Uncertainty evaluation and electronic improvements of a wavemeter to measure the wavelength of an external cavity diode laser

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Abstract. A Michelson wavemeter was developed to test the accuracy and give traceability to the wavelength of external cavity diode lasers. These lasers were stabilized using a Littrow configuration and an iodine gas cell as frequency reference, and they were used as light sources in the assembly of a new interferometric system for the gauge block calibration. Previously, a microcontroller counting device with a Vernier logic and the uncertainty evaluation of the Michelson wavemeter had to be made.

1. Introduction

The development of an interferometric system for gauge block (GB) calibration, based on frequency stabilized ECDL at 633 nm, involves measuring and giving traceability to the diode wavelength [1]. In order to carry out these measurements, a Michelson wavemeter with a Vernier counter was developed and calibrated to ensure the traceability and evaluate the uncertainty of the wavelength of external cavity diode lasers (ECDL).

2. Design

The wavemeter is based on a Michelson interferometer [2-4] which measures the number of fringes for two counter propagating laser beams, \( \lambda_R \) reference laser and \( \lambda_U \) unknown laser, produced due to the movement of a motor (DS) in the arms of the interferometer. The relationship between the wavelengths of the two lasers and their number of fringes is:

\[
\lambda_U = \left( \frac{N_R}{N_U} \right) \lambda_R \frac{n_U}{n_R}
\]  

(1)

Where, \( N_R \) and \( N_U \) are the number of fringes counted for the reference laser and the unknown one, \( n_R \) and \( n_U \) are the refraction indices in air for these lasers.

The experimental setup employed for the wavemeter comprises a He-Ne (REO 32734) reference laser, a 220 mm linear motor (DS) (Thorlabs DDS220/M), an optic mount and an electronic system in order to count the interference fringes using the Vernier method to improve system accuracy, figure 1.
3. Electronic Vernier counter

The Vernier counter is based on a microcontroller to measure and track the count of the fringes, and it is divided into three modules: an analog, figure 2, a digital coincidence detector, figure 3a, and a microcontroller, figure 3b.

The analog module is composed of two identical sections with a transimpedance amplifier, voltage preamplifier with filter, variable gain amplifier and Schmitt-trigger comparator. A positive 5V power supply with a LDO regulator, (LP2950-3.3), was used to provide the reverse polarization for the photodiodes and reference for the preamplifiers. This configuration allows the use of a single supply for all the electronics circuits.

The operational amplifier, (Texas Instruments TLE2074), was used in this module because of its good performance characteristics (low noise, 10 MHz bandwidth, 45 V/µs slew rate) and wide supply range. Noise immunity is achieved with the Schmitt-trigger comparator and its hysteresis level of ±200 mV. As it is critical for the accuracy of the system due to a small signal-to-noise ratio of the fringes, many tests were made to verify the reliability of the module.

The digital coincidence module provides the digital input for the microcontroller and it is responsible for the coincidence detection required to start and stop the fringe measurements in the Vernier method.

So far, the counter logic has been made with a microcontroller, instead of the fixed counters found in literature [2,3], and a coincidence detector. This coincidence detector generates short pulses at the positive edges of the input signals, which are combined in a high speed 74HC00 logic gate that activates a RS flip-flop. The output of this circuit triggers an external interruption on the microcontroller which starts and stops pulse counter. Microcontroller resets the flip-flop when the count is finished to allow the detection of next coincidences. For the first prototype, pulse duration was set to 100 ns to avoid performance problems on the system when input frequency is slower than 100 KHz, a resolution of $10^{-2}$ per fringe can be achieved.

Moreover the microcontroller module performs the user input, the visualization system and the counter logic, and it improves the flexibility of the system to introduce changes in hardware and software, in contrast to older designs based in wired logic [2, 3]. It was developed with MCS-51 family of microcontrollers,(Atmel AT89S52), a 24 MHz quartz crystal, a 2x16 monochrome LCD display and four pushbuttons. This limits the frequency counter of the microcontroller to a maximum of 500 KHz, enough for the incoming of the signal.
4. Uncertainty evaluation

Equation (1) can be simplified to \( \lambda_U = \lambda_R (N_R / N_U) \) due to the difference between the refractive index of air of both laser beams is less than 0.01ppm, in our laboratory environmental conditions through Ciddor equation [6]. This occur because of the similarity between the wavelength of reference and unknown lasers (<0.005 nm).

The uncertainty of the model function, equation (2), was developed from the simplified equation (1) taking into account all contribution errors that affect the measurement found in bibliography [3,4], and following the recommendation for expressing uncertainty given by the BIPM [5]. Accordingly, the uncertainty components were calculated through table 1.

\[
U(\lambda_U) = \sqrt{U^2(N_R) + U^2(N_U) + U^2(\lambda_R) + U^2(\lambda_{REC}) + U^2(\lambda_{WCU}) + U^2(\lambda_{LIG}) + U^2(\lambda_{BLG}) + U^2(\lambda_{LSP}) + U^2(\lambda_{VIB}) + U^2(\lambda_{TEM}) + U^2(\lambda_{AMB})}
\]  

The uncertainty function was applied to two lasers, the stabilized ECDL and an HP 5519A which was used to check the accuracy of the system and it has a wavelength of 632.991 368 7 nm with an uncertainty of 0.000 013 nm. The results obtained from the experimental data of tables 2 and 3 were a wavelength of 632.991 41 nm with uncertainty (at 95% with k=2) of 0.000 16 nm (0.26 ppm) for the HP 5519A, which agrees with the results of the calibrated laser given by the reference laboratory; and a wavelength of 632.992 2 nm with uncertainty of 0.0001 3 nm (2.0 ppm) for the ECDL, a value which has a high uncertainty that it does not allow to identify the \(^{127}\text{I}_2\) stabilized transition [7].
Table 1. Contributions to the uncertainty of the wavemeter.

| Description                                      | Method of calculus                                                                 |
|--------------------------------------------------|-----------------------------------------------------------------------------------|
| $U^2(N_R)$ Reference laser fringe count           | $(\lambda_R / N_U)^2 \Delta N_R^2$                                              |
| $U^2(N_U)$ Unknown laser fringe count             | $(-\lambda_R / N_U^2)^2 \Delta N_U^2$                                            |
| $U^2(\lambda_R)$ Reference laser wavelength      | $(N_R / N_U)^2 [(U(\lambda_R)/2)^2 + (D(\lambda_R)/\sqrt{12})^2]$               |
| $U^2(\lambda_{WCR})$ Wavefront curvature of the reference laser | $((\lambda_R \Delta \delta_R^2)/4)^2$                                               |
| $U^2(\lambda_{WCU})$ Wavefront curvature of the unknown laser | $((\lambda_U \Delta \delta_U^2)/4)^2$                                               |
| $U^2(\lambda_{ALIGN})$ Reference laser alignment | ${((\lambda_R/2)([\Delta x/L] + \Delta \theta_{DS} + \Delta \theta_{CC})^2}$     |
| $U^2(\lambda_{ALIGU})$ Unknown laser alignment   | ${((\lambda_U/2)([\Delta x/L] + \Delta \theta_{DS} + \Delta \theta_{CC})^2}$     |
| $U^2(\lambda_S)$ Repeatability of the measurements | $(\sigma(\lambda_S))^2$                                                         |
| $U^2(\lambda_{TEMP})$ Thermal dilation of the optics system | $[\frac{(\lambda_U + \lambda_R)}{2(\Delta T d\alpha / d)^2}]^2$           |
| $U^2(\lambda_{CIDDOR})$ Refraction index of air [6] | $\frac{(\lambda_U, \Delta \nu_{CIDDOR})^2}{\nu_{CIDDOR}^2}$                       |
| $U^2(\lambda_{VIB})$ Vibrations in the optics system | $[\frac{(\lambda_U + \lambda_R)}{2(\Delta A / d)^2}]^2$                          |

Table 2. Experimental values of the wavemeter for the HP 5519.

| Quantity                                      | Symbol | Value                      |
|-----------------------------------------------|--------|----------------------------|
| Reference laser wavelength                    | $\lambda_R$ | 632,9910325 nm              |
| Reference laser wavelength uncertainty        | $U(\lambda_R)$ | 0.0000031 nm                |
| Reference laser deviation per year            | $D(\lambda_R)$ | 0.000007 nm                 |
| Reference laser beam divergence               | $\Delta \delta_R$ | 0.6 mrad                    |
| Unknown laser beam divergence                 | $\Delta \delta_U$ | 0.2 mrad                    |
| Reference and unknown wavelength fringe error | $\Delta N_R$ and $\Delta N_U$ | 0.1 fringe                 |
| Reference wavelength fringe count             | $N_R$ | 1332045.4 fringes           |
| Unknown wavelength fringe count               | $N_U$ | 1332044.6 fringes           |
| Reference and unknown position misalignment   | $\Delta x_R$ and $\Delta x_U$ | 0.5 mm                      |
| Alignment distance                            | $L$ | 2000 mm                     |
| Direct drive stage misalignment               | $\Delta \theta_{DS}$ | 0.25 mrad                   |
| Corner cubes misalignment                     | $\Delta \theta_{CC}$ | 0.015 mrad                  |
| Standard deviation of the measured wavelength | $\sigma(\lambda_U)$ | 0.000031 nm                 |
| Air diffraction index uncertainty             | $\Delta n$ | 0.01 ppm                    |
| Corner cube base lineal expansion coefficient | $\alpha$ | 22 $\mu$m/Km                |
| Temperature gradient                          | $\Delta T$ | 0.5 K                       |
| Corner cube distance                          | $d$ | 62 mm                       |
| Vibration amplitude                           | $\Delta A$ | 50 nm                       |
Table 3. Contributions to the uncertainty of the wavemeter.

| Quantity                                      | Symbol | Value             |
|-----------------------------------------------|--------|-------------------|
| Unknown laser beam divergence                | \( \Delta \delta_U \) | 2.0 mrad          |
| Reference wavelength fringe count             | \( N_R \) | 1332023.2 fringes |
| Unknown wavelength fringe count               | \( N_U \) | 1332020.8 fringes |
| Standard deviation of the measured wavelength | \( \sigma(\lambda_U) \) | 0.000043 nm       |

5. Conclusions

According to the results obtained with the HP laser calibration, the wavelength measuring system works properly but it is not yet able to reach the required precision for GB calibration. As a result, it is suitable for making a first approximation of the measurement of the ECDL wavelength and it provides a solution for those applications where an uncertainty on the order of 1 ppm in wavelength is required.

In future, a set of improvements will be made to allow wavemeter to reduce the uncertainty and enhance the precision. Furthermore, the uncertainty equation will be extended to other wavelengths, taking into account the changes produced in the refraction index of air with Ciddor’s equation [6], and the traceability of the system will be verified with lasers away from 633 nm. In addition, an evaluation of the stability of the laser diode will be made through an Allan variance [8].

References

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