High frequency stability semiconductor laser sources at 760 nm wavelength

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Abstract: - Measurement with nanometer resolution is required for the next advance in nanotechnology. Especially the non contacting methods of measurement are very .promising. We present the set-up of the laser interferometer with nanometer resolution. We developed three types of laser sources especially for using in laser interferometry and absolute laser interferometry. The standard He-Ne laser source for conventional laser interferometry techniques can be replaced by one of these tree types of laser sources. We used Vertical Surface Emitting Laser (VCSEL) and Distributed Feed-Back (DFB) laser diodes to design these laser sources. For these laser diodes we developed several methods to improvement their wavelength stability and tunability by fiber Bragg gratings (FBGs). We developed simulation method to calculation of arbitrary fiber grating (apodized, chirp etc.) with high precision by combination of methods based on layered dielectric media (LDM) and transfer matrix. On the basis of our simulations and measurements of the commercially available fiber gratings we designed a special 100 mm long fiber Bragg grating with apodization. We expect the application of the FBG to improvement of the linewidth and mode-hop free tuning range of semiconductor lasers at the wavelength 760 nm to increase resolution of fiber laser interferometer based on these diodes. We built the absolute fiber laser interferometer with Vertical Cavity Surface Emitting Laser (VCSEL) to easy employ FBG to stabilize wavelength and control the tuning range. First set up is presented.

Keywords-Laser interferometry, Absolute measurement, Tunable laser diodes, DFB laser diode, VCSEL laser diode.

1 Introduction

Highly precise industrial distance measurements use mostly conventional laser interferometry techniques with He-Ne lasers as standard optical sources. Just using of these He-Ne lasers not allow development of new laser interferometry techniques. New advance in laser metrology is oriented to using of optical fibers and semiconductor lasers. Laser distance measurement can be used in many applications[1], [2].

Thanks to the advance in laser diode technology, a replacement of the He-Ne lasers by special types of semiconductor lasers like VCSEL (Vertical Cavity Surface Emitting Laser) [3], ECL (Extended Cavity Laser) or DFB (Distributed FeedBack)) could be possible. There are two types of the most perspective semiconductor lasers.

First type is VCSEL laser diode. The industrial production of VCSEL laser diodes started several years ago. Among others, VCSELs are equipped width the distributed Bragg reflector and the quantum well structure[4]. It improves their linewidth and decreases threshold and operating value of the injection current. The enhancement of mode-hop free tuning range up to several nanometers becomes also possible. Spectroscopic VCSEL lasers at 760 nm with mode-hop free tuning range about 1 nm are affordable now. Their small size, narrow linewidth bellow 5 MHz, small threshold and operating injection current, and Gaussian output beam (TEM00) allow their application as a laser source for techniques of laser interferometry. We developed laser head based on this 760 nm spectroscopic VCSEL diode [5].

Second type of perspective semiconductor lasers is DFB laser diode. The DFB laser diodes are known longer than the VCSEL laser diodes. But the industrial production of the DFB laser diodes with visible wavelengths started only several years ago. Now are affordable DFB laser diodes with 760 nm wavelength. Actually it is the shortest wavelength of commercially available DFB laser diodes. In comparison with VCSEL laser diodes, the DFB laser diodes don’t have Gaussian output beam due to different construction of the chip. On the other side they have linewidth bellow 1 MHz and they are available in butterfly package where are directly collimated to the optical fiber. They have mode-hop free tuning range above 1 nm and the output power is up to several tens miliwatts. Among VCSEL, 1 nm tuning range can be achieved by change of the temperature of the chip.

Table 1: Resonance properties of the F-P resonator.

	L_{FP3}=41,56 mm, R1=R2=0,9
Resonance frequency ν [THz]	394,737 (760 nm)
Axial mode numbers q	159060
Bandwidth δν [MHz]	247
Free spectral range Δν [GHz]	2,48
Max. transmision T	0,46
Decay time τ [ps]	602
Cavity quality Q [x1000]	2186
Finesse F	10

With respect to the characteristics of these types of laser diodes we can improve interferometry techniques. For the conventional laser interferometry techniques is a necessity to travel with a measuring retroreflector of the Michelson interferometer across the measurement distance. A narrow linewidth, frequency stability and beam shape of He-Ne laser lead to possibility to achieve ultra-high resolution below 1 nm. In contrast to this conventional laser interferometry, the other one based on a tunable laser source allows to detect distances in a static way without moving the reflector. In this case, the incremental process is replaced by tuning of the wavelength of the laser source of the Michelson interferometer. Then the synthetic wavelength, which is limited by a continuous tuning range of the laser, determines the scale resolution of the absolute distance interferometer. In development of these new methods of an absolute laser interferometry or the spectroscopy of certain gases, the tuning range of He-Ne lasers is not sufficient.

We present the laser sources to replace of the He-Ne laser in conventional interferometry techniques (DFB Laser source) and the laser source for absolute laser interferometry (VCSEL laser source).

2. Laser sources

For the laser sources we developed current sources and the temperature controller. The wavelength and the stability of the wavelength can be driven by the temperature and by the operating current. The wavelength can be heavily tuned by operating current for the VCSEL laser diode and by the temperature of the laser chip for the DFB laser diode. The stability of the wavelength depends on the stability of these controllers.

The wavelength tunability can be measured through optical resonator. We designed F-P (Fabry-Perot) resonator with 41 mm length and 90 % reflectivity on both sides. The resonance parameters of this F-P resonator, see Tab. 1, are sufficient for the measurement of the wavelength tunability. The resonator is made from the material SUPRASIL with a high degree of the stability of the length. A possible change of the length of a 1 m long rod made of the SUPRASIL is about 0.1 mm for 200 K temperature sweeping. Therefore the calculated temperature constant of our F-P resonator is 0.2 μm/K.

The F-P resonator can be used to improve wavelength stability of the laser diodes but it is not suitable to high stability laser sources to replace standard He-Ne lasers for conventional laser interferometry due to temperature stability of the resonator. Although the temperature stability of the SUPRASIL is really high, it is still not sufficient for the achievement of the comparable stability of the semiconductor laser to the He-Ne lasers.

For the higher level of the stability of the wavelength can be used absorption spectrums of vapors. For the wavelengths about 760 nm can be used e.g. absorption spectrum of rubidium and cesium vapor [7], [8].

2.1 VCSEL laser source

We designed the laser head and supporting electronics of the VCSEL laser diode with respect to using such a laser source in the absolute laser interferometer techniques [9]. Therefore, we oriented to spectral characterization and analysis of the laser output from the VCSEL laser diode involved in the laser head setup [10]. We used laser diode SPECDILAS V-763-OXY from Laser components. We measured the stability of polarization, long-term stability of the lasing wavelength, mode-hope free tuning range and the spectral linewidth. We arranged the measurement of wavelength tuning characteristic by a highly precise commercial lambdameter (LM007 Cluster) with 0.1 pm resolution. We measured the tuning range of the VCSEL diode with respect to full input range of the temperature controller. We could observe about 0.7 nm wavelength mode-hop free tuning range for 7000 mK temperature sweeping. We studied also the mode-hop free tuning range by means of the injection current controller tuning. The wavelength tuning interval up to 1.4 nm has been traced for 2.9 mA continuous sweeping of the injection current repeatedly. After comparison of these records it is clearly that the operation temperature of the VCSEL diode has

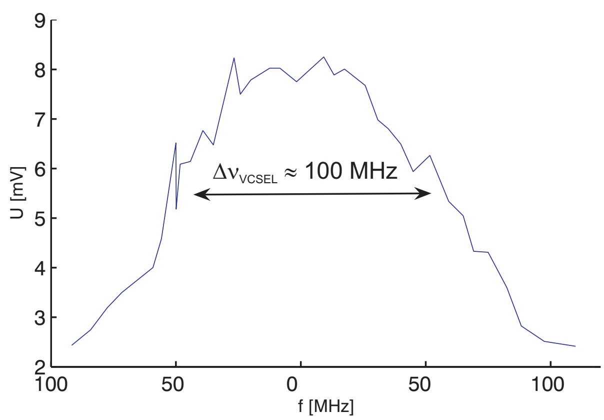

Fig. 1. Frequency beat between Ti-Sa laser and VCSEL diode.

smaller effect to the wavelength stability in comparison to tuning by means of the injection current. The long-term stability of the wavelength of the designed VCSEL laser head covers 0.5 pm limits. We measured of the spectrum of the laser head by Fabry-Perot resonator with injection current of the VCSEL diode 6.4 mA and modulation frequency 1 kHz. The linewidth 100 MHz was measured. Because the linewidth of this laser source was crucial for absolute laser interferometer we used second independed method of measurement of the linewidth by frequency beat between VCSEL laser diode and Ti-Sa laser.

The commercial Coherent Ti:Sa laser, model 899-01 was used to frequency beat. Wavelength of the Ti:Sa laser is tunable in a wide range (680 nm - 1025 nm) by birefringent filter. The linewidth of the laser with etalons is under 10 MHz. The output has been collimated to the fiber and this was brought to the VCSEL laser. Frequency beat was measured by APD (Avalanche Photo Diode) connected to the spectrometer. The linewidth of the VCSEL diode is 100 MHz., see Fig. 1.

The linewidth in the datasheet of this laser diode is 5 MHz. In this case the linewidth was measured by the Fabry-Perot spectrometer and the self-homodyne technique [5]. Coherence length calculated from the measured linewidth is about 3 m and for indicated value of the linewidth is about 60 m. Then, the maximum measurable length in the absolute laser interferometer is about 1,5 m calculated from the real linewidth. Configuration of the laser source with VCSEL laser diode is in the Fig. 2.

2.2 DFB laser source

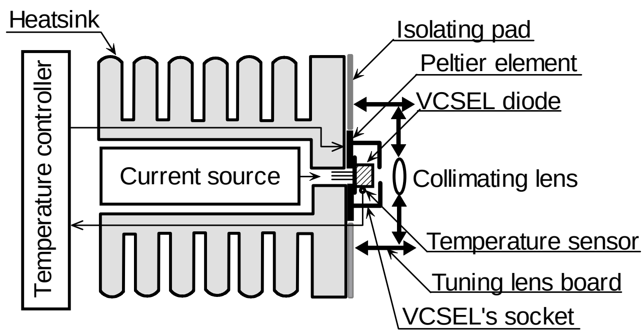

Fig. 2. Configuration of laser head with the VCSEL laser diode

Design of the DFB laser source was different. The DFB laser diodes are available in butterfly package with fiber output. We prepare electronics for this type of laser

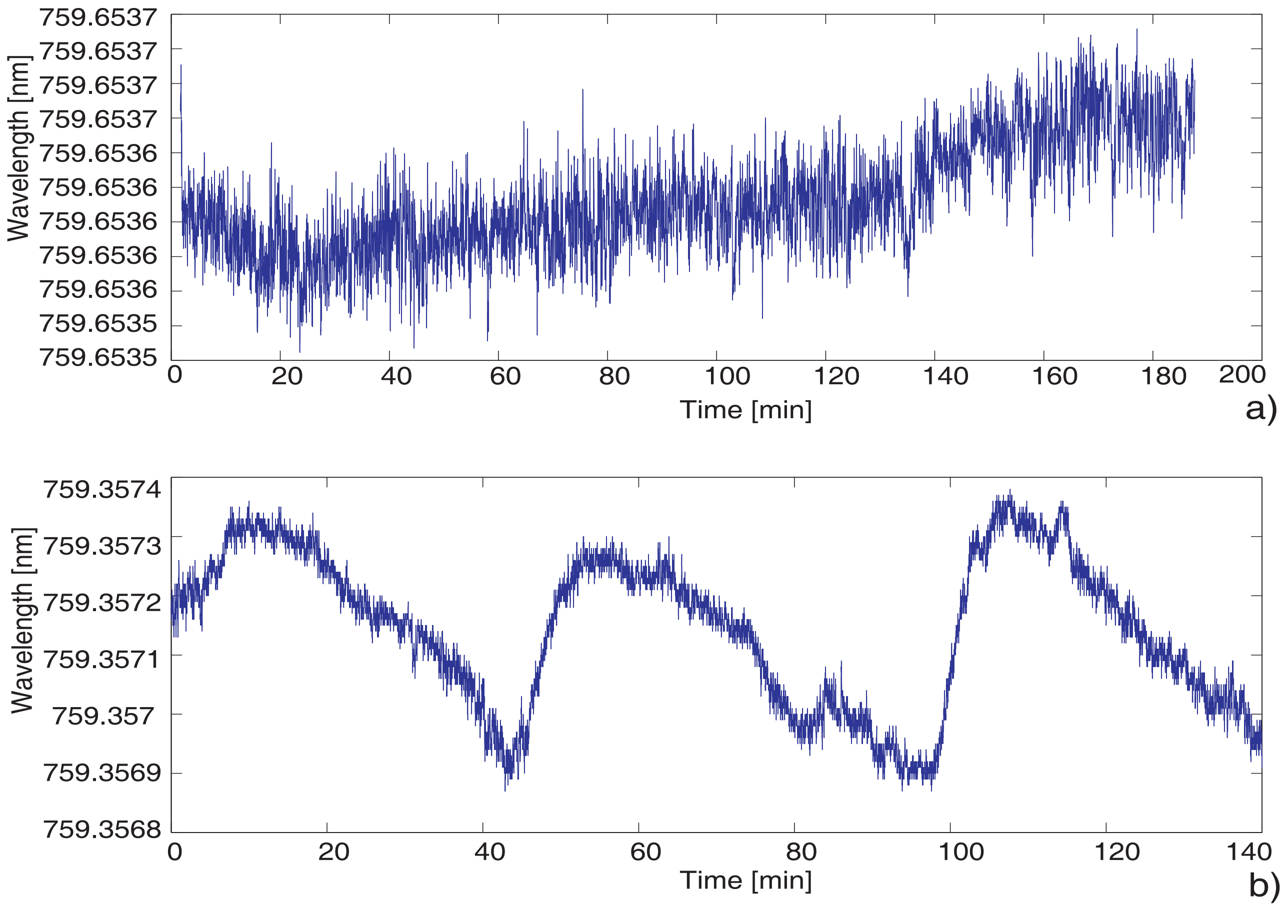

Fig. 3: Long time stability of the lasing wavelength of the a) DFB laser source, b) VCSEL laser source.

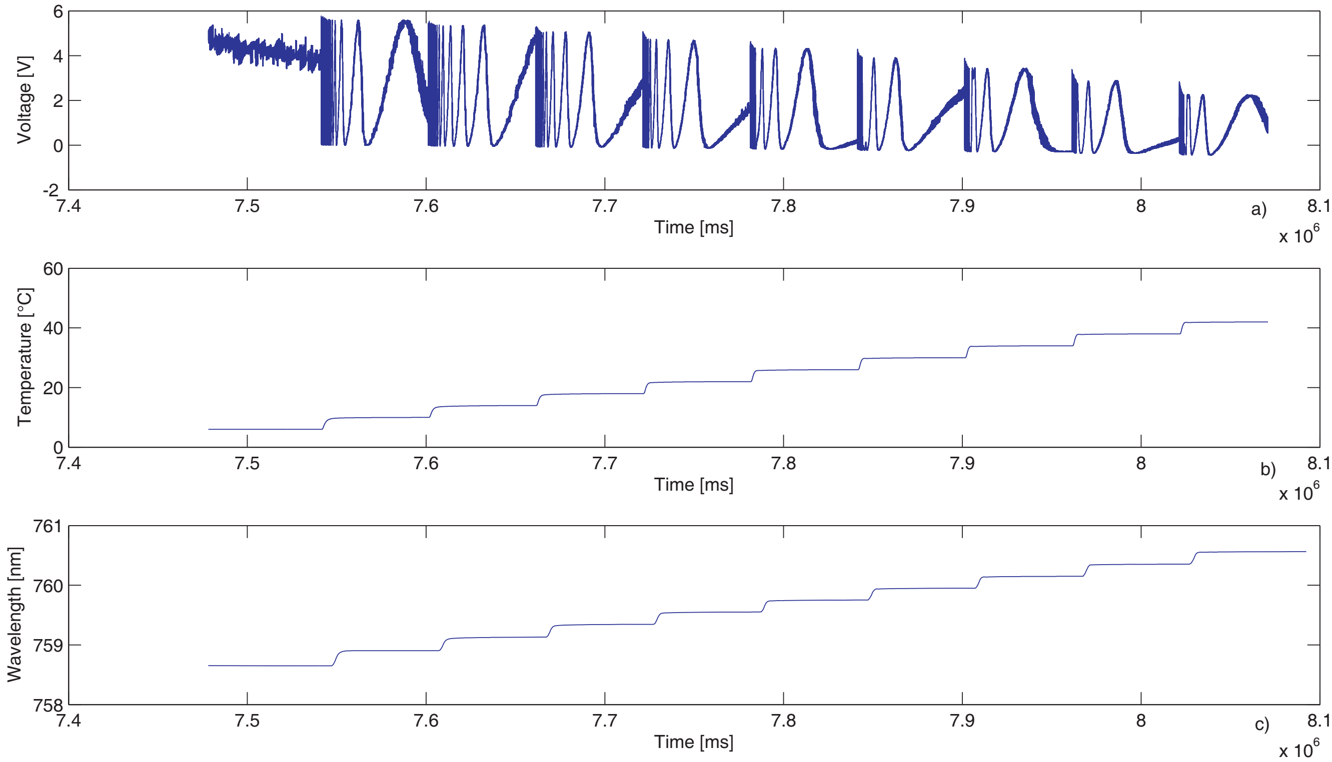

Fig. 4: The tunable range of the wavelength of the DFB laser diode by change of the temperature of the chip; a) The record from the F-P resonator - The number of passed resonance periods of a stable F-P resonator is 40 for each temperature step. b) The temperature of the chip. c) The wavelength of the DFB laser diode measured by lambdameter.

diode to connect our standard current controller and the temperature controller [11], [12]. The temperature stability under ±1 mK was achieved due to construction of the butterfly package and the calculation techniques of the temperature stabilization of the temperature controller. For our experiments we chose laser diode EYP-DFB-0760-00010-1500-BFY02-0000 from Eagleyard photonics.

We arranged the measurement of wavelength tuning characteristic by a highly precise commercial lambdameter (Angstrom WS Ultimate 30 L IR) with absolute accuracy 30 MHz. First we measured long time stability of the lasing wavelength. The experimental records of several hours stability of the lasing wavelength for both laser diodes (DFB and VCSEL) is shown in the Fig. 3. The temperature stability of the DFB laser source is in the Fig. 3a. The temperature of the DFB laser diode has been kept at 24 °C and the injection current equate to 80 mA. There are very small fluctuations of the lasing wavelength up to ± 0.1 pm. It is better in comparison to the long term stability of our previously laser source with VCSEL laser diode in the Fig. 3b. The temperature of the VCSEL laser diode has been kept at 18 °C and the injection current equate to 4 mA. The strong wavelength oscillations with 45 minutes period and 0.45 pm amplitude are probably caused by an air-conditioning system housed in the laboratory. This wavelength oscillation has no effect to DFB laser diode due to butterfly package of the DFB laser diode. The temperature of the DFB laser diode is driven more precisely and quickly due to directly stabilization of the temperature of the laser chip instead of the temperature stabilization of the package of the VCSEL laser diode. We used our laser interferometer from the Fig. 5. to control of measurement of the tunable range of the wavelength of the DFB laser diode by change of the temperature of the chip. The F-P resonator in the laser interferometer was used to measure the wavelength tunable range of the DFB laser diode. Counting of the number of passed resonance periods of a stable F-P resonator during the tuning process identified the range of the tuning of the VCSEL laser. The temperature of the DFB laser diode has been changed from 6°C to 42°C for 4°C temperature steps and the injection current equate to 80 mA. The record from the F-P resonator is in the Fig. 4a.

The number of passed resonance periods of a stable F-P resonator is 40 for each 4°C temperature step. It corresponds to measurement of the wavelength tunable range by lambdameter, Fig. 4c. The temperature of the chip is in the Fig. 4b.

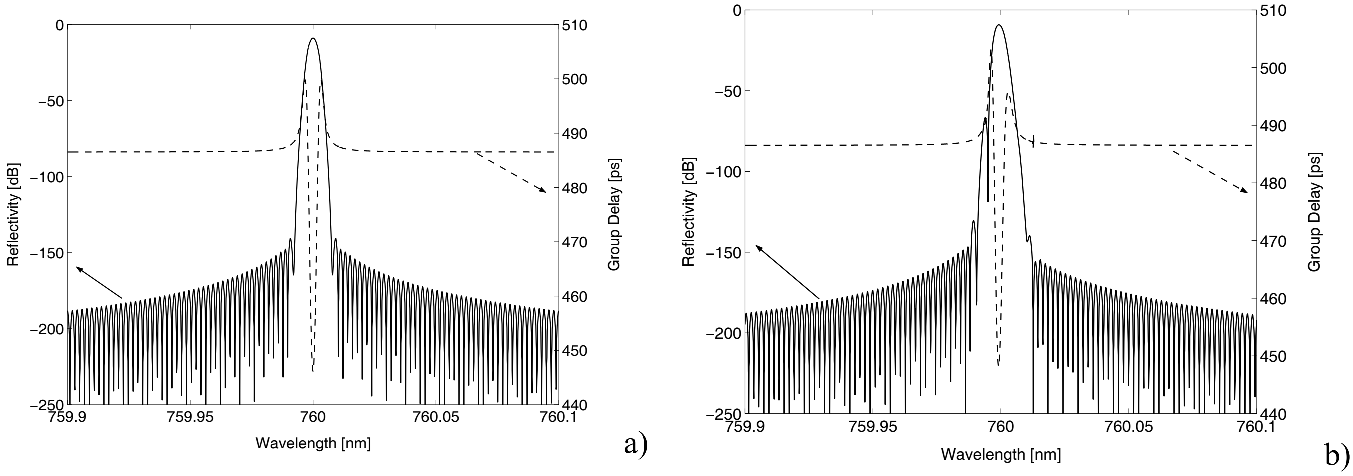

Fig. 5. a) Simulation of reflectivity and group delay spectral characteristics of Gaussian apodized with chirp compensation grating, b) Simulation of reflectivity and group delay spectral characteristics of Gaussian apodized without chirp compensation grating.

2.3 Laser diodes with FBGs

Better scale resolution of the absolute laser interferometer can be achieved by wider tunable range of the wavelength or by narrower linewidth of the used semiconductor laser. High precision fiber gratings can be profitably used to stabilize of laser wavelength for the absolute laser interferometry with high resolution and to improvement tunable range. First time we calculated fiber gratings to improvement VCSEL diode in our interferometers.

Our simulations were made in Matlab software. In all simulations, the considered fiber had the core diameter 1.8μm, the core refractive index 1.47 and the cladding refractive index 1.457 to correspond with our prepared fiber. There were the effective mode indexes, n_{eff}, of the fiber calculated for whole spectrum before the grating simulations. The n_{eff} were calculated from fiber dimensions and material properties using Bessel's functions. All simulations were calculated for sinusoidal shape of grating.

There were simulated three gratings – uniform (without apodization and chirp), Gaussian apodized with chirp compensation and Gaussian apodized without chirp compensation. For the first, the grating of length 100 mm was divided into 100 sections. Each section must contain integer number of periods with defined beginning and end to ensure the continuity of the sections. Every section can have the different grating period, Λ_s, and refractive index change, δn_s, that forms apodization and chirp profiles. Next, one period in every section was sampled; ten samples per period were chosen.

The reflectivity and the group delay were calculated over spectrum from 759.9 nm to 760.1 nm. The maximum of refractive index change, δn, was chosen 10^{-5}, which responds to the fiber photosensitivity. From the spectral characteristic of the simulation of the uniform gratings can be seen, that the suppression of side lobes is relatively small. The first side lobe is suppressed about

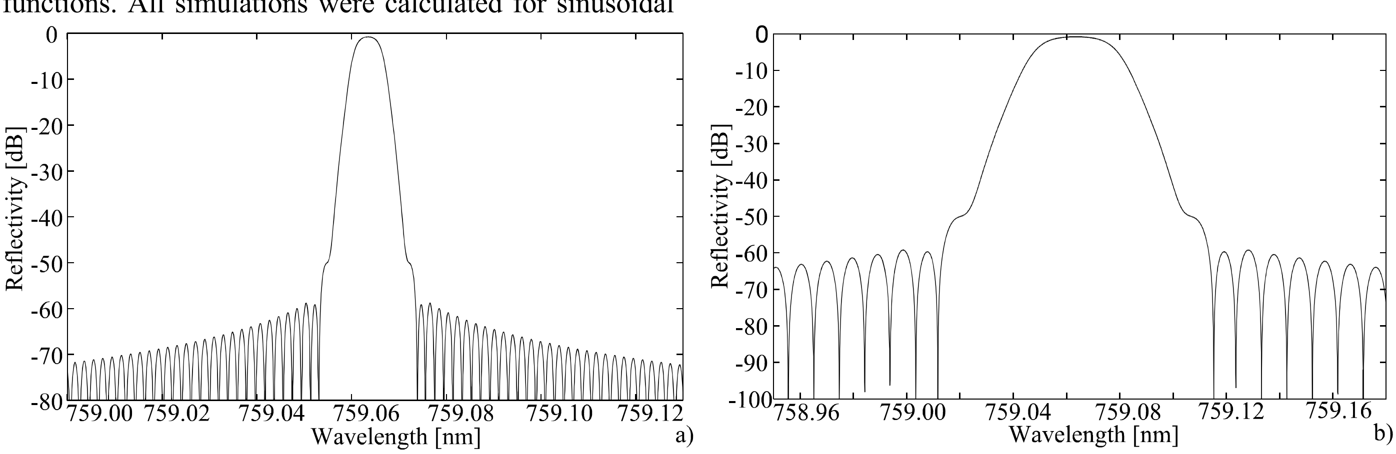

Fig. 7. Simulation of reflectivity spectral characteristics of Gaussian apodized fiber Bragg gratings, a)100 mm length fiber grating with refractive index change $2x10^{-5}$, b) 20 mm length fiber grating with refractive index change $1x10^{-4}$.

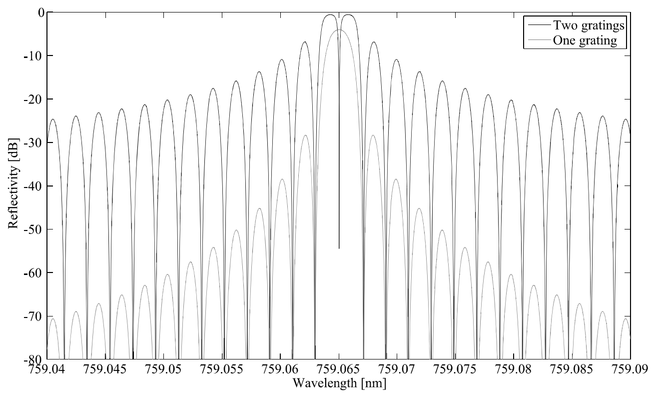

Fig. 8. Simulation of reflectivity spectral characteristics of Gaussian apodized multiple fiber Bragg grating.

19 dB against the main peak.

Spectral characteristics of Gaussian apodized grating with chirp compensation of neff change are shown in Fig. 5a. The first side lobe suppression is about 132 dB in comparison with main peak. The maximum period change over grating length is about 10-3 nm which may cause a problem for fabrication. The imperfect chirp leads to asymmetry in spectrum and lower side lobes suppression.

In Fig. 5b) can be seen, that the reflectivity and the group delay spectral characteristics of the Gaussian apodized grating without neff compensation are asymmetric. On the left side of main peak, the suppression of the first side lobe is only about 56dB. Bandwidth of the main peak is little affected by the apodization profile. The bandwidth of the main peak (calculated at declension of 3 dB) is about 2.8 pm for these cases.

At the first time we studied a commercially available apodized FBG with length 20 mm, the center wavelength equals λ=760 ± 0.5nm, full width in half maximum

FWHM = 0.2 ± 0.2nm and the reflection greater than 90%. Although these parameters are the best from commercially available fiber gratings with central wavelength 760nm, it is not suitable for desired high precision applications like the absolute laser interferometry. The recognized bandwidth is 0.1 nm and the center wavelength is 760.380 nm, obtained for the temperature equals 20 °C. Tuning range of the center wavelength up to 1 nm for 50 K temperature sweeping was measured.

Improvement of the linewidth and mode-hop free tuning range of the VCSEL diode is the main goal of our upcoming FBG. The VCSEL with the fiber grating will be very suitable laser source for new generation of the absolute laser interferometer based on our free space VCSEL interferometer.

Comparison of uniform fiber Bragg gratings with length 100 mm and 20 mm is in Fig. 6. The suppression of the first side lobe is the same for both lengths due to change of refractive index change.

In Fig. 7 is comparison of these fiber gratings with apodization. The best bandwidth of these gratings full width in half maximum FWHM is about 3 pm for 100 mm length grating with apodization. This bandwidth is too broad in comparison to the bandwidth of VCSEL. The bandwidth of the fiber gratings can be narrowed by higher refractive index change, longer gratings or by multiplying fiber gratings. Multiple fiber gratings are in Fig. 8, where we used two 100 m length fiber gratings with apodization.

3 Fiber laser interferometer

The design of an absolute laser interferometer which was intended to operate in applications oriented to precision manufacturing and testing where the ability to measure distance directly is needed and where the measured distances are relatively small ranging over no more than few cm, see Fig. 9. We opted for DFB and VCSEL laser diodes as a source of laser radiation. The shortest wavelength available was 760 nm for both laser diodes. It is unfortunately close to the red end of the

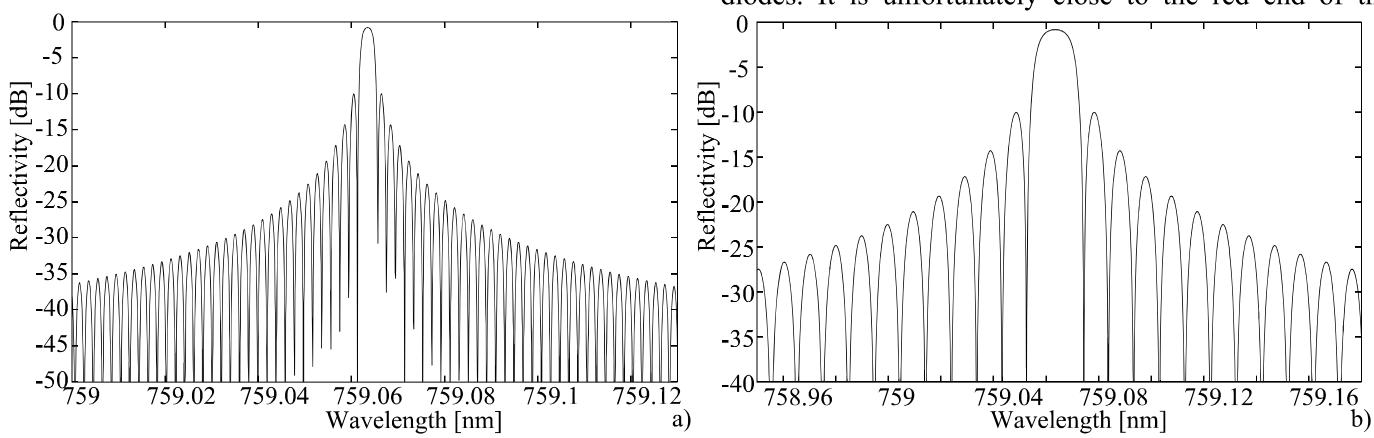

Fig. 6. Simulation of reflectivity spectral characteristics of uniform fiber Bragg gratings, a)100 mm length fiber grating with refractive index change $8x10^{-6}$, b) 20 mm length fiber grating with refractive index change $4x10^{-5}$.

visible spectral region. The visibility is not ideal but it is clearly better than infrared laser.

The output light from the laser diode is split by a coupler into 90% going into the interferometer and small part (10%) into the assembly of laser frequency stabilization and tuning control. This consists of a collimating optics, isolator, passive F-P resonator and a photodetector. The main component of the F-P resonator is a plane mirror bulk optics element made of crystal quartz glass. With reflectivity of both surfaces of 90% it performs a linewidth of 170 MHz and a free-spectral range 2.58 GHz. The F-P resonator helps to stabilize the optical frequency of the laser and also to monitor and control the tuning process.

Transmitted light is detected by a photodetector and a signal is processed by digital control electronics. Locking of the laser frequency is ensured by first harmonic

derivative spectroscopy technique with frequency modulation of the laser. The tuning is managed by current control and by counting of F-P fringes. When the certain number of interference maxima is passed the laser is relocked again on the next F-P peak. A short term stability of the F-P cavity is ensured by a precise thermal control of the whole block. It is placed into a copper enclosure and than a insulating housing. Another temperature controller holds the temperature of the F-P cavity within a mK range by a Peltier cooler. The assembly of the resonator is designed to keep the bulk cavity fixed and attached to thermal control while all the other optical elements are adjustable. The fiber collimator, quarter-wave retardation plate and polarizing beam splitter at the front and photodetector at the output side are attached to an adjustable pair of rails enclosing the cavity. This allows independend positioning of the beam axis with respect to the cavity. The whole frame includes a photodetector with integrated preamplifier monitoring transmitted light at the rear side of the cavity.

The interferometer itself is fed by the 90% of laser light from the first coupler. The core is again a coupler now with a 50% / 50% ratio. In our arrangement the measuring and reference arms are represented by a single fiber ended by the pickup. In case of a fiber-optic interferometer this is the only way how to compensate for variations in the optical length of a fiber when it is moved or bended. The end of the fiber represents a reflecting surface returning a few % of the light back into the fiber. This is here the interferometer reference arm. Reflection from the surface of the measured object is collected by a collimating optics and coupled back into the fiber. Both waves propagating back through the fiber are at the coupler separated into a photodetector and their interference pattern is detected. In our first experiments with absolute free-space interferometry we used homodyne quadrature detection system[6]. In this fiber-optic setup the detection is derived from laser frequency modulation and based on digital signal processing. Elimination of the variations of optical length of the fiber is ensured by propagation of the measuring and reference wave through a single fiber. They differ only in the path where the measuring wave leaves the fiber. This free-space path is the measured distance. Separation of both reflected waves in the 50% / 50% coupler results in losing one half of the optical power. This might be improved by implementing an optical circulator instead of the coupler. In our assembly we at this moment decided for a cheaper coupler while the principal operation of the interferometer should be the same. The fiber interferometer was assembled using single-mode fibers, not polarization maintaining. We had to avoid polarization sensitivity while the light reflected from the measured surface at the pickup may be of changed polarization. Our set-up can be used to both, relative and absolute measurement of length. Practical realization of the DFB laser source and the fiber laser interferometer is in the Fig. 11.

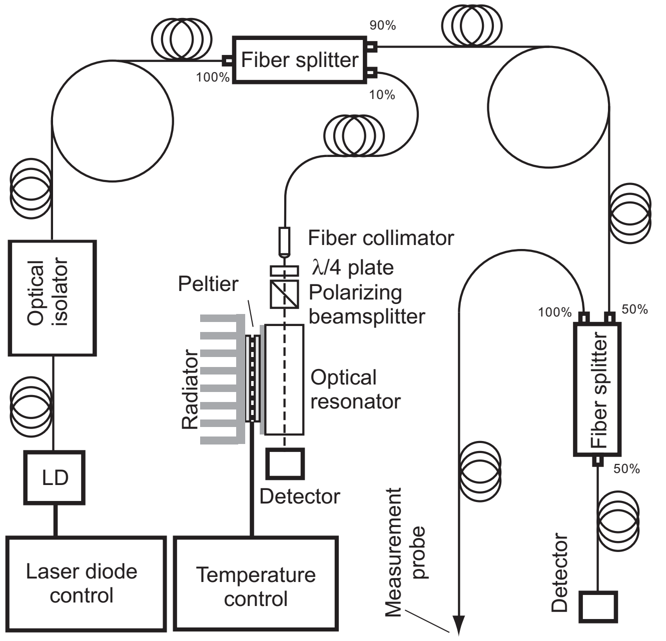

Fig. 9: Set up of the fiber laser interferometer for 760 nm wavelength VCSEL and DFB laser sources.

The interferometer can be improved by using better laser source. New laser source with similar wavelength can be connected to the input of the fist fiber splitter. We prepared several possibilities with fiber Bragg gratings.

First, in Fig. 10a), output of the VCSEL laser diode is directly collimated to the optical fiber with a FBG. The FBG is used as a mirror of extended cavity of the laser diode. Unfortunately the transverse emission spectrum of the VCSEL diode is affected by optical feedback considerably. Other set-up of using of a FBG is in Fig. 10b). A FBG is connected to laser diode by optical circulator. In this case, a FBG is a frequency filter of the

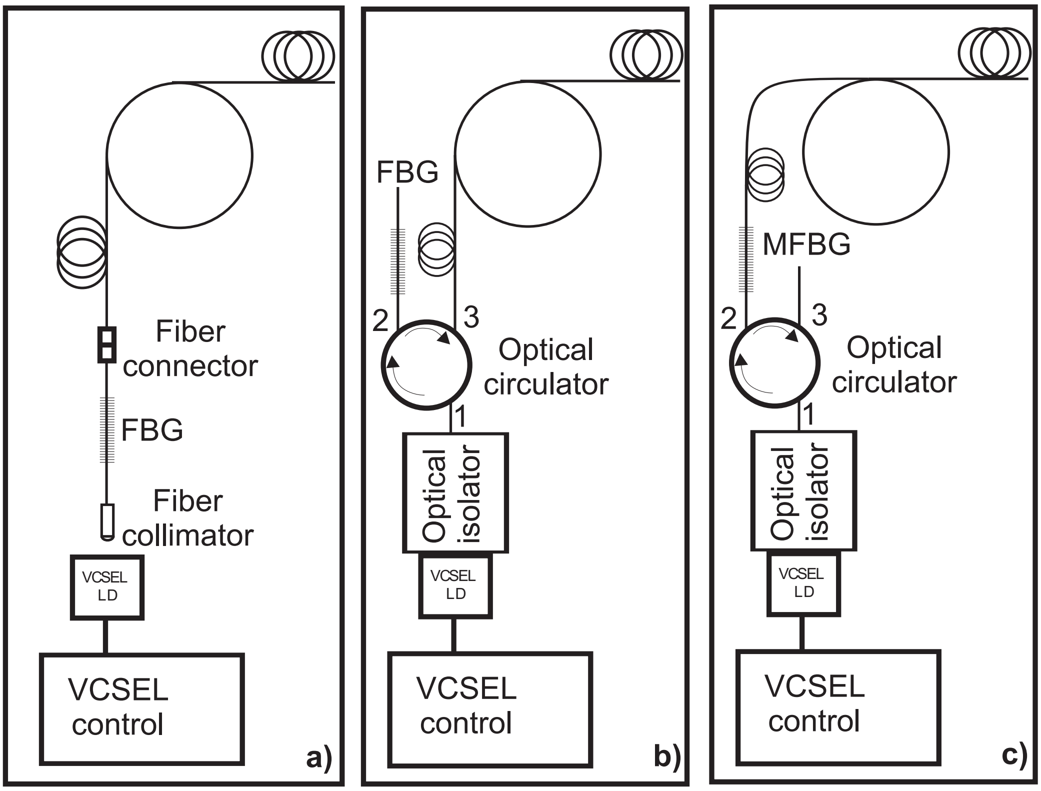

Fig. 10. Improvement of the linewidth of the laser source of the laser interferometer, a) by multiple fiber Bragg grating FBG–FBG is a mirror of an extended cavity of the laser diode, b) by fiber Bragg grating FBG connected by optical circulator– FBG is a frequency filter of the laser diode, c) by multiple fiber Bragg grating MFBG connected by optical circulator – MFBG is a frequency filter of the laser diode.

laser diode. Backreflection from the FBG is used for the laser interferometer. The FBG with very narrow bandwidth is needed. The better properties can be expected from using of multiple fiber Bragg gratings MFBG, see Fig. 10c). The set-up of the laser interferometer is connected directly to the MFBG due to different shape of the main peak of the MFBG in opposite to standard FBG. The optical circulator is used only to prevent backreflection to the laser diode.

4. Conclusion

We developed three laser sources based on 760 nm semiconductor laser diodes (VCSEL and DFB) for laser interferometry to replace standard He-Ne lasers. VCSEL laser source has been primary developed for using in absolute laser interferometry with tuning of the wavelength of the laser source. On the other side the newest DFB laser source is primary developed to single frequency regime. In this regime we plan to use methods of frequency stabilization to F-P resonator and to absorption spectrum of rubidium and cesium vapor to increase wavelength stability. We presented our first measurement with our 41 mm long F-P resonator.

We developed fiber gratings simulation method. We performed a simulation of several types of fiber Bragg gratings (FBGs). We simulated chirped and apodized fiber Bragg gratings (fiber gratings with modulation of the amplitude and with modulation of the spacing) like as uniform fiber gratings. Results of our simulations were presented. Apodization of FBGs has many advantages in comparison to other types of FBGs. Main improvement is suppressing of the side lobes in the grating spectral properties.

On the basis of simulations and measurement of the commercially available fiber gratings we designed a special fiber Bragg grating with apodization. We expect the application of the FBG to improvement of the linewidth of 760 nm wavelength VCSEL. To better improve of the linewidth of this diode we prepared simulation of multiple fiber gratings. Bandwidth of these simulated fiber gratings is narrower.

We described our setup of the fiber absolute laser interferometer to measurements of length at a small scale. The effort was oriented to assemble a compact and reliable system able to operate in industrial environment where the majority of optical components would be fiber-optic. The interferometer itself is placed in a separate box connected with the pickup only by a single fiber. The pickup can thus be attached to a positioning system of any mechanical arrangement. The use of a single fiber as

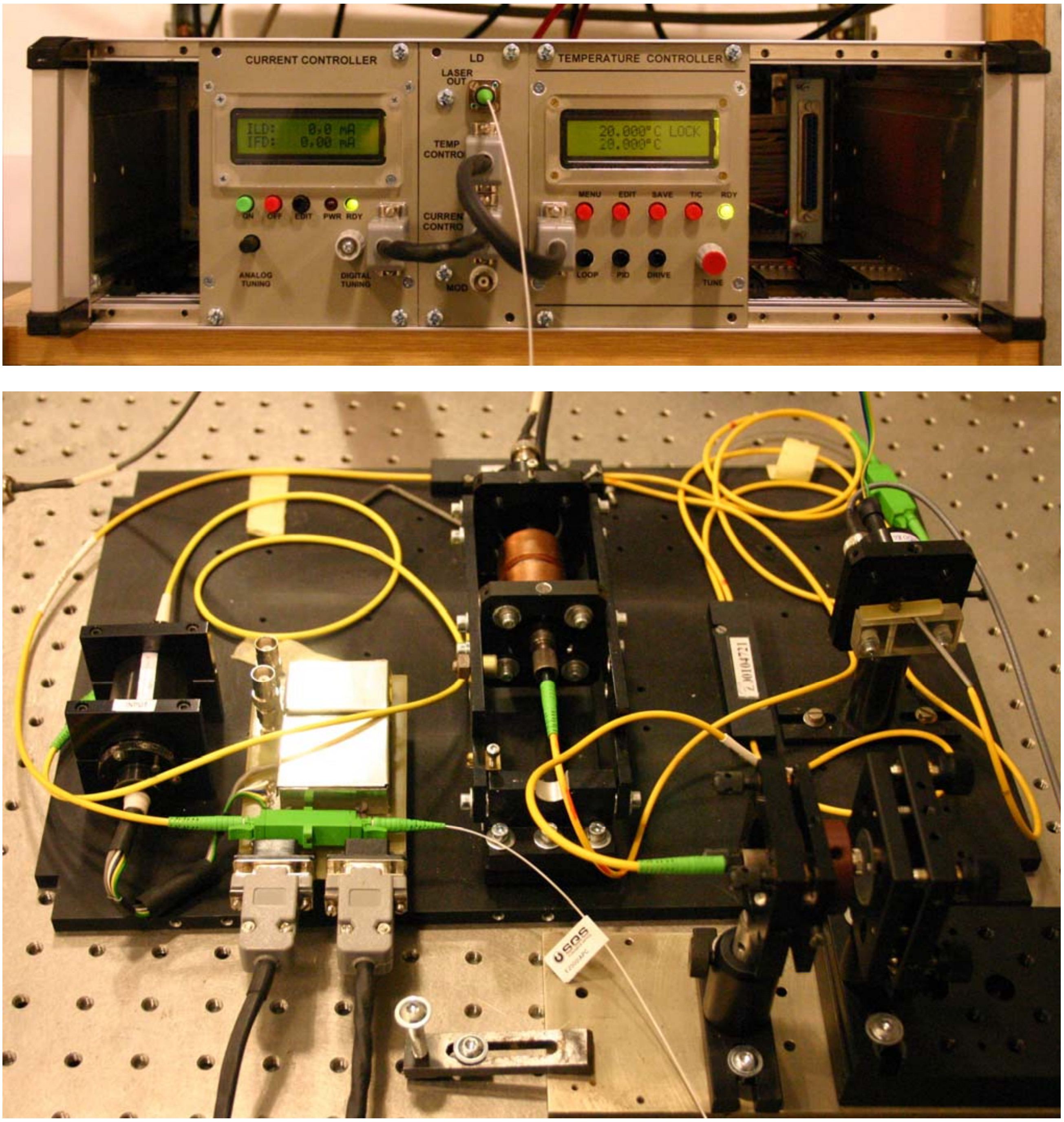

Fig. 11: Practical realization of the DFB laser source and the fiber laser interferometer.

a reference and measuring arm of the interferometer compensates variations of optical length caused by moving and bending of the fiber.

The use of a tunable laser source together with a system for precise and repeatable laser tuning, control and stabilization makes also possible to measure distances directly in absolute regime. With the laser locked to a certain peak of the passive Fabry-Perot etalon the interferometer can operate also in a more precise incremental regime. Laser control, modulation, tuning and stabilization is fully digital and based on modern digital signal processing technique.

We prepared this interferometer with respect to using of fiber Bragg gratings. We prepared three cases of the linewidth improvement of the laser source by FBGs. Set-up was presented.

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