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# Ultrastable metrology laser at 633 nm using an optical frequency comb

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## ABSTRACT

We propose a wavelength standard for highly precise dimensional measurements. An internal-mirror helium-neon laser is offset-locked to a frequency comb line in order to carry out a secondary standard with reduced phase noise and high optical power. Additional lasers can be traced back to this secondary standard, which will enable us to disseminate the accuracy and stability to the metrology lasers of our nanopositioning and -measuring machine, the so-called NPMM-200. First measurements revealed that the stability of the secondary standard is restricted by the time standard of the optical frequency comb to a value of $2.4 \cdot 10^{-12}$ ($\tau = 1\,\mathrm{s}$), which is a significant improvement in comparison to the stability of the existing metrology lasers. In further measurements a metrology laser was locked onto the secondary standard with a relative instability of $0.6 \cdot 10^{-15}$ ($\tau = 1000\,\mathrm{s}$).

**Keywords:** laser stabilization, He-Ne gas laser, displacement interferometry, nanometrology

## 1. INTRODUCTION

Displacement measuring interferometers are the most precise instruments to detect length variations in a traceable way. At present, precise length measurements over longer ranges are mainly limited by the relative frequency stability and absolute accuracy of the applied lasers if refractive index changes can be neglected. The laser of choice in the vast majority of metrological applications since decades is the helium-neon (He-Ne) laser at 633 nm. An internationally accepted realization of the meter definition is achievable by using a laser, whose frequency is stabilized to a molecular transition of iodine [1]. Such a frequency-stabilized laser has already been used to transfer its characteristics to metrology lasers of high precision machines, such as the Large Optics Diamond Tuning Machine (LODTM [2,3]) or the Sub-Atomic Measuring Machine (SAMM [4, 5]). But from an operational point of view, such a laser exhibits unwanted characteristics, which will be subject of discussion in the next section. From an engineering point of view, there is a demand to overcome these deficiencies. We come up with the fundamental idea to close this gap by developing a control system for metrology lasers, whose frequencies are linked onto an optical frequency comb (see Figure 1). This development will also pave the way to connect metrology lasers of nanopositioning and -measuring machines directly to the meter definition without using a secondary representation of the second. No systematic research is so far known to realize such a direct link between a He-Ne gas laser and a femtosecond comb. In particular, such a reference has become necessary for our new long-range nanopositioning and -measuring machine, the so-called NPMM-200 [6].

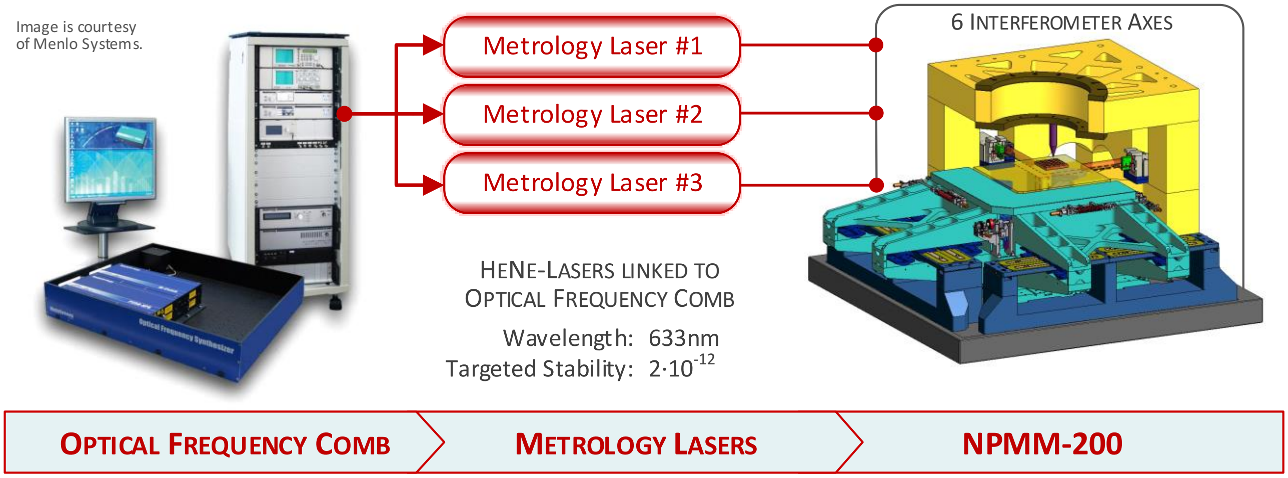

*Figure 1. Concept outline of the three metrology lasers of the NPMM-200 linked to a commercial optical frequency comb to provide a wavelength standard with high stability and a more straightforward realization of the meter definition.*

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The NPMM-200 can readily be operated under vacuum conditions down to 100 Pa, has a measuring volume of 200 x 200 x 25 mm³ and their demodulation electronics is capable to subdivide displacements digitally down to 5 pm [7], which is equivalent to a relative value of $25 \cdot 10^{-12}$. The relative stability and the absolute accuracy of its metrology lasers featuring a stability of about $1 \cdot 10^{-9}$ ($\tau < 10000$ s) have to be improved to ensure positionings and measurements with this machine in the Ångström range. In this article we propose a laser system directly locked onto a frequency comb line. It consists of FPGA-based instrumentations and has demonstrated a relative stability of $2.4 \cdot 10^{-12}$. Furthermore, the system can be easily expanded with manageable effort and provides sufficient optical power to be applied for interferometric applications.

## 2. WAVELENGTH STANDARDS FOR THE NPMM-200 AT 633 NM

The He-Ne gas laser with a wavelength of 633 nm has been the very first laser emitting continuous light in the visible spectrum when it was put into operation in 1962 at Bell Labs [8] and is still the mostly used laser when it comes to precise displacement interferometer measurements. The gain curve of a He-Ne laser exhibits a linewidth of 1.5 GHz in general, which is equivalent to a relative frequency uncertainty of $\pm 1.5 \cdot 10^{-6}$ for an unstabilized He-Ne laser [9]. In metrology applications lasers have to be frequency-stabilized with an improved uncertainty by closing a control loop, which rely on two different techniques that can be classified into (i.) internal methods based on the intrinsic gain profile (see § 2.1) and (ii.) external methods based on spectroscopy (see § 2.2). An externally stabilized laser exhibits in general a better stability and can be used in two different ways: directly, as a light source for interferometric displacement systems or, indirectly and more commonly, as a standard to calibrate the wavelength of He-Ne lasers with a stabilization technique derived from its gain profile [10].

### 2.1 Internally stabilized gas lasers based on the gain profile

Essentially, there are three stabilization techniques to stabilize a He-Ne laser based on its own gain profile: Lamp-Dip Stabilization, Two-mode Stabilization and Zeeman Stabilization (§ 9.2 in [11]). Other techniques, such as the Three-Mode Stabilization [12] and the utilization of the secondary beat frequency, turned out to be rather complex and suffer a niche existence. The authors refer to a suitable review publication [11] for a deeper insight into this topic, which would go beyond the topic of this article.

The laser system of the NPMM-200 consists of three metrology lasers (Model: SL03/1, SIOS Meßtechnik GmbH), which are stabilized with a two-mode stabilization technique [13] derived from the principal ray. The lasers are operating under controlled laboratory conditions and exhibit a relative short-term stability ($t < 1000$) of less than $0.5 \cdot 10^{-9}$. The relative stability of a laser can be improved with a more sophisticated temperature control by using a water-cooling system leading to a relative stability better than $\pm 0.15 \cdot 10^{-9}$ (peak-to-peak, [14]), which is corresponding to a ten-fold improvement over the same observation time when assuming Gaussian distributed samples. Similar results have also been achieved in the meantime by other research groups [15]. However, the reproducibility of the wavelength after warming-up the laser can change up to a few hundred kHz and this effect is not negligible with regard to the absolute accuracy of the laser. Furthermore, it has been observed that the wavelength of He-Ne lasers can drift with values between 1 MHz [16] and 3 MHz [17] per year, which corresponds to a relative drifting of up to $6 \cdot 10^{-9}$.

To make a long story short, the wavelengths of each metrology laser have to be determined precisely to guarantee comparative metrological investigations in the single digit nanometer regime over long periods of time at the NPMM-200. This is commonly ensured by a comparison with a suitable wavelength standard to be discussed in the following sections.

### 2.2 Externally stabilized gas lasers based on spectroscopy

The iodine-stabilized He-Ne laser operating at a wavelength of 633 nm has been the *de facto* standard [10, 18] to realize the SI-unit meter in the visible spectrum for many years. In order to single out a control signal the emission of the He-Ne laser has to be superposed with the absorption spectrum of the iodine molecule, which has several hyperfine transitions in this visible range [19]. The resulting saturated absorption of the specific transition leads to a 0.1% [20] to 0.15% [18] Doppler-free transmission increase on the gain profile. To resolve those small intensity changes from a noisy background usually three-derivative locking techniques have been applied. However, the output emission of an iodine-stabilized laser is always frequency-modulated exhibiting a dithering typically in the kHz range with a ~6 MHz amplitude [18, 21], which is equivalent to a relative deviation of $12.6 \cdot 10^{-9}$. However, all these techniques have in common that the iodine absorption peaks have to be identified by using an automatic identification algorithm. This algorithm has to find reliably the correct line in the middle of several multiplets. Moreover, the system has to be realized in such a fashion that the user is able to detect an erroneous locking state and can initiate appropriate actions to correct the locking procedure [10]. In order to guarantee a stable operation of the laser stabilization the mechanical structure has to be optimized. Following that, the metrological frames of such laser wavelength standards operating at national metrology institutes are mainly built up with ultra-low expansion materials, such as Zerodur® [22], Invar® [18, 23] or Super-Invar® [10]. Because metrology He-Ne lasers emit less than 1.5 mW on a single mode, only a small optical power can be used for its stabilization in comparison to a solid state laser systems with up to 100 mW [24]. That is the reason why the iodine absorption cell is not part of a separated control loop and has to be integrated in an intracavity fashion, where an intracavity beam power of $10 \pm 5$mW is guaranteed. If the recommendations of *mise en practique* [25] are met a relative uncertainty of the He-Ne laser frequency of about $21 \cdot 10^{-12}$ is achievable. The user has to guarantee that the setup is operating under well-known operating conditions [11], because the emitted wavelength is closely connected with the purity [26], temperature and pressure of the mixture inside the iodine cell [27] and power-induced frequency shiftings [28]. An iodine-stabilized laser is additionally susceptible to the optical feedback of reflected light [1], which is hard to identify and to prevent [27]. Hence, the wavelength standard is supposed to be traced in periodical intervals back to another wavelength standard to verify its proper operation, for example by comparison with other iodine-stabilized lasers [28] or an optical frequency comb [29].

Derived from this, an iodine-stabilized He-Ne laser has two major drawbacks if its wavelength is used directly for interferometric measurements in the NPMM-200. At first, the output of such an iodine-stabilized laser is always modulated in frequency and this disadvantage is a non-neglible fact when another laser is supposed to be locked onto this standard [11]. A correction of this frequency-modulated output can be realized [21] but requires comparably complex technical measures. Secondly, the limited optical power of this wavelength standard can only be used for a single interferometer axis and prevents usually a fiber-coupled setup, as well. At this point we had to decide to build up a laser array as proposed in [1, 2], where the stability of an iodine-stabilized laser is to be transferred over a fly wheel He-Ne laser [21] to our metrology lasers. Taking into account the abovementioned characteristics and drawbacks of an iodine-stabilized laser, an optical frequency comb appeared to us as a more straightforward and advantageous wavelength reference for the metrology lasers of the NPMM-200.

### 2.3 The femtosecond comb as an optical frequency ruler

An alternative standard to the iodine-stabilized He-Ne lasers has arisen with the advent of the optical frequency comb technology, which has been introduced in 1999/2000 [30]. After its introduction the frequency comb was immediately used for characterizing the existing wavelength standards, especially iodine-stabilized He-Ne lasers. Since that, the relative uncertainty of the frequency comb technology has been enhanced down to $80 \cdot 10^{-21}$ [31] over long-term measurements times ($t > 10000$s) and enables scientists to measure simply optical frequencies. A relative stability of typically $2.4 \cdot 10^{-12}$ can be achieved over an integration time of $t = 1$ s with commercial systems [32]. This stated level of stability is mainly limited by the applied GPS-disciplined oscillator (GPSDO), which serves mostly as an affordable RF standard [31]. Up to now, this technology has been used to calibrate the wavelength of stabilized lasers, but has not been used to transfer its outstanding long-term stability to a He-Ne gas laser.

However, there are four main advantages to link a He-Ne laser to an optical frequency comb to generate a so-called secondary standard (referring to [1]). At first, the control signal can be derived from the heterodyne beat node between a single frequency comb line and the laser to be stabilized. The unmodulated laser output is supposed to be used directly for the calibration of other wavelengths or to provide a highly stable wavelength for interferometer measurements. Secondly, as will be discussed later, a simple stabilization of such a secondary standard can be realized with a few parts of the overall output power guarenteeing robust operation and is the capability to preserve most of the output power for further fiber-coupled interferometer applications. Thirdly, the wavelength of the secondary standard can easily be changed by tuning the frequency comb line, which enables a tunability in steps of a few mHz over the 1.5 GHz wide gain profile of the He-Ne gas laser. In the Table 1 the main features of an iodine-stabilized standard are listed in contrast with those of an optical frequency comb (OFC)-stabilized standard. Lastly, such a secondary standard is supposed to be an excellent tool to characterize lasers under test in a more straightforward manner by simply detecting a heterodyne beat node.

We denote that no acousto-optical or electro-optical modulators have to be applied to set up such a direct link to the optical frequency comb. Additionally, no other modulation instrument (frequency synthesizer) and demodulation instrument (phase sensitive detectors, such as lock-in amplifiers) have to be applied and handled by the user. The instrumentation complexity for this approach is considerable low, because only a beat frequency evaluation system and a single digital-to-analog converter (DAC) is needed and that can in general be realized with a modern signal processing system.

*Table 1. Summary table indicating the main aspects of a wavelength standard making use of either an iodine-stabilized or an optical-frequency-comb-stabilized system.*

| **Feature** | **Iodine-stabilized wavelength standard** | **OFC-stabilized wavelength standard** |
|---|---|---|
| Laser Type | He-Ne gas laser | He-Ne gas laser |
| Wavelength | 633 nm | 633 nm |
| Reference standard | Intracavity iodine cell | Time standard (GPS) |
| Output modulation | Necessary (ca. 6 MHz) | Not necessary |
| Control variable detection | Scanning a hyperfine structure of the iodine absorption spectrum | Heterodyning with a single frequency comb line |
| Typical optical power | 100 μW | 1000 μW |
| Fiber-coupled system | no | yes |
| Tunability | discrete | continuous |
| Robustness | moderate | high |

## 3. SYSTEM DESCRIPTION

In the following sections we will describe the experimental setup to link a He-Ne gas laser directly to a single frequency comb line to form a secondary standard with high power and reduced phase noise. The key to stabilize both systems with each other is a high performance data processing and control system, which will be discussed in the following section. In a further step we will connect another laser to this secondary standard to carry out a metrology laser. Finally, both lasers are supposed to be controlled by independent FPGA-based systems to realize spatially separated subsystems in the future.

### 3.1 Laser system with two internal-mirror He-Ne tubes

The laser system to be linked on a single frequency comb line consists of two independent He-Ne lasers resonators, which are commercially available components (Model: SL02/1, SIOS Meßtechnik GmbH) and exhibit similar characteristics in terms of mechanical design and transfer behavior. The equal cavities manufactured by JDS Uniphase (Model: 1003P) were specified with a length of 216 mm [9] and consisted of glass with a thermal expansion coefficient of less than $5 \cdot 10^{-6}\,K^{-1}$. Each cavity was coated with a silver layer to form a bifilar heating coil with a resistance of 6-8 Ω. We were able to detect a longitudinal mode spacing of 725.2 MHz during stabilized operating conditions at a temperature of about 70°C and measured an optical power of 245 μW for one polarization mode after the fiber coupling. The cavity was filled with $He^4$ and a mixture of $Ne^{20}$ and $Ne^{22}$ to broaden the gain profile [33]. It is worth to mention that the mechanical framework of each laser system has not been upgraded by using ultra-low expansion materials. In contrast to off-the-shelf laser systems, the switching power supplies of both laser tubes were upgraded each with a state-of-the-art model (Model: 121T-1700-4.9, Martek Power) and the power cablings were optimized to suppress side peaks and high frequent distortions ($f_{PS} > 700\,kHz$), which provided an instrumentation noise floor level of less than -90 db [34]. Referring to [34], the linewidth of each He-Ne laser light source have also been subject of investigations and was determined to a value of about 1.5 kHz at this setup.

In other words, the gas laser represents a wavelength standard with low phase noise and high optical power [1]. But the long-term stability of this laser has been restricted so far by its stabilization method and its sensitivity to ambient perturbations, which yields to a relative long-term stability in our laboratory of about $0.5 \cdot 10^{-9}$ over integration times more than 10 000 s during measurements against an optical frequency comb. Short-term perturbations at each tube can be cancelled out with a dynamic behavior of 30 MHz/s by closed-loop operations featuring a bandwidth of up to 10 kHz.

### 3.2 Commercial optical frequency comb

The frequency comb in our experimental setup is a commercially available system (Model: FS1500, MenloSystems) featuring a mode-locked polarization maintaining erbium fiber laser operating at a center wavelength of 1552 nm. The default specification for the repetition rate $f_{\mathrm{REP}}$ and carrier envelope offset frequency $f_{\mathrm{CEO}}$ are 250 MHz and 20 MHz, respectively. The frequency of a single frequency comb line $\nu_{\mathrm{CL}}$ can be evaluated by the mode number $N$ determined by using a wavemeter (Model: WLM-VIS, High Finesse), the repetition rate $f_{\mathrm{REP}}$ and the offset frequency $f_{\mathrm{CEO}}$:

$$f_{\mathrm{CL}} = N \cdot f_{\mathrm{REP}} + f_{\mathrm{CEO}} \, .$$

A second output of the fiber laser is fed to an erbium-doped fiber amplifier (EDFA) with subsequent broadening in a highly nonlinear fiber (HNLF). The 633 nm wavelength is subsequently created by a second harmonic generation (SHG) in a periodically poled lithium niobate waveguide and provides an average optical power of about 7 mW at a spectral width of 3 nm (FWHM). This output carries ~9000 amplified frequency comb lines and one of these lines is used to generate a beat node with the light of the aforementioned secondary standard. This beat node is subsequently used to stabilize our laser system in a two-step procedure, which will be discussed in the following sections § 3.3 – 4.

The relative stability of each frequency comb line of $2.4 \cdot 10^{-12}$ an integration time of 1 s is derived from the time standard, which is the aforementioned GPS disciplined oscillator (GPDSO). This value is equivalent to a comb line dithering of $\Delta f_{\mathrm{CL}} = 1.1$ kHz at a wavelength of around $\nu_{\mathrm{CL}} \approx 473.612$ THz ($N = 1894449$). It is worth to mention that the phase noise of a time standard, e.g. quarz oscillator, is transferred into the optical domain by the multiplication of repetition rate fluctuations with the repective mode number [35]. Therefore, frequency combs referenced to such a GPSDO standard exhibit linewidths in the order of a few hundred Hz [36].

The data acquisition sub-system of the commercial instrument includes up to four Π-type frequency counters (CNT, Model: FXM50), with which the repetition rate (CNT0), carrier-envelope frequency (CNT1) and beat frequencies of two systems under test (CNT2, CNT3) can be measured.

### 3.3 Locking the secondary standard to the frequency comb line

As shown in Figure 2, the light of the secondary standard and the frequency comb are superposed with each other at a beat detection unit. This unit consists of several optical components to align both beams and to generate an optical interference signal, which is then falling onto an avalanche photo diode with a bandwidth up to 1 GHz (APD, Model: APD210, MenloSystems). This optical signal $f_{\mathrm{Beat/SS}}$ is converted into a photo current and is then converted with a transimpedance gain of $G_{\mathrm{APD210}} = 250 \cdot 10^{3}$ V/W into a voltage signal. After the fiber coupling an optical power of about 245 µW was measured, which is because of a non-perfect coupling. This analog signal is buried in noise and represents the input for the data acquisition system of the commercial frequency comb as well as the FPGA-based control system (henceforth, referred to as “FlexRIO-System”). The latter consists of a controller (Model: NI-7935, National Instruments) and a high-speed transceiver module (Model: NI-5782, National Instruments). The transceiver module has two analog-to-digital converters (ADC) with a sampling rate of up to 250 MS/s and a signal-to-noise ratio (SNR) of 70 dB, which are used to convert the analog into digital signals. The embedded FPGA unit (Model: Kintex-7-K410T, Xilinx) enabled us to implement a user-defined frequency detection method, whose basic approach is shown schematically in Figure 3. The proposed method is based on a phase-sensitive method and not on a conventionally used edge-detecting method, which goes along with pros and cons. With our system the beat frequency can be correctly singled out even at a low SNR of less than 10 dB, while conventional methods require a SNR of at least 30 dB. But nothing comes for free, our system can determine beat frequencies merely within a corridor of ±1.5 MHz around the fixed center frequency of 62.5 MHz. The width of 3 MHz is still sufficient to detect frequency deviations of most laser models. The filtering is due to a 128-pole digital low-pass, which suppresses spectral components of more than 5 MHz around the fixed mid-frequency with an attenuation of -123 dB. The first demodulation stage delivers sine and cosine variables with a data output rate of 15.625 MS/s. In the next stage these variables are used to determine the phase relationship between the external beat frequency signal and the internal reference signal by using a CORDIC-based arctangent function (ATAN2, [37]). The latter signal is directly connected with the GPSDO time reference. The resulting phase values have a width of 48 bit, so that the frequency can be subdivided down to 0.1 mHz. The discrete subtraction of each phase value to the previous one over a time slot of 64 ns results in a frequency variable, which is then filtered with a 48-pole low-pass featuring a bandwidth of 1 MHz. This final value represents the process variable of a simple PID control algorithm, which has an update rate of up to $f_{\mathrm{S}} = 1$ MHz. By means of the PID control a regulation variable is processed, which is then outputted to a power electronics as a DC coupled voltage signal using a DAC with a resolving capability of 20 bit (Model: AD5791, Analog Devices).

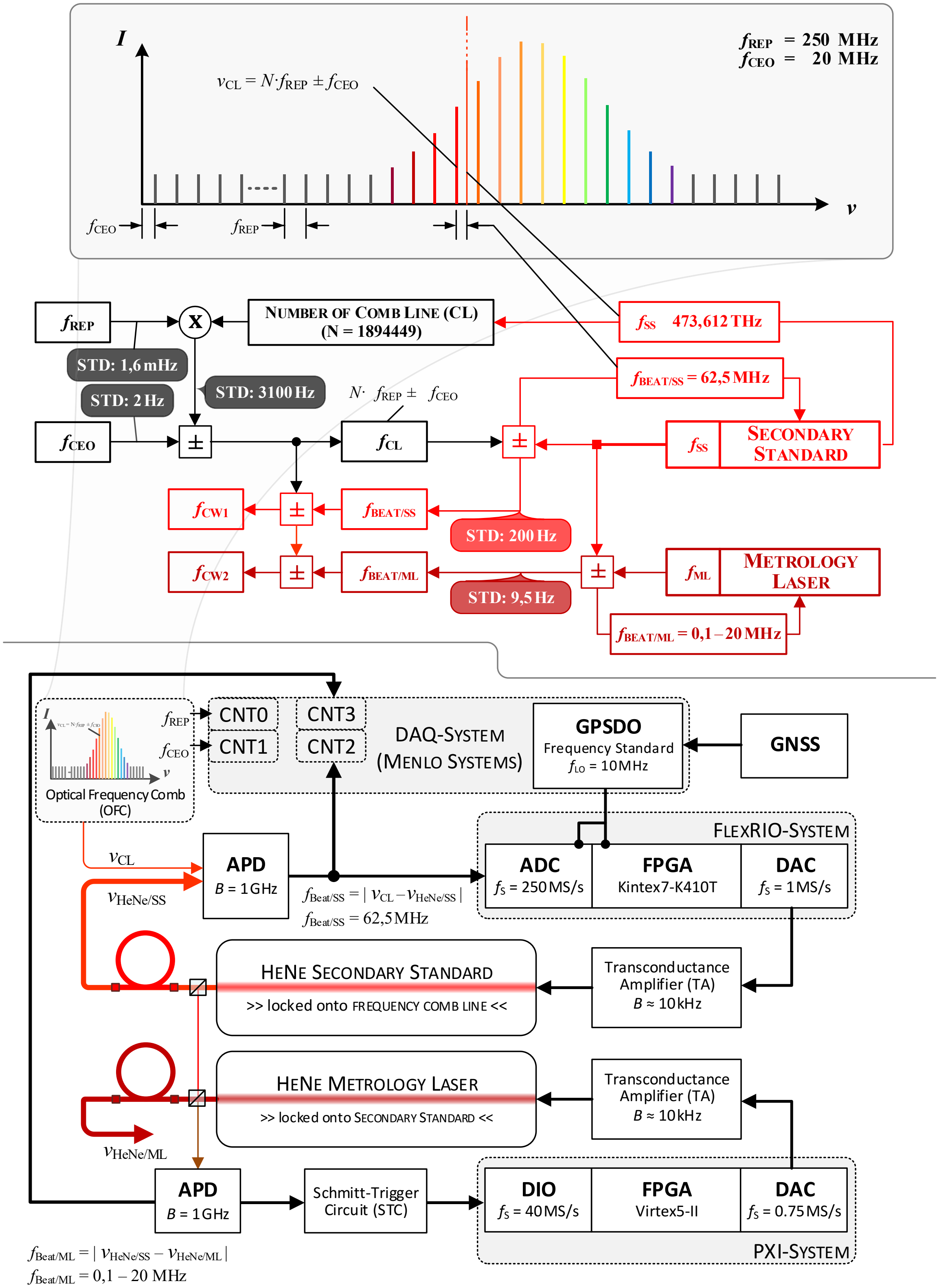

*Figure 2. Schematic representation of (a) the block diagram with the corresponding beat signals to lock the secondary standard onto a frequency comb line as well as the metrology laser (ML) onto the secondary standard (SS) and (b) the data acquisition (DAQ) and control electronics to detect the beat frequencies. The measured standard deviations (STD) are subject of discussion in section §4.*

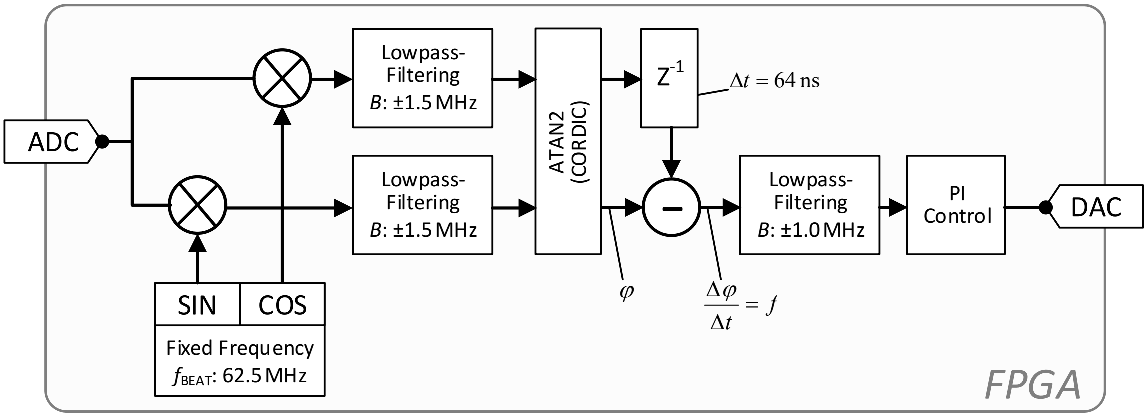

*Figure 3. Block diagram of the digital signal processing algorithm to process a control variable (frequency f) to regulate the secondary standard, which is locked onto the frequency comb line by using the heterodyning beat node sampled with an analog-to-digital converter.*

The locking procedure was realized in the two following steps. First, the comb line frequency was adjusted by changing $f_{\text{REP}}$ to be close to the center frequency while the He-Ne laser was still frequency-stabilized using its internal control loop. Secondly, the control was instantaneously changed using a hardware switch to close the loop with the proposed FPGA-based control. After that, the parameters of the PID control were empirically adjusted for a less dynamic response behavior to avoid unwanted oscillations by a high control loop gain. It turned out that this lock required only an optical power of about 3 µW and was exceptionally robust. The secondary standard could be locked over 12 days without any significant outliers and during the normal laboratory conditions, which includes slamming doors and temperature variations up to 5 K over 600 s by opening windows.

### 3.4 Locking the metrology laser to the secondary standard

As shown in Figure 2, the light of the secondary standard and the metrology laser are superposed with each other at an avalanche photo receiver in a free space fashion. Approximately 8 µW of power from the secondary standard falls on the photo receiver (Model: C5658, Hamamatsu Photonics), along with approximately 100 µW from the metrology laser, resulting in a beat signal $f_{\text{Beat/ML}}$ of 1.2 Vpp (at 1 MΩ resistor termination) with a SNR of about 50 dB at 1 GHz bandwidth. This current signal was converted with a transimpedance gain of $G_{\text{C5658}} = 250 \cdot 10^3$ V/W into a voltage signal. This analog signal is transferred into a discrete signal with TTL level by using a Schmitt-Trigger circuit and represents the input for another FPGA-based control system (referred to as "PXI-system") to lock the metrology laser onto the secondary standard. At this point, the authors refer to previous publications [34, 38], in which the developed control system has already been described in detail. The basic method makes use of only a single digital input and one digital-to-analog converter to offset-lock two lasers with a beat frequency $f_{\text{Beat/ML}}$ between 0.1 MHz and 20 MHz at our setup. For the experiments in section § 4 a beat frequency $f_{\text{Beat/ML}}$ of 4 MHz was chosen. The PXI-system is easily scalable, because eight metrology lasers can be controlled by a single FPGA card (Model: PXI-7853R, National Instruments) and seven cards can be plugged into the existing chassis (Model: PXI-1042Q, National Instruments). In theory, the electronic system enables us to link up to 56 metrology lasers to the secondary standard while all of them are operating at the same wavelength.

The authors want to emphasize that both FPGA-based control systems run independently and ensure a spatially separated operation of both lasers, whose lights can be transferred by fiber-coupling technology and this enables us to build up a link between each other over long distances. Additionally, the application of fibers with angle polished connectors (APC) reduces the impact of back reflections and minimizes an unwanted feedback into the laser cavity.

## 4. EXPERIMENTAL RESULTS

The performance of both offset-locked lasers has been evaluated with frequency counters of the commercial system. The beat frequency of the secondary standard $f_{\text{Beat/SS}}$ is measured with a signal input (CNT3). The input signal detection is limited by a lowpass-filter to frequencies within a corridor of ±10 MHz around a fixed center frequency of 60 MHz. The beat frequency of the metrology laser $f_{\text{Beat/ML}}$ is measured with a different signal input (CNT4). This input signal is not limited in its bandwidth by using low-pass filtering techniques. The time standard of the counting electronics operated on the basis of the same GPSDO reference. This data acquisition setup enabled us to detect synchronously the beat frequencies by using the same type of frequency counter. In the following, the proposed setup has been investigated in two different setups.

At first, the frequency comb has been operated with the default operating parameters of the PI control loops for the carrier-envelope oscillation ($f_{\mathrm{CEO}}$) and repetition rate ($f_{\mathrm{REP}}$) stabilization. The secondardy standard has been locked onto a single frequency comb line. The beat frequency variations $\Delta f_{\mathrm{Beat/SS}}$ representing the difference between the comb line and the HeNe gas laser are shown as a red curve in Figure 4.a) and exhibited a peak-to-peak deviation of less than 2.5 kHz. The stability of the comb line was subject of a jittering of the repetition rate ($\Delta f_{\mathrm{REP}}$) multiplied with the mode number ($N$) and the carrier-envelope offset frequency ($\Delta f_{\mathrm{CEO}}$). The addition of the three frequency variations resulted in an overall jitter ($\Delta f_{\mathrm{CW1}}$), while the influence of $\Delta f_{\mathrm{CEO}}$ could be neglected. The same set of data consisting of frequency values acquired with an integration time of 1 s and over a measurement time of 9000 s was subsequently processed to evaluate the Allan deviation relatively to the absolute frequency of about 473.612 THz, which is shown in Figure 4.b). The relative Allan deviations over shifting integration times indicated the impact of the various variations. The impact of the repetition rate ($\Delta f_{\mathrm{REP}}$) on the overall jitter ($\Delta f_{\mathrm{CW1}}$, black color) decreased down to a integration time of 300 s, while the beat frequency variation ($\Delta f_{\mathrm{Beat/SS}}$, red color) was the major influence at integration times higher than 300 s. At an integration time of 1 s the relative stability of the overall fluctuation and the offset-locked secondary standard was mainly limited by the comb line jittering, which resulted in Allan deviations of 1.1 kHz ($2.4 \cdot 10^{-12}$) and 300 Hz ($0.6 \cdot 10^{-12}$), respectively. This jittering in the optical domain was presumably caused by the noise characteristics of the GPS disciplined oscillator in the time domain. We observed fluctuations of more than 200 kHz using a spectrum analyzer at a residual bandwidth of RBW = 10 kHz (Model: HMS-X, Rohde & Schwarz), which was comparable to former results measured with a fiber-based frequency comb [36]. We assume that the offset-locked secondary standard was not capable to follow the comb line jitters.

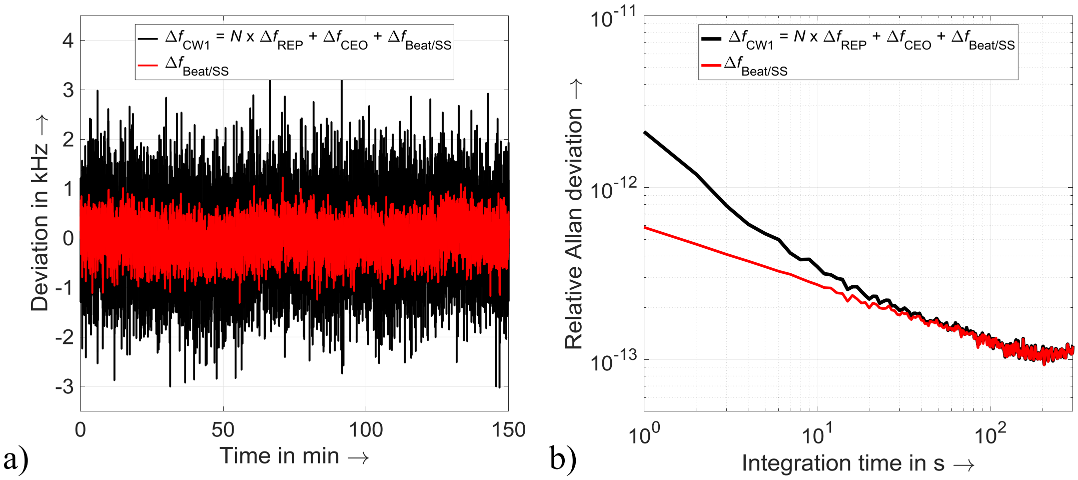

*Figure 4. First measurement results to determine the characteristics of the offset-lock between the secondary standard and the optical frequency comb over a measurement time of 9000 s. The left-side plot shows the frequency deviation of the* $f_{\mathrm{CW1}}$ ($\Delta f_{\mathrm{CL}} + \Delta f_{\mathrm{Beat/SS}}$*, black curve*) *and* $\Delta f_{\mathrm{Beat/SS}}$ (*red curve*) *while the right-side plot shows the corresponding relative Allan deviation. The measurement results were captured with the data acquisition system of the manufacturer Menlo Systems, which was based on a Π-type frequency counter.*

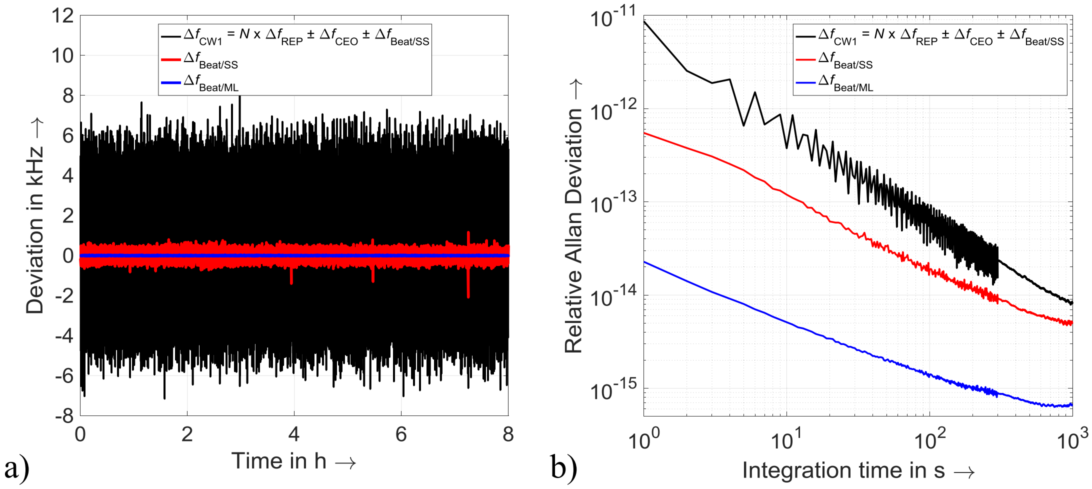

*Figure 5. Measurement results of the laser system in the time domain and over shifting integration times after evaluating the relative Allan deviation. The black curves show the frequency deviation* $\Delta f_{\mathrm{CW1}}$ *between the frequency comb line and the secondary standard caused by the beat frequency deviation* $\Delta f_{\mathrm{Beat/SS}}$ *(red curve) and the comb line jittering (*$N \cdot \Delta f_{\mathrm{REP}} \pm \Delta f_{\mathrm{CEO}}$*). The blue curves show the beat frequency deviation* $\Delta f_{\mathrm{Beat/ML}}$ *between both He-Ne lasers, which is up to two orders less than* $\Delta f_{\mathrm{CW1}}$*.*

Secondly, we modified the control parameters at the frequency comb to change the impact of high frequent distortions caused by control loop stabilizing the repetition rate. The parameters of the control loop were changed from -10 dB to -18 dB for the proportional term and from 1000 Hz to 10 Hz for the integration term of the PI controller, which resulted in a more slowly control response behavior. Moreover, the beat frequency stabilities of the secondary standard ($\Delta f_{\mathrm{Beat/SS}}$) and the metrology laser ($\Delta f_{\mathrm{Beat/ML}}$) were investigated in the following measurements. The measurement results shown in Figure 5 are comparable to the former presented results in Figure 4, but two features had changed. The fluctuations of the repetition rate ($\Delta f_{\mathrm{REP}}$) had a greater influence on the overall fluctuation due to the limited dynamic of the dedicated PI controller, which led to an increased overall jittering ($\Delta f_{\mathrm{CW1}}$) resulting in a two-fold increase (from 3 kHz to about 6 kHz at $\tau = 1$ s), while the beat frequency variations $\Delta f_{\mathrm{Beat/SS}}$ were similar to the prior measurement results. Additionally, the behavior of the metrology laser locked onto the secondary standard was verified by measuring the beat frequency $f_{\mathrm{Beat/ML}}$·(blue curve). At an integration time of 1 s the fluctuations $\Delta f_{\mathrm{Beat/ML}}$ had a value of 10 Hz, which is equivalent to a relative Allan deviation of $20 \cdot 10^{-15}$. At an integration time of $\tau = 1000$ s the relative Allan deviation was reduced to a level of $0.6 \cdot 10^{-15}$. Consequently, the metrology laser featuring a similar transfer behavior as the secondary standard could be locked with a thirty-fold improved stability comparing to the secondary standard lock onto the frequency comb line. We assume that a secondary standard can be locked onto a frequency comb line with the same stability behavior if high frequent distortions of the comb line can be minimized to such a level of stability. A stabilization on an external cavity is often used to increase short-term stability at $\tau < 1$ s [39] since the short-term stability is finally limited by the phase noise of the time standard. Additionally, fiber-based distribution techniques are also promising alternative to serve as a time reference with reduced phase noise.

## 5. CONCLUSION AND OUTLOOK

Since decades the helium-neon laser at 633 nm is the light source of choice in the vast majority of metrology applications. In this contribution we have offset-locked, to our knowledge for the first time, a He-Ne laser onto a single comb line of an optical frequency comb. The measurement results show that the offset-locked laser is suitable to provide relative stabilities of about $2.4 \cdot 10^{-12}$ ($\tau = 1$ s), which is mainly limited by the applied time standard of the frequency comb. This level of performance has not been achieved by now with an iodine-stabilized He-Ne laser representing an internally accepted secondary representation of the SI-unit second. Further results between two He-Ne lasers have shown that a relative stability of about $0.6 \cdot 10^{-15}$ ($\tau = 1000$ s) is achievable. We believe that metrology lasers locked onto an optical frequency comb will become a state-of-art technique to realize interferometer measurements in the sub-nanometer range. Recent developments on the field of optical frequency combs have turned out that these measuring instruments become more compact and affordable [40, 41].

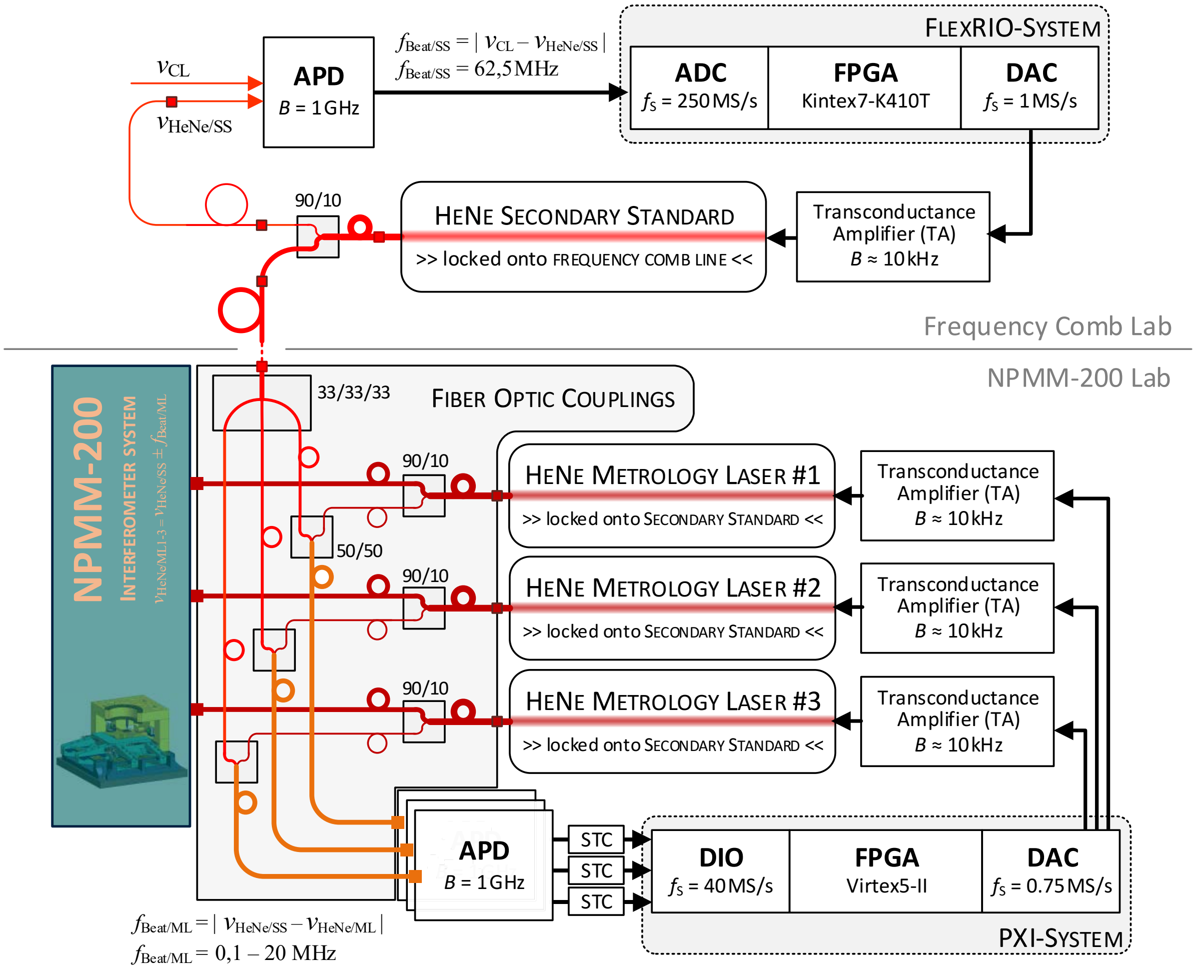

*Figure 6. Schematic overview of the future system to link metrology lasers of the NPMM-200 onto a secondary standard, which is connected with a frequency comb line. The metrology lasers can spatially be separated to the secondary standard and optical frequency comb by means of a polarization maintaining fiber delivery between two laboratories.*

Moreover, the impact of refractive index changes in air or vacuum can be investigated in a more straightforward way if frequency fluctuations of the metrology lasers are neglectable. We assume that He-Ne lasers will still play an important role as metrology lasers in the future, although the basic concept has been proposed almost six decades ago. These light sources still outperform laser diodes particularly with regard to beam shape, lifetime, mode-hopping and intrinsic linewidth at this wavelength and are less costly than solid-state lasers, such as Nd:YAG systems in the visible spectrum. We aim to realize a setup in which all metrology lasers of our machine are linked to a secondary standard, which is directly connected with a comb line. A schematic setup for a potential future setup with a fully fiber-coupled arrangement is displayed in Figure 6, which will be subject of discussion within further publications.

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