FREQUENCY METHOD OF SUB-NANOMETER DISTANCE MEASUREMENT USING THE OPTICAL RESONATOR AND TUNABLE SEMICONDUCTOR LASER

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ABSTRACT

Several methods of scale non-linearity measurements of Michelson interferometers have been presented but their uncertainty is comparable approximately with the total resolution of the interferometers. We developed and experimentally verified a new method where order-times smaller uncertainty of the distance measurement is possible. The method takes advantage of a direct conversion of the relative changes of the optical path in measuring arm of the Michelson interferometer to relative changes of the resonant optical frequency of the Fabry-Perot resonator. Frequency changes of the resonator have been monitored by a beat-frequency comparison between tunable semiconductor laser and $HeNeI_2$ optical frequency standard at 633nm.

INTRODUCTION

Today rapid development in productions of microelectronic circuits, nano-positioning systems in machine-tools industry and nanometrology require precision of the distance measurement in the sub-nanometer region. High-resolution Michelson laser interferometers with electronic subdivision of the interference fringe are able to fulfill these requirements but distortions in their optical and electronics detection chains limit that precision. Causes of the scale non-linearity in the interferometers have been discussed earlier [1] and an efficient compensation method for laser interferometers with amplitude division of the interference fringe has been developed as well [2].

TECHNIQUE AND INSTRUMENTATION

The incremental technique of the Michelson interferometers knows two fundamental detection systems: 1^{st}, the laser interferometer with a two-frequency laser and heterodyne detection system (frequency mixing) [3] and 2^{nd}, the laser interferometer with a single-frequency laser and amplitude division of interference fringes [4].

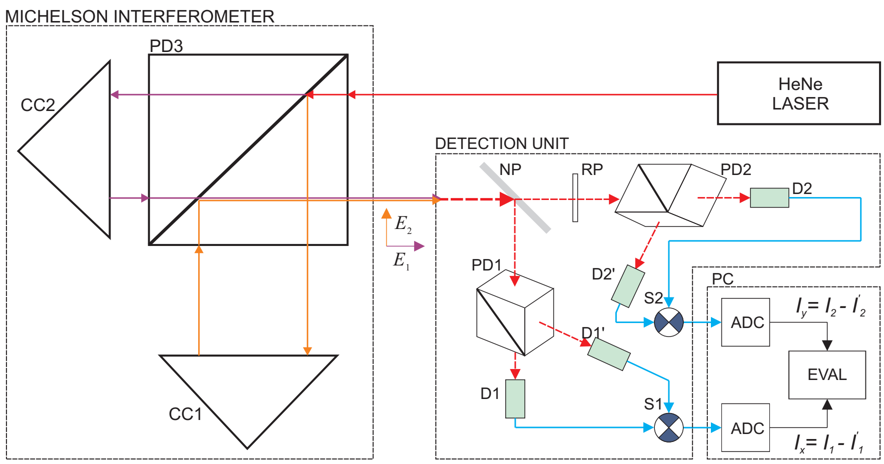

Fig. 1. Principle of the detection system of Michelson interferometer with signals in quadrature: *CC1* and *CC2* are corner cubes in measuring and reference arm of the Michelson interferometer, respectively, E_1 and E_2 are orthogonal components of the electric vector of the laser beam, *NP* is non-polarizing divider, *RP* is the retardation plate $\lambda/4$, *PD1*, *PD2*, and *PD3* are polarizing dividers, *D1*, *D1'*, *D2*, and *D2'* are photoelectric detectors, *ADC* are analog-to-digital converters that sample and quantify signals I_x and I_y.

The other mentioned system can be improved by the detection technique with signals in quadrature. The principle of operation of such a technique is explained in Fig. 1. Measuring and reference beams come from the Michelson interferometer setup to the detection unit in common. They don't interfere because of their orthogonal orientation of the linear polarization. The non-polarizing divider *NP* splits beams partially to *x*-axis and *y*-axis section of the detection unit. In the *x*-axis section, the polarizing beam splitter *PD1* turns each component of the electric vector of laser beams to an identical polarization. Such a combination of laser beams interferes. Detectors *D1* and *D1'* generate signals of the interference amplitude which the differential amplifier *S1* subtracts; it produces the first quadrature signal I_x. In the *y*-axis section, the signal processing is similar but the quarter-wavelength plate *RP* introduces phase-shift 90° for incoming interference beams. The second quadrature signal I_y is available on the output of the differential amplifier *S2* as well. Thus, the phase-shift between the signals I_x and I_y is 90° (in an ideal case). They are called quadrature signals. The digital signal processing of the signals allows additional subdivision of the interference fringe, e.g. if 8-bit level analog-to-digital converter (*ADC*) is used then λ/512 resolution can be achieved for the interferometer with λ/2 optical resolution (single-pass of laser beam through measuring arm of the Michelson interferometer).

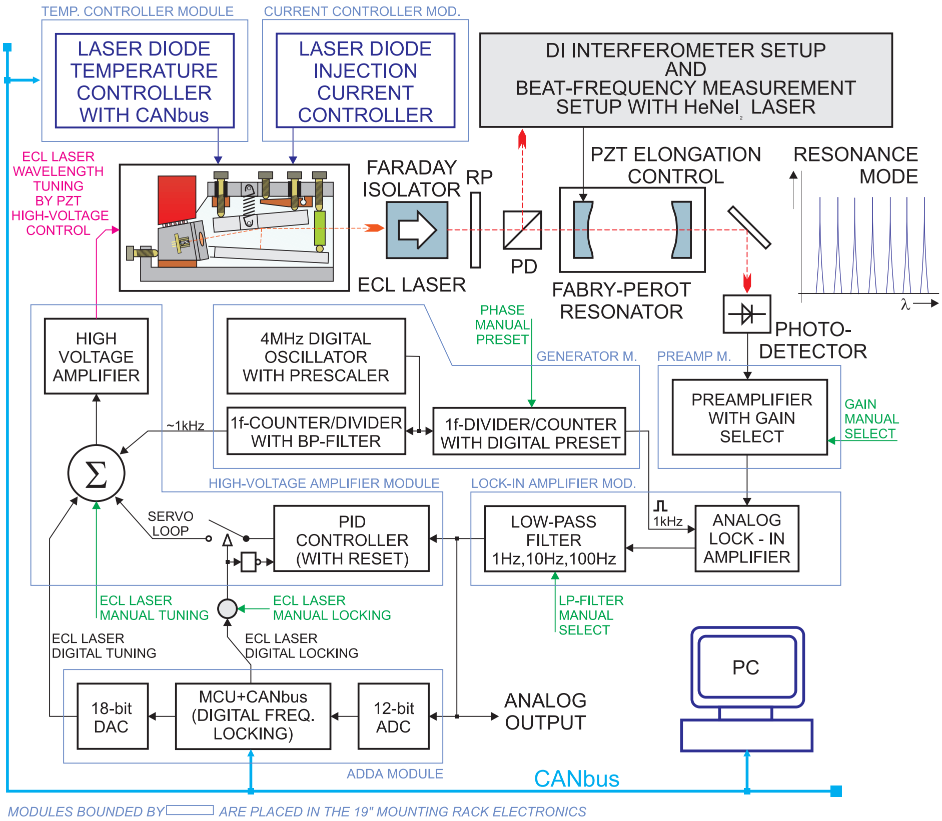

Fig. 2. Principle of the optical frequency locking of the ECL laser to any resonance mode of the F.P. resonator. The Faraday isolator setup with 35 dB suppression eliminates possible back-reflections came from the F.P. resonator or from other optical components. The temperature and injection current controller determine the ECL laser operation wavelength. The piezo-electric-transducer (PZT) provides the ECL laser tuning up to 50 GHz mode-hop free tuning range. The PC through the Controller Area Network communication bus and the remote AD/DA card monitors important values of the setup, like an operation temperature of laser diode or amplitude of the synchronously detected photo-detector signal.

Principle of the F.P. resonator distance measurement is presented in Fig. 2. We used the extended cavity laser (ECL) based on 633 nm laser diode for the optical frequency locking technique. We developed that ECL laser in our institute [5]. The sinusoidal signal of 1 kHz modulates the ECL laser optical frequency with 5 MHz modulation widths. The optical frequency of the ECL laser is tuned along the adjacent resonant modes of the illuminated F.P. resonator. The photo-detector obtains a low-frequency signal if the resonator mode and the optical frequency of the laser are in the coincidence. In this case, the F.P. resonator can be considered as a frequency-to-amplitude discriminator. The lock-in amplifier synchronously processes the amplified photo-detector signal with 1 kHz pilot switching frequency. The consequential low-pass filter removes higher frequency components and noise of the processed signal. If the phase between the switching lock-in signal and the photo-detector signal equals to zero and the frequency of the ECL laser and selected F.P. resonant mode is aligned approximately too, then maximum value of the DC component of the low-pass filter output signal is available. The manually or digitally controlled analog switch closes the frequency locking servo-loop through the PID controller, summator, and high-voltage amplifier. If the optical length of the F.P. resonator changes, then the PID controller produces the action signal for the ECL laser de-tuning towards the right optical frequency position. So that, the ECL laser is frequency locked to one of the F.P. resonant modes. The linear dependence between changes of the F.P. resonator length ΔL_{FP} and changes of the frequency $\Delta \nu_{FP}$ of the resonant mode can be expressed by:

$$\Delta L_{FP} = \frac{L_{FP}}{c} \cdot \lambda \cdot \Delta \nu_{FP},$$

where λ is the ECL laser wavelength ($\lambda \approx 632.991$ nm), c is the speed of light ($c \approx 3.10^{8}$ m.s^{-1}), and L_{FP} is the F.P. resonator optical length ($L_{FP} \approx 148.465$ mm). Because definition of the meter unit is based on the iodine stabilized $HeNeI_2$ laser at 633 nm wavelength with the relative frequency stability of the order 10^{-11} [6], the changes of the resonant optical frequency $\Delta \nu_{FP}$ of the F.P. resonator can be measured by an optical heterodyne mixing. This technique produces the radio-frequency signal that is equaled to a value of the frequency difference between mixed optical frequencies: the ECL laser and the iodine stabilized $HeNeI_2$ laser.

EXPERIMENTAL SETUP AND RESULTS

An ultra-stable differential Michelson interferometer D.I. with quadruple passes of the laser beam and with the digital correction of the scale non-linearity has been experimentally tested [7].

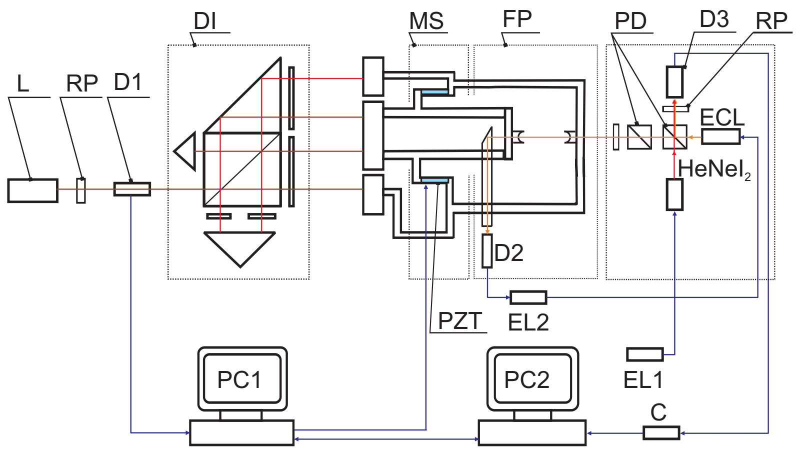

Fig. 3. Scheme of the experimental setup for the scale non-linearity measurement by means of the F.P. resonator: *L* is the HeNe laser, *RP* are retardation plates, *DI* is the quadruple-pass differential interferometer D.I., *MS* is the moving system driven by the piezoelectric transducer *PZT*, *FP* is the F.P. resonator, *PD* is the polarizing divider, *ECL* is the ECL laser, frequency locked to the F.P. resonator, $HeNeI_2$ is the iodine stabilized $HeNeI_2$ laser, *D1* is the detection unit of the *DI*, *D2* is the photo-detector of the frequency locking loop, *D3* is the avalanche photo-detector, *EL2* is electronics for the frequency locking servo-loop (according to Fig. 2), *EL1* is electronics of the $HeNeI_2$ frequency stabilization, and *C* is the fast frequency counter.

We assembled the interferometer comparison measurement setup according to Fig. 3. We provided the mechanical coupling of the reflecting mirror of the interferometer measurement arm with one of the mirrors of the F.P. resonator by means of a crystal quartz tube. A piezoelectric transducer (PZT) with ± 400 nm elongations is the action element of that mechanical shift *MS*. We have used 2.9 GHz high-resolution counter *C* for counting the resultant radio-frequency signal as a product of the optical mixing between ECL laser and $HeNeI_2$ laser. We measured the frequency values $\Delta \nu_{FP}$ and values of the interference phase acquired by the high precision differential interferometer D.I. simultaneously. We chose 1 V step for PZT-voltage incrementing and decrementing in the interval ± 132 V. Then we sampled step by step these values for each elongation of the PZT element. Note, the measurement accuracy strictly depended on the stability of the arrangement of the whole equipment. Owing to the influence of temperature changes, it was necessary to carry out the measurement in a short time period (below 20 minutes). An example of experimental records is shown in Fig. 4: (A), the distance measurement of ± 400 nm PZT-shift, acquired by the D.I. interferometer and F.P. resonator, (B), distance difference between D.I. and F.P. with linearized and non-linear scale of the D.I., it is provided by the mentioned digital correction technique [7], (C), uncertainty of the distance measurement by the F.P. resonator - it is given by the beat-frequency measurement uncertainty for the integration time $\tau = 3$ s, (D), theoretically calculated scale error of the D.I. interferometer for the distance measurement interval.

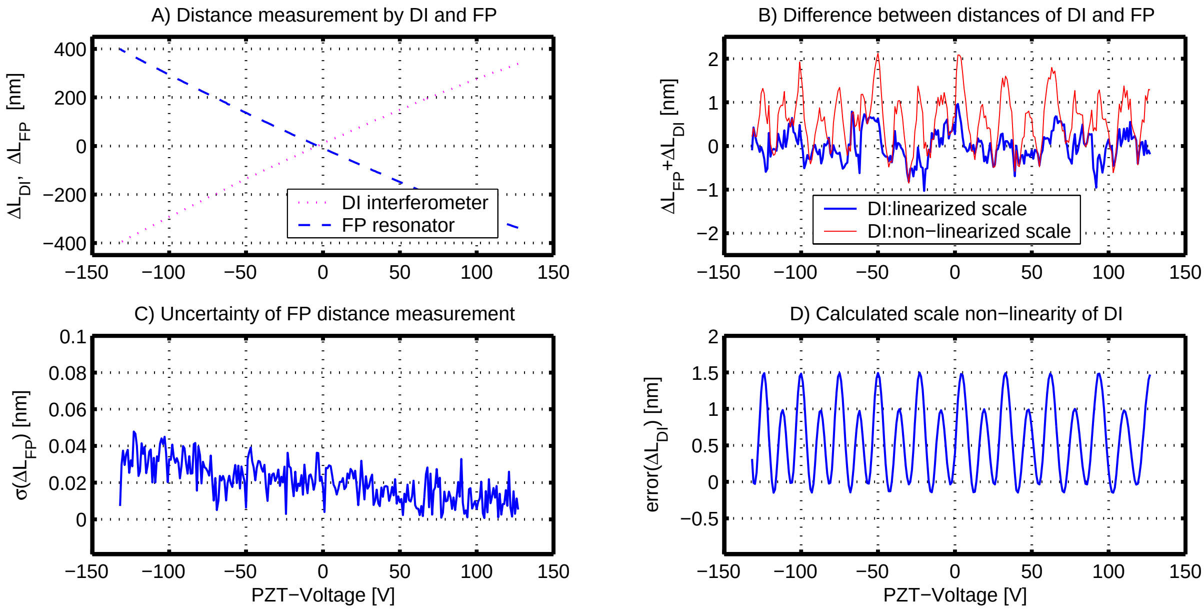

Fig. 4. Records of the distance measurement by means of the interferometer D.I. and F.P. resonator.

CONCLUSION

The averaged scale non-linearity smaller than ±1.0 nm of the high-resolution differential interferometer D.I. with equipped digital correction technique has been verified on basis of the comparison measurement with F.P. resonator technique; see Fig. 4(B). We used the tunable ECL laser at 633 nm for the F.P. resonator frequency locking. The beat-frequency measurement has been provided by means of the iodine stabilized $HeNeI_2$ laser. We achieved the frequency stability of the F.P. resonator with accuracy of the order of 100 kHz approximately ($\tau = 3$ s). It corresponds to uncertainty of the relative distance change better than 0.05 nm; see Fig. 4(C). We employed the linearized differential interferometer D.I. for determination of refraction index of air with precision 10^{-8} order in Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany. We have compared the ECL laser during the first international comparison of semiconductor lasers (ICLAD'99 meeting) in Paris, France, managed and supervised by BIPM [8].

ACKNOWLEDGEMENTS

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