WAVELENGTH CONTROL OF VCSEL LASER EMPLOYED IN THE ABSOLUTE LASER INTERFEROMETER

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ABSTRACT

In the work, we present the absolute distance interferometer with a narrow-linewidth tunable VCSEL laser (Vertical-Cavity Surface-Emitting Laser) working at $\lambda \approx 760$ nm. As a detection technique, we use a fast wavelength-scanning interferometry improved by an amplitude division of the interference fringe with using two signals in quadrature. Used VCSEL laser is wide tunable with the mod-hop free tuning range more than 1.2 nm by means of the amplitude modulation of the injection current. We control the stabilization and tuning process of the laser wavelength with using the frequency lock to a Fabry-Perot glass plan-parallel etalon with high-fines. The optical set-up of the interferometer uses polarized beams and Michelson structure of the interferometer. A detection unit of the interferometer produces the combination of two perpendicularly polarized laser beams with production of two electronic signals in the quadrature. Our fast analog-to-digital card equipped with the digital signal processor (DSP) samples these signals.
We experimentally compared the developed absolute interferometer with a conventional – incremental Michelson interferometer based on a single frequency He-Ne laser that has the resolution 1.2 nm. We achieved the relative uncertainty below 10^{-4} order for a range of tested distances $L \in <78;\ 118>$ mm.

Keywords: wavelength-scanning interferometry, absolute interferometry, tunable laser, scale linearity

1. INTRODUCTION

The Michelson laser interferometers based on He-Ne lasers belong to high-precise industrial distance measuring devices. This kind of interferometers utilizes the following expression for calculation of the optical path difference L between the two beams (measuring and reference):

$$L = \frac{\lambda}{2} \cdot \frac{\varphi}{2\pi} = \frac{\lambda}{2} \cdot (N + \varepsilon), \qquad (1)$$

where λ is the laser wavelength, φ is the total phase between interference beams, N is the integer part of the order of the interference fringe, and ε is the excess fraction. Because the integer part N cannot be determined in static regime of the interferometer, it requires movement of a measuring mirror of the interferometer along the whole unknown path ΔL. The interferometer works in the incremental regime. Then the initial and end position of the measuring mirror can be indexed by indexes *1* and *2* of symbols L, N and ε. Then the path ΔL travelled by the measuring mirror is expressed:

$$\Delta L = L_1 - L_2 = \frac{\lambda}{2} \cdot \left[(N_1 + \varepsilon_1) - (N_2 + \varepsilon_2)\right] = \frac{\lambda}{2} \cdot \left[(N_1 - N_2) + (\varepsilon_1 - \varepsilon_2)\right] = \frac{\lambda}{2} \cdot \left[\Delta N_{12} + \Delta\varepsilon_{12}\right], \qquad (2)$$

where ΔN_{12} is the integer part difference of the order of the interference fringe and $\Delta\varepsilon_{12}$ is the excess fraction difference between these two positions of the mirror. If the interferometer beam is interrupted during the measuring process anyway the counter of interference fringes N fails and the process must be started again. Such a situation belongs to main disadvantages of the incremental interferometer.

2. METHODOLOGY

On the contrary, a laser interferometer with scanning of the laser wavelength allows the detection of the unknown position L in a static way - without moving of the measuring mirror. Otherwise, the conventional incremental measuring process can be replaced by sweeping of the laser wavelength. This method is known as the wavelength-scanning interferometry [1]. On basis of the sweep interval we are able to calculate a synthetic wavelength λ_S that determines the maximum scale resolution dL of the absolute interferometer:

$$\lambda_S = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|}, \qquad (3)$$

where λ_1 and λ_2 are the initial and the end wavelengths of the tuneable laser during the scanning process. With wavelength scanning, the synthetic wavelength varies continuously from infinity to the shortest value that is determined by Eq. (3) for the scanning interval $\Delta\lambda = \lambda_1 - \lambda_2$. When the wavelength sweeps from λ_1 to λ_2, the length of the path L is expressed as:

$$L = \frac{\lambda_S}{2} \cdot (\Delta N + \Delta\varepsilon) = \frac{\lambda_S}{2}(\Phi_1 - \Phi_2) = \frac{\lambda_S}{2} \cdot \Delta\Phi, \qquad (4)$$

where $\Delta\Phi = \Delta N + \Delta\varepsilon$. The variables ΔN and $\Delta\varepsilon$ are the variations in width of N and ε, respectively, according to the wavelength scanning. The variables Φ_1 and Φ_2 are instantaneous values of detected interference phase for the wavelength position λ_1 and λ_2, respectively. If the scanning interval $\Delta\lambda = \lambda_1 - \lambda_2$ is wider, then the total resolution of the absolute scale of the interferometer is more precise too. Eq. (4) expresses this clearly.

A widely tunable laser source is the main problem of the development of such a kind of laser interferometers. Thanks to the recent advance in laser diode technology, a replacement of the He-Ne lasers by any special type of the semiconductor laser could be possible. Even though the ordinary single-mode laser diodes are able to tune in very large range of wavelengths (several nanometers), but the mode-hop free operation of the laser in this range is not usual. Only laser diodes based on structures like Distributed Brag Reflector (DBR) or Distributed Feedback (DFB) are able to fulfil such a requirement. If the laser interferometer is used in the metrology practice the laser beam must be recognizable (visible), especially during the adjustment process. Unfortunately edge-emitting laser diodes with DBR or DFB structure are not accessible in the visible part of the light spectrum.

However, a special kind of Vertical cavity surface laser VCSEL at 760 nm operating wavelength is available [2]. This VCSEL (called SPECDILAS) has Brag reflector mirrors that help to improve the linewidth of the generated laser beam. At the same time, such a technology decreases threshold and operating value of the injection current and leads to mode-hop free tuning range $\Delta\lambda$ up to 1.2 nm. For the tuning range from $\lambda_1 =$ 760.0 nm to $\lambda_2 = 761.03$ nm ($\Delta\lambda = \lambda_1 - \lambda_2 = 1.03$ nm) the synthetic wavelength equals to $\lambda_S \approx 561.5$ µm. If the laser interferometer with the wavelength-scanning method uses an electronic subdivision [3] of the interference fringe ($\lambda_S/256$), then on basis of Eq. (4), the total resolution of the absolute Michelson interferometer equals to $dL = 1.097$ µm.

A proposed arrangement of the VCSEL based absolute interferometer is shown in Fig. 1. The stabilization of the wavelength-scanning interval of the wavelength λ_{VCSEL} is a necessary part of the arrangement. We proposed a Fabry-Perot (F.-P.) resonator as an etalon of the optical frequency for these purposes.

Therefore in Fig. 1, the polarizing beam splitter *PBS3* splits the VCSEL beam onto two optical set-ups: the VCSEL absolute interferometer and the F.-P. resonator *FPR*. While the laser sweeps the wavelength λ_{VCSEL}, the reflected part of the beam passes through the etalon *FPR*. We obtain the spectral profile of the F.-P. resonator by means of the photo detector *DU*. The amplitude modulation of the VCSEL injection current provides wavelength-scanning of the λ_{VCSEL}. The wavelength control electronics *WCE* uses the spectral profile as an optical frequency rule. From the basis equations for the optical frequency ν_{NFP} of the respective mode N_{FP} of the F.-P. resonator can be calculate the number of passed resonant modes ΔN_{FP}:

$$\Delta N_{FP} = \mathrm{int}\left[2 \cdot L_{FP}\frac{1}{\lambda_1}\cdot n\right] - \mathrm{int}\left[2 \cdot L_{FP}\frac{1}{\lambda_2}\cdot n\right]. \tag{5}$$

where n is the index of refraction of the cavity environment, and L_{FP} is the length of the cavity. It leads to $\Delta N_{FP} = 214$ for the tuning range from $\lambda_1 =$ 760.00 nm to $\lambda_2 = 761.03$ nm. The cavity length equals $L_{FP} = 40.0$ mm. The F.-P. resonator is made from a high-stable glass material, thus the index of refraction equals $n = 1.50$. With respect to Eq. (5) we can program the electronics *WCE* for wavelength scanning of the laser along this number $\Delta N_{FP} = 214$ of F.-P. modes. If the scanning process is started, at the same time the detection electronics of the interferometer (*IDE*) analyses the course of interference fringes. Because that interferometer employs the detection technique with signals in quadrature [3], the electronics *IDE* monitors the interference phase Φ with using the detection unit *QDU1*. The total phase difference $\Delta\Phi = \Phi_1 - \Phi_2$ is used for calculation of the position L in accordance with Eq. (4). Fig. 2 presents an example of one sweep period of the wavelength λ_{VCSEL} from λ_1 towards λ_2.

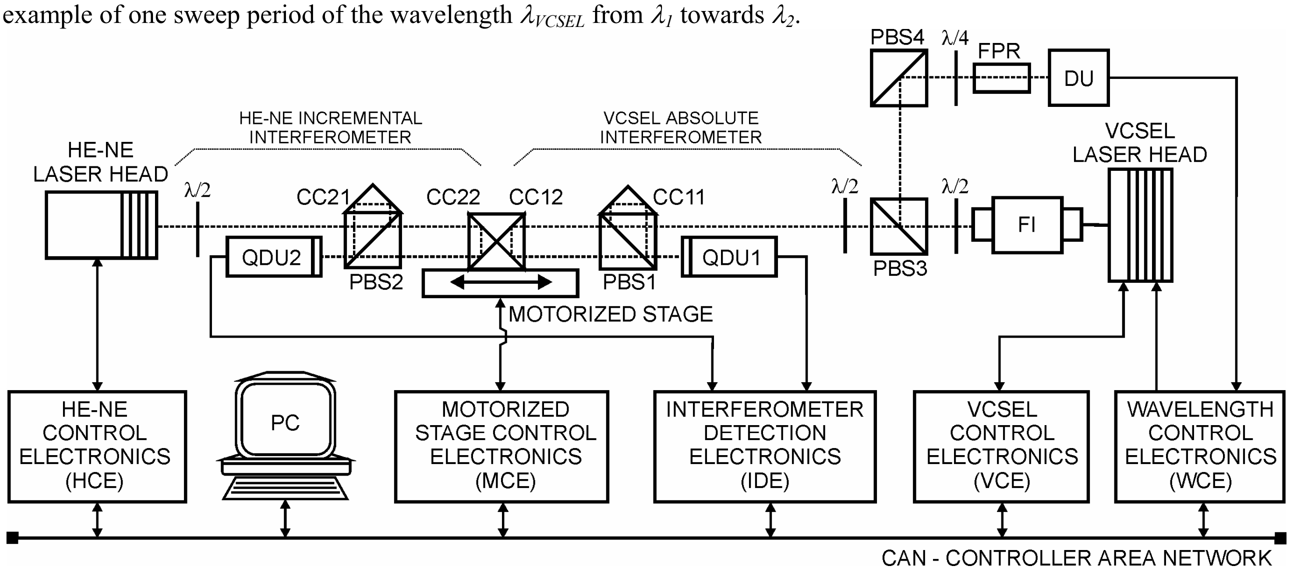
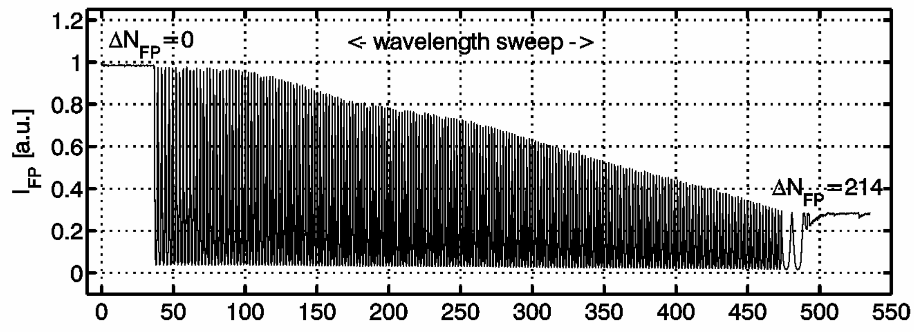


Fig. 1. The arrangement of the VCSEL absolute interferometer in the comparison set-up with the incremental interferometer: *QDUx* are quadrature detection units, *DU* is the photo detector, *FPR* is the quartz glass Fabry-Perot resonator, *FI* is the Faraday optical isolator, *CCx* are corner cube prisms, *PBSx* are polarizing beam splitters, λ/2 are the half-wave plates, and λ/4 are the quarter-wave plates.

(a) The spectral profile of the Fabry-Perot glass etalon



(b) One of quadrature interference signals of the VCSEL based Michelson interferometer

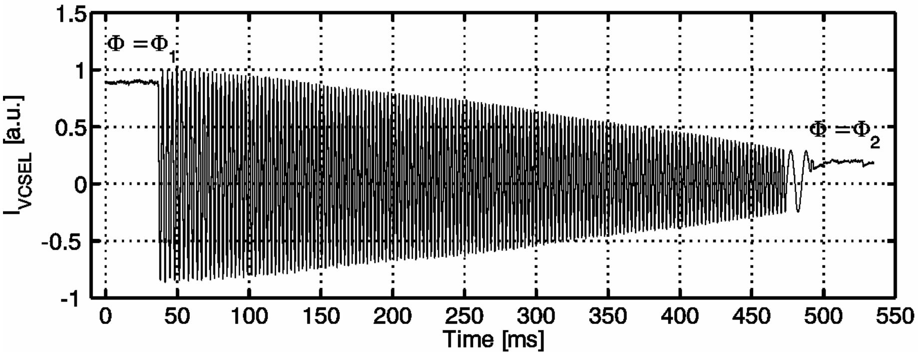


Fig. 2. The example of one sweep period of the wavelength of the VCSEL based laser interferometer. The wavelength λ_{VCSEL} at points λ_1 and λ_2 is frequency stabilized with using a servo-loop controller ($\lambda_1 = 760.00$ nm and $\lambda_2 = 761.03$ nm delimit the tuning interval of VCSEL wavelength). (a) The spectral profile of the F.-P. glass etalon (ΔN_{FP} is the counter of passed resonant modes); (b) the course of one of quadrature interference signal of the VCSEL based laser interferometer (Φ_1 and Φ_2 express the total interference phase for wavelengths λ_1 and λ_2, respectively).

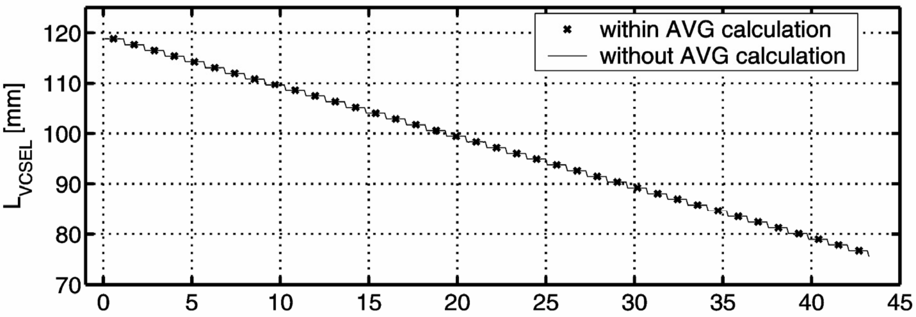
3. EXPERIMENTAL ARRANGEMENT AND MEASURED RESULTS

We developed the experimental arrangement of the VCSEL laser interferometer in accordance with the proposal shown in Fig. 1. The VCSEL laser head we made formerly as the first step on the way towards the absolute distance interferometer. The detailed description of our design of the mechanical and optical set-up of the VCSEL head, a solution of our temperature controller and injection current driver we presented in [4]. For the optimal wavelength-scanning process, we used the first-derivative spectroscopy technique with 1 kHz frequency modulation of the laser beam. We programmed a digital signal processor inside the electronics *WCE* for automatic wavelength scanning of the VCSEL inside the delimited range $<\lambda_1;\lambda_2>$. Thanks to digital interconnection of both electronics *WCE* and *IDE* with the Controller Area Network communication bus (CAN), the computer *PC* is able to calculate instantaneous values of the distance L in the real-time.

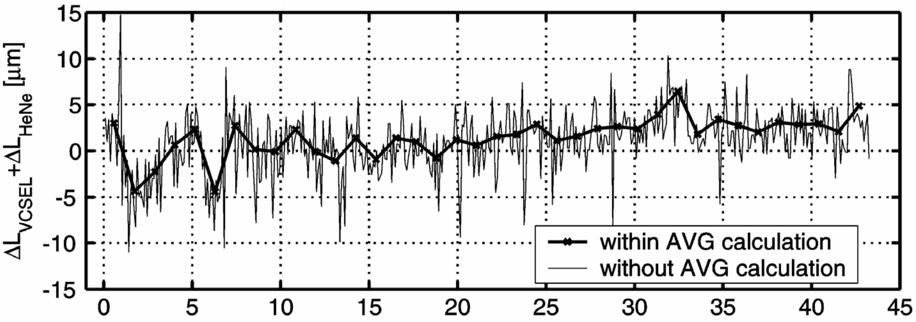
Because we need to verify the accuracy and resolution of the proposed method, we placed the measuring mirror *CC12* (corner cube mirror) to the motorized stage. As a position sensor of the stage we used an additional He-Ne incremental Michelson interferometer working at the wavelength 633 nm. Therefore we linked the other measuring mirror *CC22* of that interferometer to the motorized stage too. Consecutively, we connected output signals of the quadrature detection unit *QDU2* to the second detection channel of the interferometer electronics *IDE*. Thanks to development of a digital control electronics[8] *MCE,* we can change the position of the motorized stage remotely too (via CAN network). It is obvious, our effort led to completion of an optical comparator where the tested interferometer has the absolute scale and the reference interferometer uses the incremental regime with high-resolution. The computer *PC* controls the whole comparator by means of our sophisticated programming and CAN network.

The first experimental results are presented in Fig. 3. We chose the movement of the motorized stage in the range $\Delta L \approx 40$ mm with a step 1.1 mm approximately. After the computer *PC* places the stage at required position, the wavelength-scanning process measures the absolute distance L twelve-times. Then the computer *PC* starts the movement of the stage to a new position. As is visible in the part (a) of the Fig. 3, the incremental interferometer is not able to measure the absolute position of the motorized stage but the absolute interferometer shows the right value of the distance L. If we transfer the position L measured by the absolute interferometer to the incremental regime ($\Delta L_{VCSEL} = L - L_0$) we can compare both interferometer systems by easy summation. The variable L_0 is the initial position of the stage, where the incremental interferometer is mostly reset. The comparison result – the accuracy – is presented as the part (b) of the Fig. 3. The calculation of the average is done for each step of the motorized stage movement. The calculation of the standard deviation $\sigma(\Delta L_{VCSEL})$ and $\sigma(\Delta L_{HeNe})$ for both interferometers is made for each step of measurement too. Both results are available as the part (c) of the Fig. 3.

(a) Distance measurement by VCSEL interferometer vs. HeNe incremental interferometer



(b) Accuracy of distance measurement by VCSEL interferometer



(c) Uncertainty of distance measurement by VCSEL and HeNe interferometer

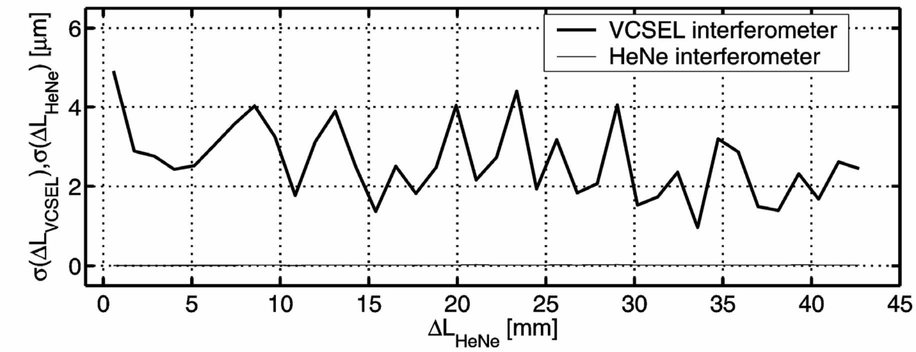


Fig. 3. The scale linearity verification of the differential interferometer by means of F.-P. resonator set-up – larger distance measurement: ΔL_{FP} is the elongation of the resonator and ΔL_{DI} is the elongation of the measurement arm of the differential interferometer ($\tau = 1$ s average). The transfer constant $K \approx 2.690$ MHz/nm.

6. CONCLUSION

We proposed and experimentally verified the absolute laser interferometer based on VCSEL tunable laser working at the wavelength 760 nm. We improved the WSI technique by introduction of the amplitude division of the interference fringe ($\lambda_S/256$) and by ultra-precise stabilization of the scanning interval of the wavelength. For that stabilization we used the high-stable quartz-glass Fabry-Perot etalon and the first-derivative spectroscopy as the detection technique. We applied the DSP techniques for control and automation of whole measurement. We arranged the sophisticated comparison set-up where the developed absolute interferometer had been compared with the conventional incremental interferometer. On basis of measured results we reached the accuracy of the VCSEL interferometer scale ± 5 μm and the uncertainty better then 4 μm for the range of tested distances $L \in < 78; 118 >$ mm. The total relative uncertainty of the developed interferometer is better than 8×10^{-5}.

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