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Description and accuracy tests of an improved lambdameter

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Résumé. — Nous décrivons un ondemètre interférométrique à lecture numérique. Il s'agit d'un interféromètre de type Michelson dans lequel la translation d'un réflecteur mobile (double coin de cube) engendre simultanément deux systèmes de franges sur les voies référence (longueur d'onde étalon) et mesure (longueur d'onde inconnue). Un dispositif électronique compare les deux longueurs d'onde au centième de frange et affiche numériquement le résultat. La plupart des erreurs systématiques sont éliminées grâce à la superposition totale des chemins optiques sur les deux voies, assurant ainsi une exactitude potentielle élevée. A titre d'exemple, nous avons remesuré avec ce dispositif la longueur d'onde de la raie $\lambda = 612$ nm émise par un laser à hélium néon asservi à un pic d'absorption saturée de l'iode. Les résultats présentent une dispersion statistique de $\pm 6 \times 10^{-9}$ autour d'une valeur moyenne qui s'accorde à $1,6 \times 10^{-9}$ près avec celle, plus exacte, obtenue au BIPM.

Abstract. — An interferometric wavemeter with digital display is described. Fringes of an unknown and a reference wavelength are simultaneously generated through the motion of a moving double corner cube reflector in a Michelson-type interferometer. An electronic device compares the two wavelengths to within one hundredth of a fringe and numerically displays the result. Most of the systematic errors are eliminated by the total superposition of the optical paths of the reference and the measured beams, ensuring a high potential accuracy. As an illustration, we have remeasured with this device the wavelength of the $\lambda = 612$ nm radiation generated by a He-Ne laser stabilized on a saturated absorption peak of iodine. The results exhibit a statistical dispersion of $\pm 6 \times 10^{-9}$ about a mean value which agrees to within 1.6×10^{-9} with the more exact result obtained at BIPM.

1. Introduction. — The recent development of high resolution laser spectroscopy created, in many laboratories, the need for accurate optical wavemeters. For instance, the study of heavy molecules or of atomic Rydberg states requires a fast and reliable way to measure the wavelength of the laser with a precision better than a tenth of a wavenumber (or one Doppler width). In two photon spectroscopy where very narrow ($\ll 10^{-3} \text{ cm}^{-1}$), but sometimes very weak signals are to be expected, one eventually wishes an accuracy of the order of a milliwavenumber, which is, by far, not achievable by any monochromator.

This common need led our laboratories to work together for the realization and the evaluation of two highly performant and easy to operate versions of a Lambdameter [1]. This kind of wavemeter has

been chosen among others [2], [3] because of its combination of very high accuracy, wide wavelength range, direct frequency or wavelength display and low cost. Optical and mechanical designs were made in Grenoble while electronics design and accuracy tests were performed at Orsay.

2. Principle of operation. — The basic set-up is described in figure 1. Its principle is derived from the one described in reference [1], we will therefore recall it only briefly. It is essentially a moving mirror Michelson interferometer which records two fringe systems, one from a reference laser whose vacuum wavelength λ_r is known with suitable accuracy, and a second one whose wavelength λ_u is to be measured. For a given displacement L of the moving mirror, the number of fringes counted on each beam will be

$$N_r = \frac{F \times 4 L \times n_r}{\lambda_r} \quad \text{and} \quad N_u = \frac{F \times 4 L \times n_u}{\lambda_u}$$

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Fig. 1. — Lambda-meter basic set-up.

where n_r and n_u are the refractive index at wavelengths λ_r and λ_u , respectively. F is a resolution extension factor obtained electronically (see Section 5). So, we find

$$\lambda_u = \lambda_r \times \frac{N_r}{N_u} \times \frac{n_u}{n_r}.$$

The resolution $R = \lambda/d\lambda$ is limited by the ± 1 counting uncertainty and is equal to $R = \frac{4FL}{\lambda_r + \lambda_u}$. For $F = 128$, $L = 1$ m, $\lambda_r = \lambda_u = 0.6 \times 10^{-6}$ m, we get $R = 4.2 \times 10^8$.

The accuracy is limited by alignment and diffraction effects and also by our knowledge of the air refractive index.

3. Optical design. — The main points of interest of our version are the following :

a) The reference beam and measurement beam follow identical and opposite optical paths. This not only helps the alignment (the reference beam is used as a tracing beam for the injection of the other one), but also reduces the sensitivity to acoustic perturbations and air drifts.

b) The apparatus is fully symmetrical due to its triangular shape and beam splitter compensator device. The resulting zero path difference in the middle of the carriage displacement allows one to eventually measure the mean wavelength of a multi-mode laser.

c) As can be seen in figure 1, the optical path (for each beam) consists of two triangles in two parallel planes. It can be shown that if the beams are originally aligned and a misalignment comes from a translation of the corner cubes perpendicular to their motion, the optical path lengths for the two beams will remain exactly equal, so the system is highly insensitive to imperfections of the carriage motion.

d) Not represented in figure 1 are afocal beam expanders which also allow spatial filtering.

4. Mechanical design. — The moving carriage, made of aluminium alloy, holds the two oppositely directed corner cubes coaxially mounted in a brass cylinder. This ensemble is easily removable in order

to facilitate the initial settings. Five precision ball bearings ensure a smooth ride of the carriage on two precision machined cylindrical steel bars. The carriage is driven by a belt and pulley system moved by a small dc electric motor. With some care on the choice of these elements (our present system uses a belt made of a polyester ribbon) it is possible to ensure a translation velocity of 4 cm/s uniform to within $\pm 2\%$, the jitter frequency spectrum being maximum at about 2 Hz. A system of optical barriers and relays reverses the rotation of the motor at each end of the available path.

The two steel bars forming the track are clamped on a rigid aluminium alloy chassis which also holds the fixed optical parts (beam splitter, mirrors, photo-detectors). A demountable cylindrical stainless steel tank with optical windows allows the whole system to be operated under vacuum, although this possibility has not yet been used. The overall appearance of the device is shown in figure 2.

Fig. 2. — Photograph of the apparatus.

5. Electronic design. — A simplified block diagram of the electronic system is shown in figure 3. It consists of two nearly identical channels which count simultaneously the fringes from the reference and unknown beams. The sinusoidal fringes received by each Si

Fig. 3. — Electronic design.

photodetector are symmetrically amplified and limited and fed to a level detector which provides TTL compatible pulses. The minimum laser power needed to trigger the level detector is around 30 μ W.

These pulses are compared in a phase detector to the output of a voltage controlled oscillator (VCO) which has previously been frequency divided by the factor F ($F = 64$ or 128). The output of the phase comparator is used to phase lock the VCO. The servo loop is slightly overdamped and has a bandpass of 20 kHz. The capture range is equal to one octave. These performances allow us to use a resolution extension factor F of 128 with the present simple version of the moving carriage. The output of the phase comparator is also used to eventually produce an *unlock signal* which disables and resets the counters, so as to forbid the readout of a measurement during which a perturbation happened.

On the measurement channel, the counter is preset to a quantity P which can be dialed with 9 coding wheels. The number of significant digits is selected with one more wheel. The other counter is triggered and stopped by the first one and outputs on a LED display. So, if we dial P as having the same significant figures as λ_r , we get a readout

$$N_r = \lambda_u \frac{n_r}{n_u}.$$

In the final version, the interferometer will be under vacuum, then $N_r = \lambda_u$.

6. Tests and performances. — **6.1 RESOLUTION.** — The resolution limit of this apparatus with its present 1 m travel length and a factor of 128 electronic resolution extension is 1.4 fm around

$$\lambda = 6 \times 10^8 \text{ fm} \quad (1 \text{ fm} = 10^{-15} \text{ m}).$$

We have tested the practical resolution by measuring the wavelength of a He-Ne laser locked to various hyperfine components of the $^{127}\text{I}_2$ 11-5 R(127) and 9-2 R(47) lines at 6.33×10^8 and 6.12×10^8 fm [4], [5]. The typical root mean square uncertainty of a set of 50 measurements was 5 fm, 3.5 times worse than the theoretical resolution. This enabled us to clearly resolve the iodine hyperfine structures and to remeasure these well known splittings [4], [6] in terms of wavelength with a precision on the order of 2.5 fm (4×10^{-9} or 2 MHz).

6.2 ACCURACY. — The accuracy of the wavelength measurement has been tested by comparing two He-Ne lasers respectively stabilized to the iodine hyperfine components g of the 11-5 R(127) line at

$$6.33 \times 10^8 \text{ fm} (\lambda_r)$$

and i of the 9-2 R(47) line at 6.12×10^8 fm (λ_u). The wavelength of this last line had been previously determined on the BIPM Michelson interferometer [7] with an accuracy of 0.2 fm. As the two wavelengths

are not very different, the correction due to the index of refraction of air with a moderately accurate determination of ambient pressure, temperature and humidity is precise enough [8] and does not represent a serious limitation.

The effect of the beam alignment, the beam divergence and of wavefront quality is expected to be more critical. We first made the measurements with spatially separated laser beams, using different sectors of the corner cubes. This configuration is convenient because there is no coupling between the two lasers, but the alignment errors on the two beams are then independent and the scatter of the results is large (± 10 fm or ± 1.7 part in 10^8).

We finally chose to use coincident counterpropagating beams. The coupling problem was easily solved with an interference filter on one end, and a dispersive prism on the other end. Then, the alignment procedure was the following : one of the laser beams is used to align the λ meter. This first alignment is considered as satisfactory when the fringe visibility $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ is larger than 90 % over the whole travel length of the corner cubes. One of the two emerging beams from this first laser is now used as a tracing beam for the alignment of the second laser beam, which can be performed very precisely if a common path of a sufficient length is available. The alignment errors are then nearly the same for both lasers. In order to test the practical accuracy, 5 different experimentalists performed 8 independent runs of measurements, between which the whole set-up was completely disaligned and realigned. The beam waists ranged from 1 to 3 mm and were approximately the same for both lasers, so the difference in the diffraction corrections between the two beams varied in the range 10^{-9} to 10^{-10} and was neglected. Wavefront cleaning with a spatial filter improved slightly the fringe visibility but did not change the results.

The results of these measurements are shown in figure 4. The error bars show the statistical uncertainty of each series of N measurements. This uncertainty is much smaller than the dispersion of the results, so this dispersion reflects the residual effect of the misalignment errors.

Fig. 4. — Wavelength measurements.

From these results, we can derive the following conclusions :

a) The inaccuracy of one run of about 50 measurements was never larger than 10 fm, which demonstrates that an accuracy of 2×10^{-8} is obtained for a measurement time of the order of half an hour. Such a result compares favorably with the performances of other devices [1-3, 9].

b) A higher accuracy can be obtained if one tries to randomize the alignment errors with successive realignments [9, 10]. The average of our 8 runs is :

$$\lambda[i; 9-2 R(47)] = 611\,970\,459.5 \pm 2 \text{ fm} .$$

(The incertitude stated here is the standard error of the mean.) This value agrees to within 0.9 fm with the more accurate measurement made at BIPM [7] :

$$611\,970\,458.6 \pm 0.2 \text{ fm} .$$

Consequently, the sum of all remaining systematic errors is probably smaller than 2.9 fm, which indicates an accuracy of 5×10^{-9} .

7. **Conclusion.** — The described interferometer has proved to be easy to build and to operate. It provides precise wavelength measurements, with a rms uncertainty of 5 fm ($2 \times 10^{-4} \text{ cm}^{-1}$) and an accuracy of 5×10^{-9} after averaging. These performances should be obtained throughout all the visible wavelength range once the interferometer will be evacuated, at least for lasers with sufficiently low amplitude noise.

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