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Ultrastable, traceable optical frequencies for length metrology in long-range nanopositioning and nanomeasuring machines

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Abstract

Precise interferometric distance measurements play a crucial role in length measuring and positioning systems that provide resolving capabilities down to the sub-nm-range. Especially for applications in nanotechnology, length metrology has to face additional challenges due to increasing measurement ranges and traverse speed. Nanopositioning and measuring machines (NPMM) meet the demands on positioning with nm-accuracy over long measurement distances. Currently, the next generation of NPMMs (NPMM-200) provide a measuring range of 200 mm × 200 mm × 25 mm with a measuring repeatability up to 20 pm. This also sets new demands on the frequency stability of the laser sources used for interferometry. In this study we present two new approaches to create traceable, ultrastable optical frequencies at 633 nm that provide frequency stability below the electronic resolution limit of the interferometers ($\Delta s = 25{\cdot}10^{-12}$) thus allowing to practically eliminate the influence of frequency distortions in the NPMM-200. Both approaches utilize an optical frequency comb to ensure traceability and long-term frequency stability. The first approach permanently couples the metrology lasers of the NPMM-200 to a comb line. The second approach is based on a diode laser stabilized to an ultrastable cavity. This allows to set up a frequency reference with enhanced-short-term frequency stability and high output power. Thus, in combination with the optical frequency comb a frequency stability better than 10^{-12} independent on integration time is prospectively accessible.

Keywords: Nanopositioning- and nanomeasuring machines, He-Ne-laser, frequency comb, cavity stabilized diode laser, frequency stability

1. Introduction

The implementation of "traceable 2D and 3D metrology at (sub)nm accuracy over several 100 mm range" has been expressed as one of the central targets for nanometrology up to the year 2025 within the iMERA roadmap "Dimensional metrology for micro- and nano-technologies" [1].

Nanopositioning and nanomeasuring machines (NPMM) that combine three dimensional positioning and measuring capabilities on a macroscopic scale of several ten to hundred millimeters with an accuracy of nanometers can contribute to the implementation of new measurement and fabrication approaches for nanometrology.

Since the turn of the millennium the TU Ilmenau has put extensive research effort in the development of NPMMs. As a result the NPMM-1 with a measurement volume of 25 mm × 25 mm × 5 mm became commercially available [2]. A multisensor approach for different optical and tactile systems was added [3] and lately the integration of tip- and laser based nanofabrication approaches for a three-dimensional design of nanostructures was demonstrated [4]. Currently the next generation of NPMMs (NPMM-200) provide a measuring range of 200 mm × 200 mm × 25 mm. Recently a one-point positioning stability and repeatability of less than 2 nm for lateral measurements over the whole measurement area has been experimentally demonstrated [5] and vertical repeatability measurements of a 5 mm step height standard revealed a standard deviation of 20 pm [6].

The demand for increasing measurement ranges and scanning speeds to fulfill more complex measurement tasks steadily increases the requirements for the underlying positioning and length measurement systems of those machines. Length measurements within NPMMs rely on high-precision interferometers. These interferometers do not only determine the position in x-, y- and z-direction but also measure angular deviations of the guidance system with an interferometric angle measurement [5,6].

Therefore, the reduction of uncertainty contributions of the existing interferometric measurement systems play an important role in the overall research activity on NPMMs.

One fundamental uncertainty contribution in displacement interferometry is the accuracy and stability of the vacuum wavelength of the laser source serving as measuring standard [7]. In NPMMs usually polarization-stabilized HeNe-lasers that provide narrow linewidths in the kHz-range are deployed [5]. Nevertheless, their-long-term frequency stability is limited. Typically these lasers exhibit relative maximum frequency deviations of $\Delta f = (2.5\text{-}5.7){\cdot}10^{-9}$ over a 24h-measurement series resulting in a length measurement error of 0.5-1.1 nm for a maximum positioning range of 200 mm [8]. Furthermore, their lifetime frequency stability is limited to $\pm$ 1 - $2{\cdot}10^{-8}$ [9,10]. Thus, the HeNe lasers have to be periodically measured against a BIPM compliant frequency standard to determine changes of their absolute frequency and guarantee traceability of the interferometric length measurements to the SI meter definition.

To practically eliminate the influence of frequency distortions on the interferometric length measurements in NPMMs with extended measurement areas of several hundred millimeters, the respective length measurement errors have to fall below the digital resolution limit of the interferometers which can currently be set to $2.5 \cdot 10^{-11}$ (5 pm at 200 mm measurement range with 16-bit A/D-converter [7]). A possible further extension of measurement ranges up to 1 m and resolution enhancement in A/D conversion will prospectively make even a frequency stability of $\leq 10^{-12}$ desirable. Since high positioning dynamics benefit from wavelength standards with enhanced short-term frequency stability, a frequency stability of 10^{-12} independent on integration time is preferable. To additionally control the absolute frequency, the laser source should ideally provide a permanent link to a primary frequency standard [11]. Finally the laser source should possess enough output power to be suitable for fiber coupling.

This requirements all together cannot be fulfilled with the currently used polarization-stabilized HeNe-lasers. In fact, they are not even feasible within one single laser system.

Nevertheless, decades of research and development in precision spectroscopy, pulsed laser systems and ultrastable laser sources have paved the way for a commercial availability of traceable, ultrastable optical frequencies that have for a long time only been accessible to national metrology institutes.

In this study we present two new approaches to implement traceable, ultrastable optical frequencies at 633 nm for displacement interferometry in NPMMs with a measurement range of several hundred millimeters.

2. Ultrastable, traceable frequencies at 633 nm

The approaches for an experimental implementation of a laser source with the aforementioned features and a wavelength of 633 nm are presented in Fig. 1. The core element is a GPS-referenced frequency comb to ensure traceability and a long-term frequency stability of better than 10^{-12}. The optical frequency comb (OFC) is a commercial system (Model:FC1500-250-WG, Menlo Systems) that contains an additional unit for frequency conversion down to 633 nm.

The repetition rate f_{Rep} and the carrier envelope offset frequency f_{CEO} of the comb are phaselocked to a 10 MHz-output from a GPS disciplined oscillator (GPSDO) [12]. The accuracy and long-term stability of this RF-reference is obtained from the GPS signals that are used to steer the frequency output of the local oscillator [13]. Since the GPS signals are directly traceable to UTC(USNO) a direct and permanent link of the local oscillator to an atomic clock as a primary standard for the realization of the SI unit time is realized and transferred into the optical domain. The overall uncertainty of the GPS-referenced frequency comb is determined by the frequency stability and accuracy of the GPSDO (see e.g.[14]). Based on a comb-comb-comparison of two GPS-referenced frequency combs the manufacturer guarantees a relative frequency stability (relative Allan-Deviation) of $4 \cdot 10^{-12}$ at $\tau = 1$ s and a relative accuracy better than $8 \cdot 10^{-12}$ at $\tau = 1$ s [12]. The relative accuracy at $\tau = 1$ s is limited by the maximum Allan deviation of the GPSDO. It drops down to approximately 10^{-12} for an integration time of one hour. For integration times ($\tau > 10^4$ s) the accuracy is limited to $3 \cdot 10^{-13}$.

The relative Allan deviation of the GPS-referenced frequency comb in comparison to a polarization stabilized HeNe-laser is depicted in Fig. 2c). The Allan deviation of the comb shows a maximum of $3.6 \cdot 10^{-12}$ at 64 s and monotonically drops down to $5 \cdot 10^{-13}$ at $\tau = 10000$ s due to the synchronization with the GPS signal (see e.g. [15]). On the other hand the limited long-term stability of the stabilized HeNe-laser can be clearly deduced from the increasing Allan-deviation reaching a value of $4 \cdot 10^{-10}$ at $\tau = 10000$ s. Currently the NPMM-200 is powered by one single-frequency polarization-stabilized HeNe-laser for each interferometer axis with a maximum output power of 1.2 mW prior to fiber coupling. These lasers operate independently from each other and show a slightly different frequency stability behavior [8].

On the contrary, the 7 mW-output power of the OFC at 633 nm is spread over several thousand comb modes. Thus each comb line possesses only a low optical power of about 800 nW and cannot be used directly as wavelength standard for interferometry in the NPMM-200.

Therefore, the comb has to be combined with a metrology laser of higher output power to provide a traceable, ultrastable frequency standard with enough power to feed all of the interferometers within the NPMM-200 at the same time.

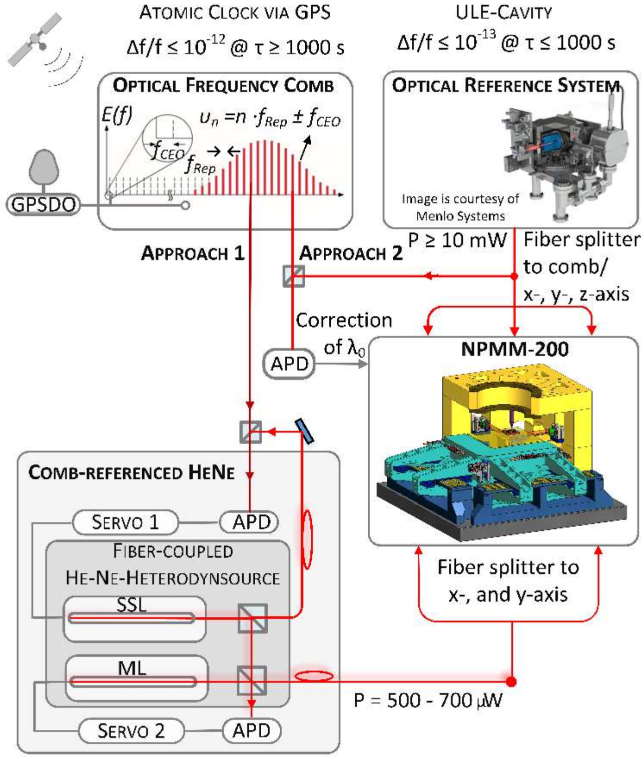

Figure 1. : Approaches for the implementation of ultrastable, traceable frequencies for interferometry in the NPMM-200. The abbreviations denominate: GPSDO - GPS-disciplined oscillator, ULE – Ultra-low-expansion, APD – Avalanche photodiode, SSL – Secondary standard laser, ML – Metrology laser.

The first approach we implemented and comprehensively described in [8,16] is based on a fiber-coupled HeNe-heterodyne source directly and permanently stabilized to a single comb line. The first laser of the HeNe-source is used to create a beat note with one of the comb modes. The generated beat signal serves as the input of a control system stabilizing the laser to the comb mode ("Servo 1" in Fig. 1). This laser serves as the "Secondary standard laser" (SSL). Some µW optical power of the SSL and the second laser of the heterodyne source are afterwards used to create a beat note signal between these two lasers. This beat signal is the input of a second control loop ("Servo 2" in Fig.1) that is used to lock the second laser with an adjustable frequency offset between 0.1 – 20 MHz to the SSL. This laser serves as the actual metrology laser (ML). Once the laser is locked to a respective comb line no adjustment of the vacuum wavelength for the interferometric measurements of the NPMM-200 within daily operation is necessary [8].

We recently demonstrated that the applied control system allows the SSL to follow the comb line with a maximum frequency deviation of 2.3 kHz ($4.8 \cdot 10^{-12}$) over a time window of 1h (Fig. 2a) and b)). The relative Allan deviation of the locked SSL and ML fall below the Allan deviations of the comb line for integration times τ ≥ 1 s [8] (Fig. 2c). Thus it could be shown that the SSL and ML are able to follow the comb line properly. With the designed control system an increase in long-term stability of three orders of magnitude in comparison to the Allan deviation of the polarization-stabilized HeNe-laser can be achieved for t = 10000 s (see Fig. 2c). Furthermore, the tunable frequency output of the metrology laser allowed us for the first time to directly observe the influence of frequency distortions on the interferometric length measurements within the NPMM-200 [8].

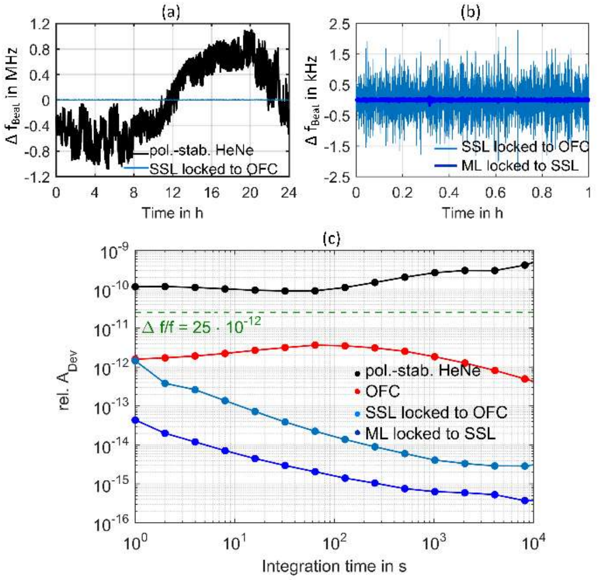

Figure 2: Frequency stability of the comb-referenced HeNe-lasers. a) Deviation of the beat frequency from the mean value between the SSL and a comb line prior and after lockig the SSL onto the comb line, b) Deviation of the beat frequency between the SSL and a comb line as well as the ML and the SSL when locked to the comb line, c) Respective relative Allan deviations. The interferometer resolution of the NPMM-200 is indicated as a green line.

With the applied locking scheme a direct and permanent link of an interferometric measurement to an atomic clock was created. Nevertheless, a frequency stability of ≤ 10^{-12} is only achievable for integration times higher than 1000 s. The short-term stability and frequency noise are still limited by the properties of the GPSDO and the HeNe-lasers.

In addition, the HeNe-lasers provide only limited power output. In the current configuration the comb-referenced metrology laser provides an output power of 500-700 µW after fiber coupling. This power can be used to feed up to two interferometer axis (x- and y-axis) of the NPMM-200. To feed each of the interferometer axis the current comb-referenced heterodyne source would have to be complemented by a third laser. Although the current control design is easily scalable to control several metrology lasers it is questionable if the build up of a laser array is desirable, especially in terms of possible different frequency noise properties of the respective laser sources.

Nevertheless, these deficiencies can be overcome by the additional implementation of a diode laser stabilized to an ultrastable reference cavity. These systems rely on a cavity as reference and possess an excellent short-term stability [17]. Furthermore, they provide a higher optical power in comparison to a HeNe-laser. On the other hand their long-term stability is usually limited by frequency drifts due to aging and temperature fluctuations of the high-finesse cavity [17,18].

At the TU Ilmenau a commercial Optical Reference System (ORS) from Menlo Systems is used [19]. It consists of an ECDL-laser (MOGLabs Littrow external cavity diode laser; wavelength: 632.8 nm) that is locked to a high-finesse cavity made of Ultra-Low Expansion glass via the Pound-Drever-Hall locking scheme. The ULE glass exhibits a linear shrinking drift rate of approximately 0.15 Hz/s [20]. The optical cavity is temperature stabilized, embedded in an ultra-high vacuum (UHV) system and mounted on an additional vibration isolation platform. The cavity-stabilized diode laser provides an output power of 10 mW that can be accessed via a fiber coupled, polarization-maintaining output port [20]. The CW-laser, ULE-cavity, optics for the PDH-lock and control electronics are integrated into a compact 19" rack.

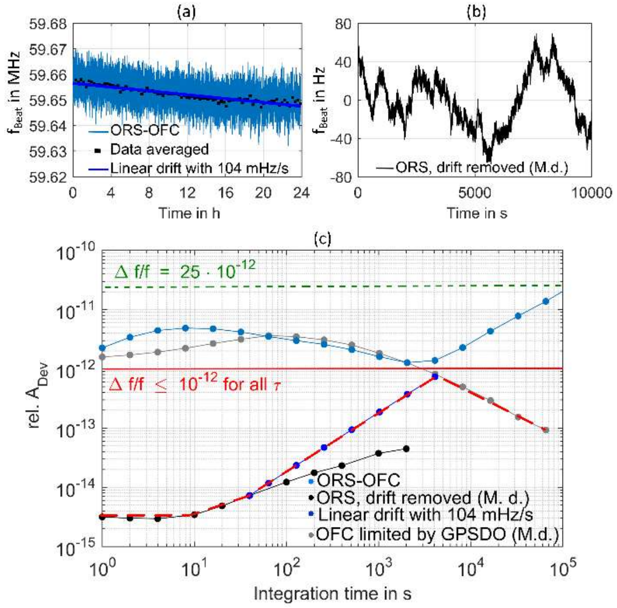

Figure 3: Frequency stability of the optical reference system in comparison to the GPS-referenced frequency comb. a) 24h-measurement series of the beat frequency between the ORS and a comb line; b) Time dependent beat frequency between two optical reference systems of comparable frequency stability with the linear drift removed, c) corresponding relative Allan deviations. The red dashed line indicates the expected frequency stability of the ORS with linear drift for τ ≤ 4000 s and the overall stability prospectively achievable by a combination of both systems. The abbreviation "M.d." stands for manufacturer data.

In Fig. 3 frequency stability data of the ORS in comparison to the OFC is presented. Fig. 3a) displays a 24h-measurement of the beat frequency between the OFC and the ORS. The bright blue line shows the measurement data for an integration time of 1 s. Fig. 3b) presents a measurement of the ORS against another optical reference system of comparable frequency stability [21]. This dataset was provided by the manufacturer and is already corrected for the drift rate of the cavity [21]. The respective Allan-deviations are depicted in Fig. 3c). Due to the outstanding short-term stability of the ORS with $A_{Dev} \leq 5 \cdot 10^{-13}$ for τ ≤ 1000 s the observable short-term frequency changes of the beat frequency with a maximum frequency deviation of 12.6 kHz within a timeframe of 1h in Fig. 3a) reflect the fluctuations of the respective comb line. The differences in the Allan deviation of the OFC between the manufacturer data (grey line in Fig. 3c) and the measured data (blue line) for integration times below 30 s are currently under investigation. Nevertheless, within the 24h-measurement time the drift of the ORS-system is clearly visible. For illustration purposes the black data points additionally present the measured data averaged in 1000 s samples. In accordance to [18] a linear fit is applied, resulting in a drift rate of 104 mHz/s and a frequency change of 9 kHz within the 24h-measurement window.

Thus a permanent monitoring and periodic correction of the absolute frequency of the ORS is necessary to keep the influence of this frequency changes below the current resolution limit of the interferometers of $2.5 \cdot 10^{-11}$. For this purpose some power of the ORS has to be branched off for a parallel measurement of the beat frequency with the frequency comb (Fig.1).

Future research will concentrate on the practical integration of the ORS for interferometric measurements in the NPMM-200. This additionally requires the estimation of a possible frequency stability degradation due to fiber dissemination (see [8]). To profit from the long-term stability of the comb without losing the exceptional short-term stability of the ORS-system, a suitable correction procedure for the absolute frequency of the reference system has to be established to prospectively enable the implementation of an ultrastable, traceable optical frequency with a frequency stability of 10^{-12} independent on the integration time as illustrated as solid red line in Fig. 3c).

3. Conclusion

Ultrastable and traceable wavelength standards are a key component for interferometric length measurements, especially in nanopositioning and -measuring machines with measurement ranges up to several hundred millimeters. The commercial accessibility of optical frequency combs and ultrastable laser sources paved the way for new solutions in the precise determination of optical frequencies and the formation of wavelength standards with outstanding frequency stability performance.

With the approach of a comb-referenced HeNe laser it was possible to create direct and permanent traceability of the interferometric length measurements within the NPMM-200 to a primary frequency standard and thus the SI unit second. Additionally the longterm stability of an individual comb line was transferred onto the HeNe-lasers increasing their longterm stability by three orders of magnitude. Thus the influence of frequency related length measurements errors practically drops below the digital resolution of the interferometers for the first time.

To provide a frequency stability of better than 10^{-12} for integration times below 1000 s, the GPS-referenced frequency comb was expanded by a diode laser stabilized to an ULE-cavity. A combination of these systems allows perspectively to establish a wavelength standard of high output power and frequency stability better than 10^{-12} independent on integration time. From such a wavelength standard not only interferometric length measurements in NPMMs with extended positioning ranges up to 1 m will benefit. It will also provide new possibilities for a precise frequency determination and characterization of laser sources beyond 633 nm, an on-site dissemination of these ultrastable frequencies or the implementation of alternative interferometric approaches for refractive index compensation.

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References

[1] http://technology-roadmaps.eu/doku.php?id=micro_and_nano

[2] https://sios.de/produkte/nanopositionier-und-nanomessmaschine/

[3] E. Manske et al., A multi-sensor approach for complex and large-area applications in micro and nanometrology. *NCSLI Measure*, **7** (2), p. 44-50, 2012.

[4] I. Ortlepp et al., Tip- and Laser-based 3D Nanofabrication in extended macroscopic working areas. *Nanomanufacturing and Metrology*, **4** (3), p.132-148, 2021.

[5] G. Jäger et al., Nanopositioning and nanomeasuring machine NPMM-200 – a new powerful tool for large-range micro- and nanotechnology. *Surface Topography: Metrology and Properties*., **4** (3), p. 034004, 2016.

[6] E. Manske et al., Progress of nanopositioning and nanomeasuring machines for cross-scale measurement with sub-nanometre precision. *Measurement Science Technology*, **31** (8), p. 085005, 2020.

[7] G. Jäger, Limitations of precision length measurements based on interferometers. *Measurement*, **43** (5), p. 652-658, 2010.

[8] U. Blumröder et al., Comb-referenced metrology laser for interferometric length measurements in nanopositioning and nanomeasuring machines. submitted to *Technisches Messen*,2022.

[9] V. Badami and P. De Groot, Displacement measuring interferometry. *Handbook of optical dimensional metrology*, 4. Jg, 2013.

[10] W.-K. Lee et al.,Vacuum wavelength calibration of frequency-stabilized He-Ne lasers used in commercial laser interferometers. *Optical Engineering*, **50** (5), p. 054301, 2011.

[11] SI Brochure – 9th edition (2019)- Appendix 2, Mise en pratique for the definition of the metre in the SI, https://www.bipm.org/en/publications/mises-en-pratique.

[12] Menlo Systems GmbH, GPS-8 10 MHz RF Reference. *User Manual*, Menlo Systems GmbH, 2016.

[13] M. A. Lombardi, The use of GPS disciplined oscillators as primary frequency standards for calibration and metrology laboratories. *NCSLI Measure*, **3**(3), p. 56-65, 2008.

[14] J. E. Stone et al., An optical frequency comb tied to GPS for laser frequency/wavelength calibration. *Journal of Research of the National Institute of Standards and Technology*, **115**(6), p. 413, 2010.

[15] M. A. Lombardi et al., Characterizing the performance of GPS disciplined oscillators with respect to UTC (NIST). In: *Proceedings of the 37th Annual Precise Time and Time Interval Systems and Applications Meeting,* p. 677-684, 2005.

[16] P. Köchert et al., Ultrastable metrology laser at 633 nm using an optical frequency comb. In: *Optical Micro-and Nanometrology VII. International Society for Optics and Photonics*, p. 106780S, 2018.

[17] U. Sterr et al. ,Ultrastable lasers: new developments and applications. In: *Time and Frequency Metrology II*. SPIE, p. 33-46, 2009.

[18] P. Dubé, et al., A narrow linewidth and frequency-stable probe laser source for the 88Sr+ single ion optical frequency standard. *Applied Physics B*, **95** (1), p. 43-54, 2009.

[19] https://www.menlosystems.com/products/ultrastable-lasers/

[20] Menlo Systems GmbH, Optical Reference system. *General System Description,* 2019.

[21] Menlo Systems GmbH, Optical Reference system. *Final Test Report,* 2020.