the users measured are given in fig. 9 and fig. 10. One laser exhibits jumps in frequency up to 40 MHz, moreover the behaviour as observed on a frequency analyser suggests that the stabilizing circuit is oscillating at irregular intervals. As this oscillation might well escalate, it would be advisable to have the electronics serviced by the manufacturer. It came to our attention [3] that in another laboratory a laser was found to oscillate continiously. In this case the laser did not stabilize at all, although all controls indicated normal operation.

CONCLUSIONS

From the measurements reported it might be conluded that the lasers are within the rather course range specified by the manufacturer.
It must be stressed that in the experiments just described the laser frequency is measured and the properties of the interferometer are *not* taken into account. If the mechanical setup is not perfectly stable the short-time instability might be larger than reported here. Further, the accuracy of measurement of temperature and pressure needed for the calculation of the coefficient of refraction of the air, or the accuracy of the sensor in an automatic correcting accessory enter into the accuracy of the measurement.

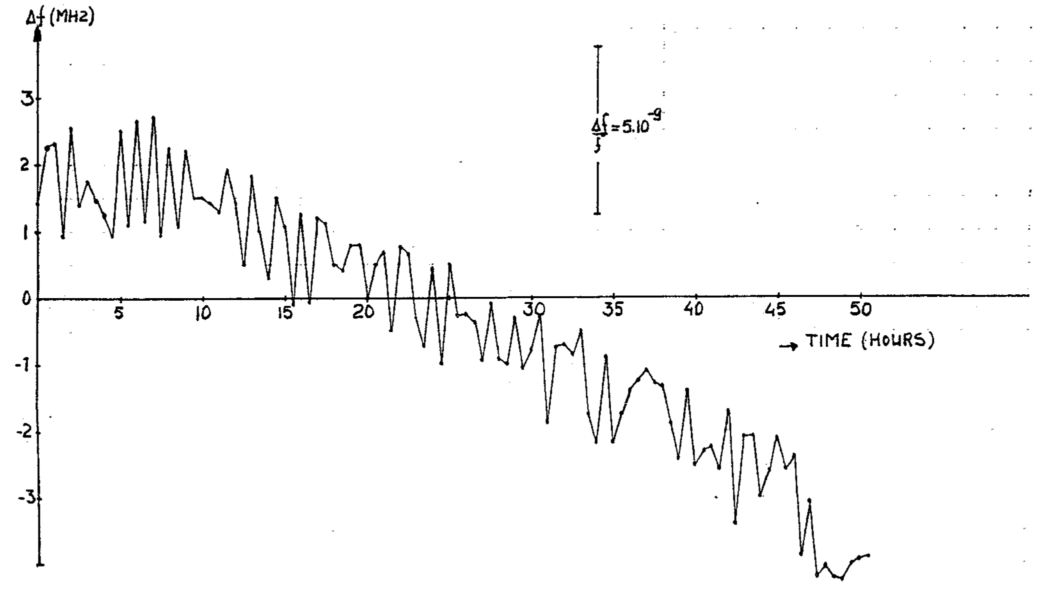

Fig. 6. Frequency behaviour of a stabilized He-Ne laser (Zeeman-splitting) as measured by a I_2-stabilized He-Ne laser.

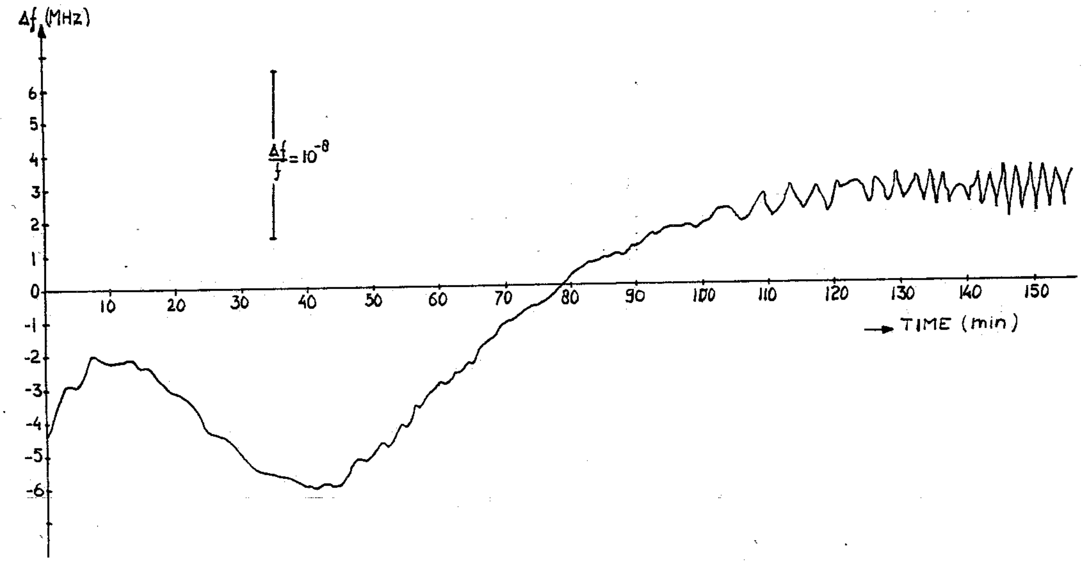

Fig. 7. Frequency behaviour of a stabilized He-Ne laser (Zeeman-splitting) during warming-up time.

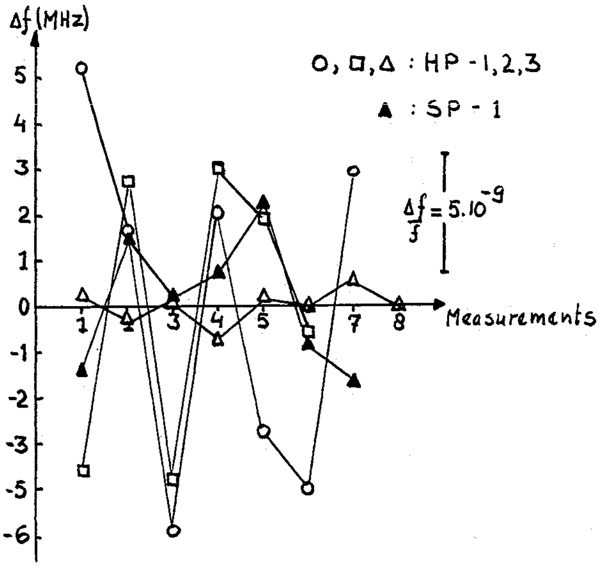

Fig. 8. Reproducibility of frequency of different stabilized He-Ne lasers. Measurements after one hour warming-up time. Measuring period: 1 week.

Tabel I

Age	Number	Stabilization type	Vacuum Wavelength (nm)
1971	HP-4	Zeeman-Splitting	632,991359
1971	HP-5	"	632,991366
1977	HP-1	"	632,991385
1970	HP-2	"	632,991413
1978	HP-3	"	632,911400
1978	HP-6	"	632,991380
1975	SP-1	Lamb-dip	632,991433
1977	SP-2	"	632,991423
1977	T-M 1	Two-mode	632,991382
1978	T-M 2	"	632,991255

Fig. 9. Wavelengths of a number of stabilized He-Ne lasers.

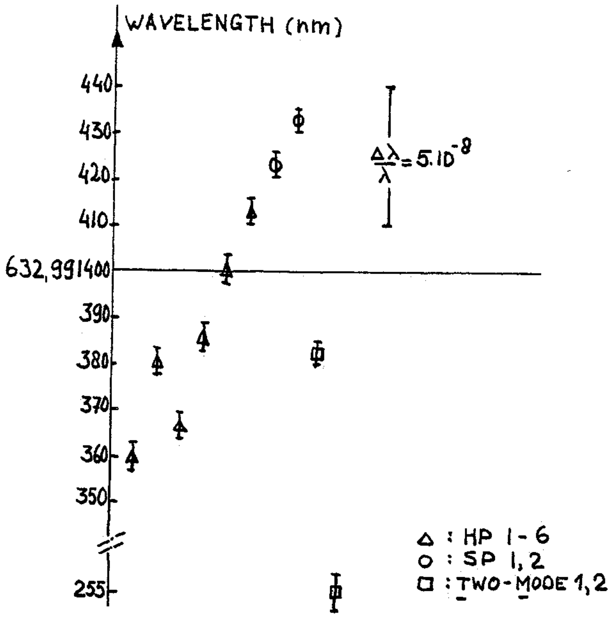

Fig. 10. Wavelengths of a number of stabilized He-Ne lasers.

A higher accuracy can be achieved only if the laser is calibrated recently and if the user can handle the rather severe requirements for the measurement of pressure and temperature required. In any case it is advisable to operate the laser for one hour before measurements start.

LEGAL TRACEABILITY OF LASER WAVELENGTH

The problem remains if lasers and laser interferometers can be used for length measurement they are required to be traceable to the primary standard *without* individual calibration by a standards laboratory. In our opinion that is not the case. The physical properties of lasers which are confirmed by the measurements reported in this paper, indicate that a given laser is within 10^{-7} of the intended wavelength, *provided* the gas discharge tube is filled with the proper gas mixture of the proper isotope content. In our opinion a laser measuring system can be considered traceable to a few times 10^{-7} *provided* at least one check of wavelength or frequency has been made, and provided the operator has the facilities to measure coefficient of refraction to the accuracy required. The measurement of wavelength could well be done by the manufacturer provided his apparatus for doing this has been checked by a standards laboratory.

Such lasers can be used to a higher accuracy provided the user can handle the corrections for atmosferic conditions to the required accuracy and the laser is calibrated by a standards laboratory immediately after the measuring run.

Another problem is the traceability of the iodine-stabilized laser.

The evidence of numerous intercomparisons [4] assure that such lasers give identical frequencies within 10^{-10}, well within the accuracy of the primary standard. Calibrations of such lasers against the primary standard agree within the accuracy of this standard. Therefore, iodine stabilized lasers should be considered traceable to the full accuracy of the primary standard, the numerical value for the wavelength recommended by the "comité consultatif pour la définition du mètre" [5] should be used.

Of course, this statement must be reconsidered if in the near future a redefinition of the meter is contemplated.

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