FREQUENCY COMB-COUPLED METROLOGY LASERS FOR NANOPOSITIONING AND NANOMEASURING MACHINES

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Abstract. This article shows how a direct readout of the interferometric length measurement in nanopositioning machines can be transferred by connecting the metrology laser to a frequency comb line. The approach is based on a GPS-referenced frequency comb with which the stability of the timer (atomic clock via GPS) is transferred to the metrology laser of the nanopositioning and nanomeasuring machine NPMM-200. The necessary prerequisites for ensuring traceability are discussed. It is demonstrated that with this approach an improvement in the long-term stability of the metrology laser by three orders of magnitude can be achieved.

Key words: Interferometric length measurement; Nanopositioning and nanomeasuring machine; Metrology laser; Frequency comb.

1. Introduction

The rapid increase in nanotechnological approaches in industry and research requires new manufacturing approaches and characterization methods that make it possible to map structures down to the (sub) nanometer range on ever-larger measuring ranges [1, 2].

This requires highly precise positioning of the corresponding measurement objects, which are generally based on interferometric measurement methods. The TU Ilmenau has been working on the development of nanopositioning and measuring machines (NPMM) for more than 20 years, which enable 3D positioning of objects to be measured with nanometer accuracy and which can be equipped with a variety of different sensors or manufacturing tools [3, 4]. The new generation of nanopositioning machines developed at the TU Ilmenau covers a measuring range of 200×200×25 mm and guarantees positioning repeatability of $\leq$ 4 nm over the entire measuring range with a resolution of 8 pm [3, 5]. The positioning system of the NPMM-200 is based on a six-axis, fiber-coupled interferometer system that uses three stabilized He-Ne lasers as the measuring standard for interferometric length measurement [3]. Stabilized He-Ne gas lasers have become the most frequently used laser sources for precise interferometric length measurements [6]. They are typically inherent in frequency stability (24 h) in the range of 2×10^{-9} and thus, with a maximum travel distance of 200 mm, lead to a length measurement error of 0.4 nm solely due to frequency fluctuations. In addition, degradation effects can lead to a drift in the center frequency of up to ±5 MHz/*a* ($\Delta f/f = 10^{-8}/a$) [8]. To ensure the traceability of the interferometric length measurement, the metrology lasers of the NPMM-200 must therefore be measured at periodic intervals against a BIPM-compliant frequency standard. For decades, iodine-stabilized He-Ne lasers with a recommended uncertainty of u = 10 kHz (21×10^{-12}) have been used for this purpose [9]. This uncertainty can increase to 10^{-10} for reference standards certified at national metrology institutes and applied in industrial or research laboratories. In addition, iodine-stabilized lasers are distinguished by low output power and are therefore not suitable for direct application in multi-axis or fiber-coupled interferometric systems [6].

With the commercial availability of frequency comb technology, however, in recent years new possibilities have opened up for reducing the wavelength to the meter definition. The optical spectrum of a frequency comb (OFC) according to:

$$f_n = n \cdot f_{REP} \pm f_{CEO}\,, \tag{1}$$

can be described in [10]. A single optical frequency f_n of the comb spectrum is thus completely determined by two frequencies in the radio frequency range (the repetition rate of the laser system f_{Rep} and the "Carrier Envelope Offset" f_{CEO} [10]) and the corresponding mode number n. The two comb parameters f_{Rep} and f_{CEO} are usually linked to a frequency standard in the radio frequency range (e.g. cesium clock or GPS disciplined oscillator GPSDO), which increases the stability of the timer (e.g. atomic clock via GPSDO with $u_{rel} = 1.8\times10^{-12}$ for $k = 2$ and τ = 22 min [11]) can be transmitted into the optical range. In contrast to an iodine-stabilized laser, an optical frequency comb can thus contain many optical reference frequencies in a wide spectral range from VIS-NIR with e.g. In some cases, provide less uncertainty [11, 12]. As a result, they are increasingly used for metrological purposes such as the calibration of laser sources [12, 13]. In addition, through a direct connection of external lasers to a comb line and thus to the seconds standard of an atomic clock, following the recommendations of the CIPM for the highest accuracy requirements, synchronization to a primary frequency standard can be realized [14].

This article describes how the length measurement in the NPMM-200 of the TU Ilmenau can be traced back directly by coupling the metrology laser to a frequency comb. Problems to be considered in the practical implementation to ensure traceability are discussed and it is shown that by transferring the laser frequency of the metrology lasers to the frequency comb, their long-term stability can be improved by three orders of magnitude.

2. Frequency comb-coupled metrology lasers

2.1 Basic concept

The basic concept for connecting the metrology lasers of the NPMM-200 to a primary frequency standard with a frequency comb is shown in Fig. 1. A GPS-referenced frequency comb acts as a "self-calibrating" frequency standard [11]. The GPSDO uses the signals received from the GPS satellites to control the frequency output of a local oscillator [15]. The short-term stability is provided by the local oscillator, while the long-term stability and accuracy of the output frequency are generated by the connection to the GPS signals, which are directly traceable to UTC (USNO) [15]. This direct connection of the oscillator to the GPS signal ensures traceability to the primary standard for realizing the SI unit of time [11].

To transfer the stability of the primary standard to the metrology laser, the external laser and the frequency comb line must first be superimposed. On this basis, the absolute frequency of the laser can be determined and corrected by an appropriate control. The stabilized laser frequency of the metrology laser can then be applied for transmission to the interferometer of the NPMM-200.

For a practical implementation of this approach, the aspects shown in Fig. 1 must be considered to guarantee the traceability of the laser frequency. These include (1) proper functioning of the GPS-referenced frequency comb to be able to guarantee the uncertainty specified by the manufacturer for the frequency of a comb line, (2) a correctly determined frequency of the metrology laser by the user, (3) a control-technical connection of the Metrology laser, which enables the long-term stability of the ridgeline to be transmitted to the external laser and (4) ensuring an interference-free transmission path between the metrology laser and the NPMM-200. The latter guarantees the transmission of the stabilized laser frequency to the interferometers of the NPMM-200. These individual links are described in more detail below.

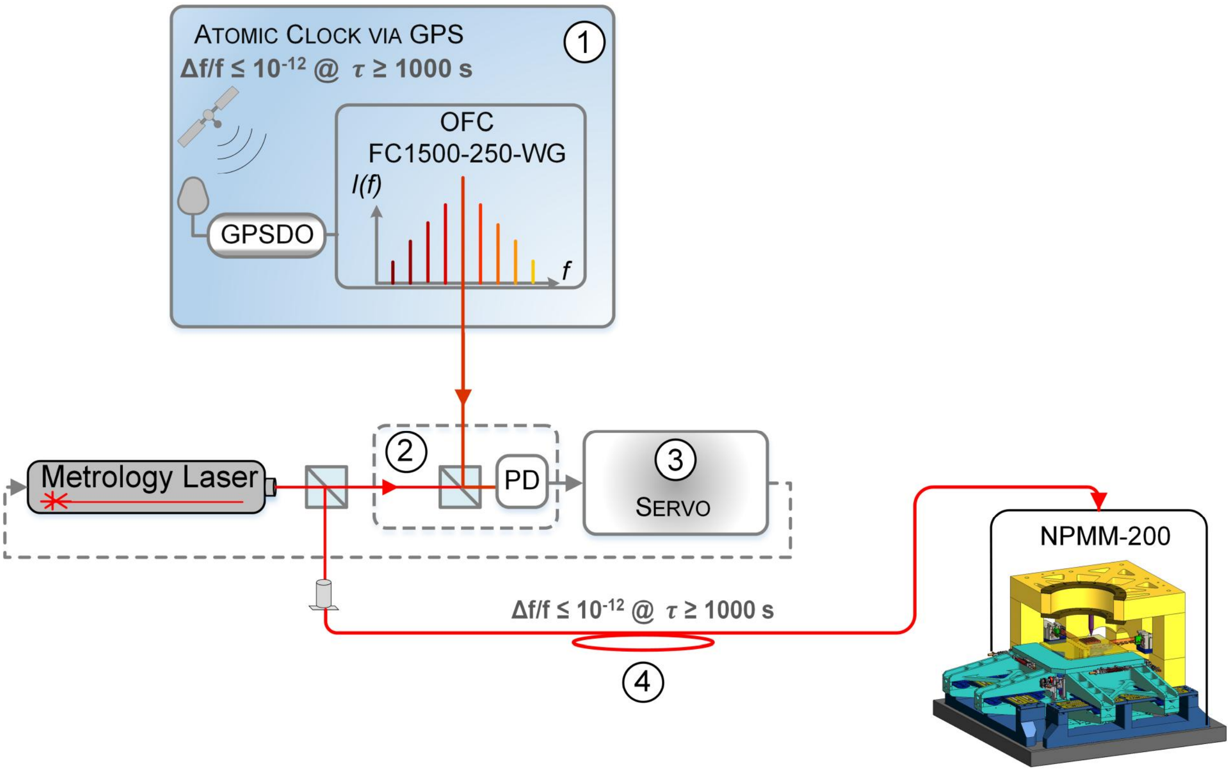

Fig. 1. The basic concept of a frequency comb-coupled metrology laser for connecting the interferometric length measurement to an atomic clock. The abbreviations describe: OFC – Optical Frequency Comb; GPSDO – GPS disciplined oscillator; and PD – photodiode. The individual links in the feedback chain (1)–(4) are explained in the text

2.2. Experimental realization

2.2.1 GPS-referenced frequency comb

The GPS-referenced frequency comb from the TU Ilmenau is a commercial model from Menlo Systems (model: FS 1500-250-WG, Menlo Systems, see Fig. 2). This is based on a mode-locked, polarization-maintaining erbium fiber laser with a central wavelength of 1552 nm [16]. The system is equipped with two amplifier units. One of these units is applied to determine the CEO phase using a 2f-f interferometer [17]. The second unit is intended to generate a 633 nm output for superimposition with He-Ne laser sources.

The GPSDO is based on a VCO (voltage-controlled oscillator) that delivers an output frequency of 10 MHz [18]. This is then distributed to the control electronics and the frequency counter (π-type, FXM50) via an SDU (Signal Distribution Unit). The control electronics for stabilizing the comb parameters contain two phase-locked loops that stabilize the repetition rate and the CEO phase to a multiple of the 10 MHz output of the GPSDO. The standard repetition rate is 250 MHz, the CEO phase is 20 MHz. The comb parameters are monitored utilizing the frequency counter. Two additional channels of the frequency counter are available for measuring floating signals between the comb and external lasers.

The stabilization of the comb parameters is directly linked to a fail-safe mode of operation of the GPSDO. This must primarily be ensured by the suitable positioning of the GPS antenna. In addition, permanent monitoring of the GPS signals is recommended [15]. At the TU Ilmenau, this is guaranteed by evaluating the NMEA protocols via the serial interface of the GPSDO. The relevant data on the status of the GPS signal and the number of available satellites are stored centrally. Additional information about the failure-free functioning of the GPS satellites can only be obtained from publicly available comparative data from metrology institutes, which compare the GPS signals with national frequency standards [15, 18].

In addition to the functionality of the GPSDO, the lock status of the control for the comb parameters must also be checked. This includes ensuring a sufficient signal-to-noise ratio of the comb frequencies, especially the f_{CEO}, as well as permanent monitoring of both parameters [11].

The uncertainty of a GPS-referenced comb is mainly determined by the short-term noise behavior (time scales <24 h) of the GPSDO [11, 15]. To quantify the resulting frequency fluctuations of the comb, comparisons are made between frequency combs [12, 20] or against an at least comparably stable reference laser [11]. In the case of the commercial OFC of the TU Ilmenau, based on a comparison of two GPSDO-referenced frequency combs, the manufacturer guarantees a relative accuracy of better than 8×10^{-12} ($\tau = 1$ s) and relative stability (relative Allan deviation) of 4×10^{-12} ($\tau = 1$ s) [18]. The accuracy is determined (see also [12, 20]) using the standard deviation of the mean value over an approximately 13-hour measurement ($N = 47600$):

$$u = \frac{s}{\sqrt{N}\cdot\sqrt{2}}\,. \tag{2}$$

Factor $\sqrt{2}$ takes into account that the measurement contains the proportion of both frequency combs.

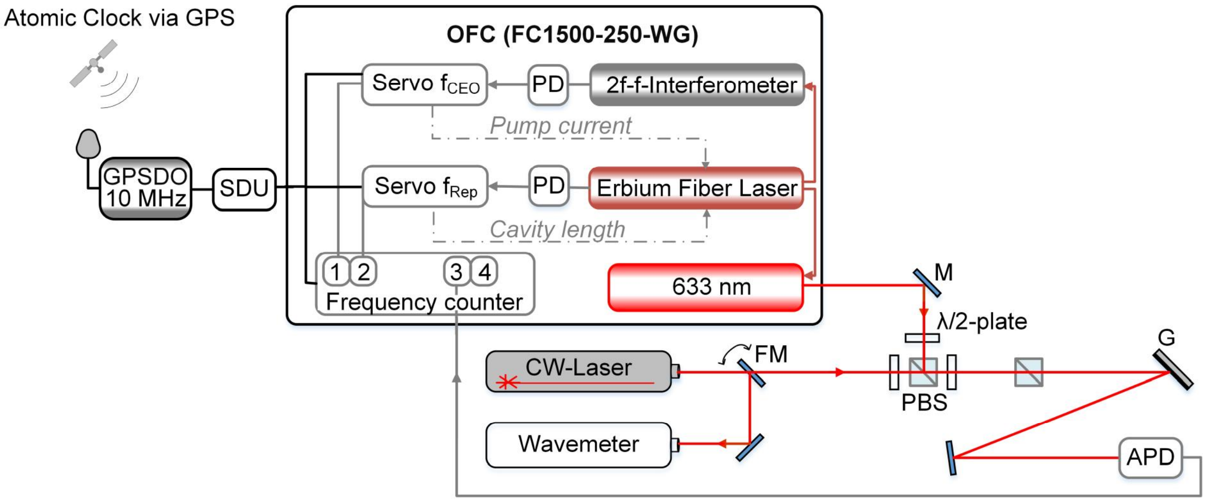

Fig. 2. GPSDO-referenced frequency comb with beat detection unit for creating a beat note between an external CW laser and an optical comb line. Abbreviations are: GPSDO – GPS disciplined oscillator; SDU – Signal distribution unit; APD – Avalanche Photodiode; PD – Photodiode; FM –Mirror with flip mount; PBS – Polarizing beam splitter; G – grating; M – Mirror; λ/2 – Half-wave plate

2.2.2. Determination of the absolute frequency of a metrology laser using a frequency comb

By superimposing a frequency comb line on an external laser source f_{CW}, its absolute frequency can be determined by measuring the beat frequency f_{Beat}:

$$f_{CW} = n \cdot f_{REP} \pm f_{CEO} \pm f_{Beat} = f_n \pm f_{Beat}. \qquad (3)$$

For a correct determination of the absolute frequency, systematic measurement errors must be avoided. The last is primarily caused by the generation of a beat signal with an insufficient signal-to-noise ratio (SNR), sign errors in the determination of f_{CEO} and f_{Beat}, and an incorrect determination of the model number.

The generation of a beat signal with sufficient signal strength is of fundamental importance for the correct counting of the beat frequency employing the frequency counter. The 633 nm output of the frequency comb has an average output power of 7 mW and a spectral width of 3 nm (FWHM). This power is distributed over several thousand modes so that a maximum power of around 800 nW per mode is available for generating a beat signal with an external laser source. This power is further reduced by the optical components for spatial superimposition and adaptation of the polarization of both laser beams (Fig. 2 and [11, 21]). The performance of the other comb modes primarily contributes to a deterioration in the signal-to-noise ratio in the case of detection through a photodiode. In the free beam unit for superimposing the two laser beams, there is therefore an additional preselection of the modes via a grid (Fig. 2 [10, 21]). Our investigations into the influence of the SNR of the beat signal on the frequency measurement through a frequency counter showed, following [21], that for an $SNR \leq 28$ dB, measurement deviations are to be expected. Depending on the level of the SNR, they can amount to several MHz.

If a sufficient SNR of the beat signal is ensured, the signs of f_{Beat} and f_{CEO} must first be determined. This is usually done by slightly varying the repetition rate and the CEO [11, 17, 22].

If the absolute frequency of the laser to be measured is already known (e. g. via a calibration certificate or datasheet) with an uncertainty $\leq f_{Rep}/2$, the model number can be obtained directly from Eq. (3) and can be calculated. If no further data is available about the laser at hand, the model number can be determined using a comparative measurement with a wavemeter, which must also guarantee an uncertainty of $\leq f_{Rep}/2$. However, this requires regular calibration of the wavemeter. The model number can also be determined without additional aids by varying the repetition rate [11, 17, 22]. At the TU Ilmenau, a wavemeter (High Finesse, Ångstrom Super Precision WLM-VIS, 350–1100 nm, absolute accuracy 100 MHz) and the variation of the repetition rate are applied to determine unknown laser frequencies. A combination of these methods is occasionally used for He-Ne lasers of known frequencies as a consistency test to monitor the functionality of the frequency comb and the wavemeter.

2.2.3. Connection of the metrology laser to a frequency comb line

The six-axis interferometer system of the NPMM-200 is supplied by three fiber-coupled, stabilized He-Ne lasers. Since not each of these lasers can be coupled to a comb line at the same time, the connection was implemented via a “master-slave arrangement”. This concept is shown in Fig. 3. First of all, the fiber-coupled He-Ne laser module of the NPMM-200 was expanded to include a fiber-coupled He-Ne heterodyne source [23]. This system consists of two commercially available, stabilized He-Ne lasers (model: SL02/1, SIOS Messtechnik GmbH, $P = 1$ mW).

A laser from this heterodyne source is generated a beat signal with a frequency comb line. Almost all of the power available after fiber coupling is used for this purpose. The generated beat signal is first applied to determine the absolute frequency of this laser and then applied as the input signal of an FPGA-based control system. The control uses a phase-sensitive detection of the beat signal with which the difference to a reference frequency derived from the 10 MHz output of the GPSDO is determined and then controlled by a digital PID controller. The laser frequency is adjusted by changing the length of the resonator employing the heating coil of the laser tube. The laser stabilized in this way then functions as a secondary standard [6].

The second laser of the heterodyne source serves as the actual metrology laser (ML). It is linked to the secondary standard laser (SSL) with a frequency offset that can be freely set between 0.1–20 MHz. For this purpose, a few μW of the power of the secondary and metrology laser are decoupled by two beam splitters for superimposition and used to generate a floating signal with a high SNR in the range of at least 50 dB. This analog signal is first converted into a TTL signal using a Schmitt trigger, which forms the input signal for another FPGA-based control system. However, the frequency is determined by edge detection. The number of counted pulses is compared with a setpoint frequency specified by the user, which determines the frequency offset between SSL and ML. The difference is fed to a digital PID controller whose output signal is also used to control the heating of the ML [23]. A detailed description of the signal processing systems and control loops can be found in [6, 23].

In the locked status, the beat signals between SSL and comb line or SSL and ML are permanently monitored by two channels of the frequency counter of the signal processing unit of the frequency comb. After switching on the laser source, the lasers are first brought into their internal stabilization. A manual switch can then be employed to switch to the external frequency comb control.

The remaining power of the ML (approx. 500–700 μW) is then used to operate two measuring axes (x, y) of the NPMM-200. A 50:50 splitter with a 6 m long fiber leads the power directly to the interferometer axes of the NPMM-200.

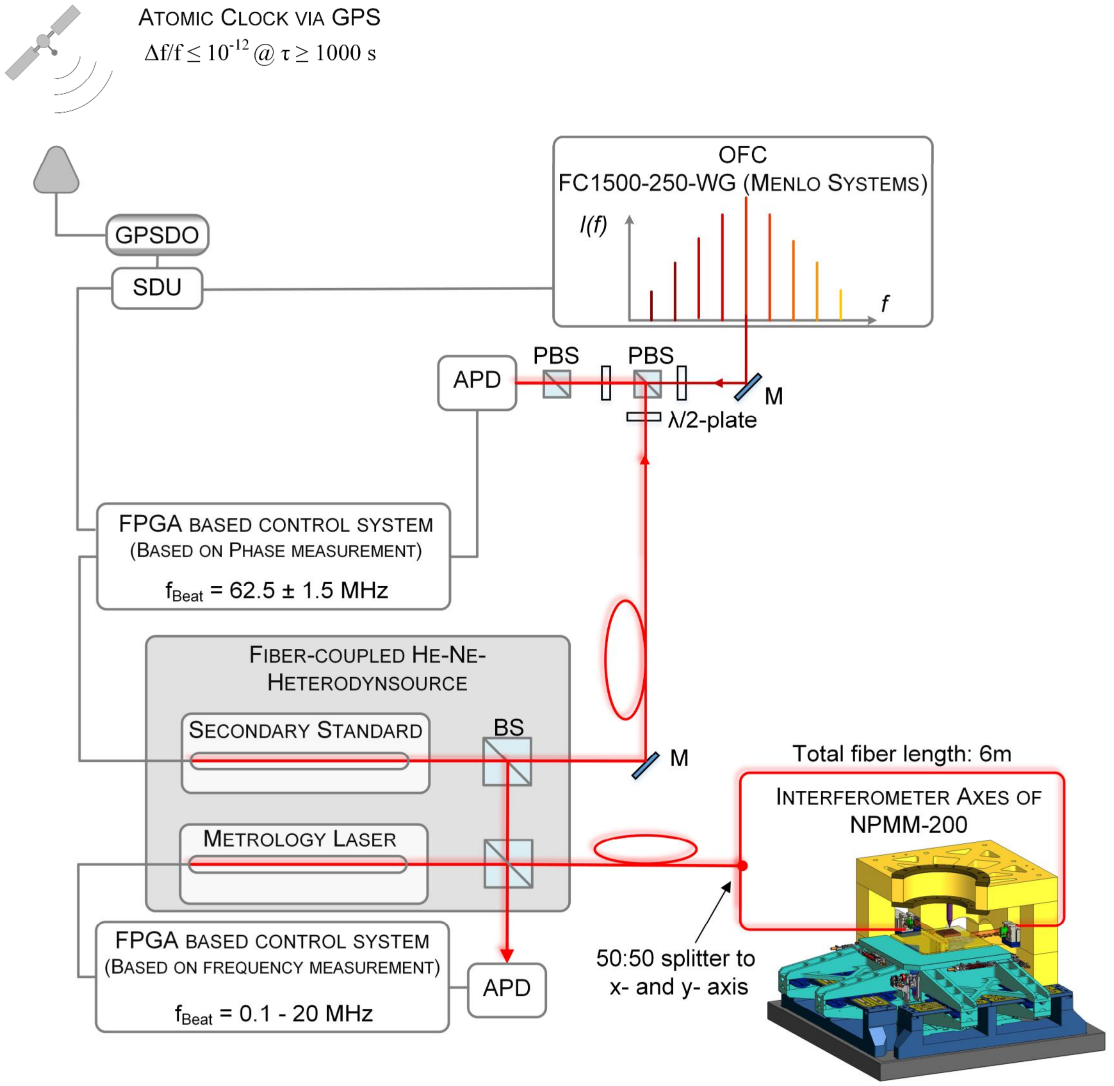

Fig. 3: Setup for locking the metrology laser to a single comb line. Abbreviation used in the figure are: GPSDO – GPS disciplined oscillator; SDU – Signal distribution unit; APD – Avalanche Photodiode; PBS – Polarizing beam splitter; M – mirror; λ/2 – Half-wave plate; BS – Beam splitter

2.3 Results

Fig. 4 shows a 24-hour series of measurements of the beat signals between the SSL and a ridgeline as well as between SSL and ML. The figure above demonstrates the deviation of the beat signal from the mean value $\left(\Delta f_{Beat} = f_{Beat} - \overline{f_{Beat}}\right)$ between the SSL and a ridgeline before and after the SSL was lured onto the ridgeline. The black curve shows the SSL in its internal stabilization. In this case, the ridgeline acts as a stable reference frequency, and the frequency fluctuations are completely determined by the SSL. It helps to fix a maximum frequency deviation of 1.1 MHz (2.3×10^{-9}) over 24 hours. The resulting Allan deviation (Fig. 5) notices a clear increase for integration times longer than 100 s.

If the lock to the ridgeline is closed, the frequency fluctuations of the SSL are almost eliminated. Then, the beat signals make it clear how well the SSL or ML can follow the ridgeline with a suitable choice of the control parameters. The deviation of the mean value of the measured beat frequencies from the setpoint of the control was 47 Hz (9.9×10^{-14}) with f_{Soll} = 62.5 MHz for the SSL and 204 Hz (4.3×10^{-13}) for the ML f_{Soll} = 4.5 MHz. The maximum frequency deviation from the mean value of the respective beat signals over a time window of 1 hour is 2.3 kHz (176 Hz) for the SSL (ML), which corresponds to a relative frequency deviation of 4.8×10^{-12} (3.7×10^{-13}). Isolated outliers due to severe acoustic disturbances with a maximum frequency deviation of 11.7 kHz were observed over the entire measurement period of 24 hours.

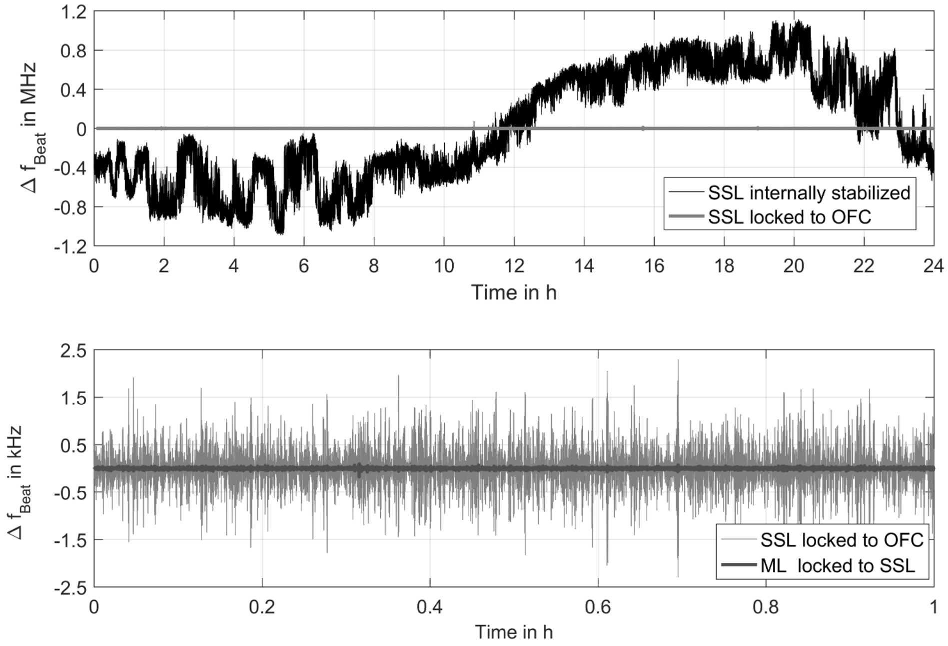

Fig. 4: Frequency deviation of an SSL and ML tied to a ridgeline throughout 24 h (top) and 1 h (bottom)

The Allan deviations calculated from the entire series of measurements are shown in Fig. 5. The red curve demonstrates the frequency stability of the GPS-referenced frequency comb. The relative Allan deviations of the beat signals of the two locked He-Ne lasers are below the Allan deviation of the comb for integration times ≥1 s. This shows that the control ensures the connection of a metrology laser to a ridgeline and that the accuracy and stability of the stabilized laser frequency are dominated by the frequency fluctuations of the ridgeline while avoiding severe external acoustic disturbances up to an integration time of 10.000 s. For an integration time of 10000 s, the relative Allan deviation of the ridgeline drops to 5×10^{-13}. The connection of the He-Ne lasers to a ridgeline results in an improvement in long-term stability by three orders of magnitude compared to the internally stabilized He-Ne lasers with a relative Allan deviation of 4×10^{-10}. For integration times ≥1 s, the influence of frequency fluctuations is for the first time below the relative electronic resolution limit of the interferometer of 25×10^{-12} (5 pm with a maximum travel distance of 200 mm [6]) and can thus be eliminated as an influencing factor in interferometric length measurement.

However, the frequency stability of the ML must finally be passed on to the NPMM-200 via a fiber coupling. In Fig. 3 it becomes clear that possible interferences caused by the fiber feed of the ML to the NPMM-200 are not compensated by the control. Frequency fluctuations due to fiber feed lines can mainly occur due to environmental disturbances (thermal, acoustic). By keeping the fiber length as short as possible and setting up the comb and the metrology laser in the same air-conditioned laboratory as the NPMM-200, such influences can largely be avoided. A worst-case scenario estimate based on [24] resulted in a thermally (max. Temperature change of 7 mK/s) caused maximum frequency change of 8×10^{-16}/m fiber length for the environmental conditions of the air-conditioned laboratory. The neglect of the influence of the fiber feed on the frequency stability of the metrology laser has to be confirmed by further experimental investigations.

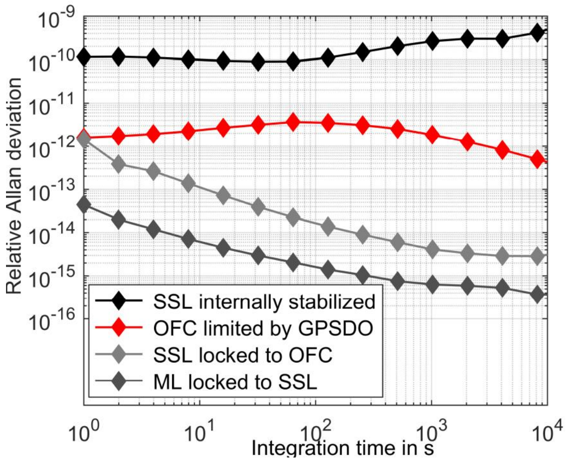

Fig. 5. Relative Allan deviations of a metrology laser before and after being connected to a ridgeline

3. Summary and outlook

The commercial availability of frequency comb technology opens up new possibilities for the development of highly stable, optical frequencies for interferometric length measurement. By coupling a He-Ne laser to a frequency comb line, a direct connection of the interferometric length measurement of the NPMM-200 to an atomic clock could be demonstrated. The presented approach enables the frequency stability of a ridgeline to be transferred to a metrology laser of the NPMM-200, which results in an improvement in long-term stability by three orders of magnitude. However, the characterization of the frequency stability is currently limited by the limitation of the stability of the ridgeline to integration times above ≥ 1 s. Future investigations will therefore concentrate on the characterization and improvement of the short-term stability for integration times below 1 s.

4. Thanksgiving

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