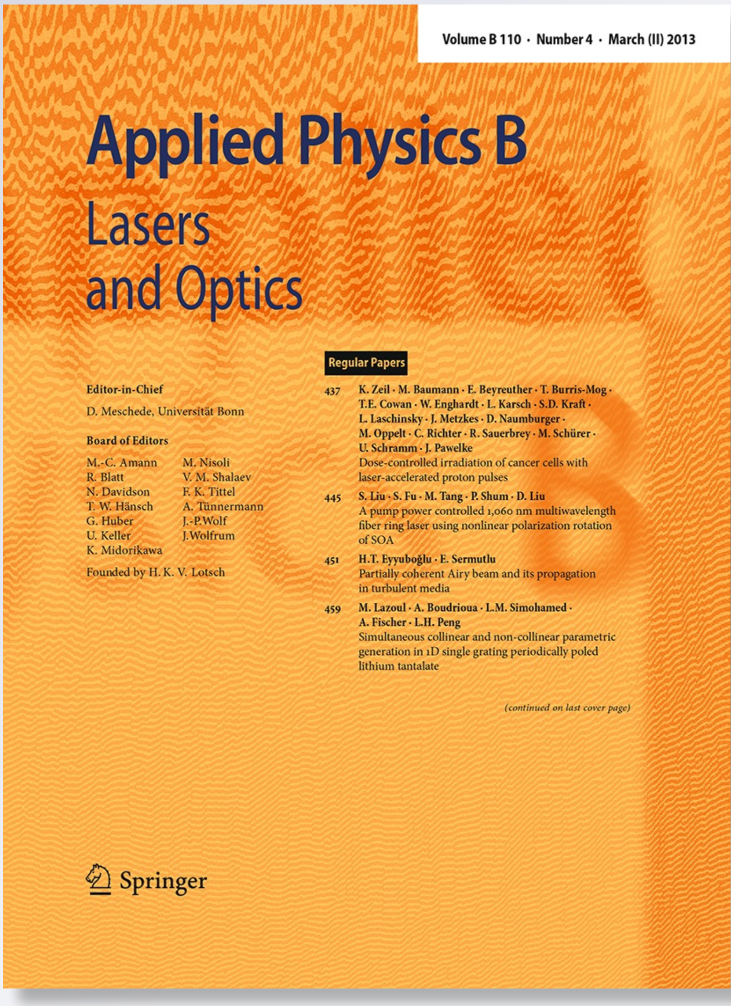
Subhertz-linewidth infrared frequency source with a long-term instability below 5×10^{-15}

S. M. F. Raupach, T. Legero, C. Grebing, Ch. Hagemann, T. Kessler, A. Koczwara, B. Lipphardt, M. Misera, H. Schnatz, G. Grosche, et al.

Applied Physics B
Lasers and Optics

ISSN 0946-2171
Volume 110
Number 4

Appl. Phys. B (2013) 110:465-470
DOI 10.1007/s00340-012-5280-6



Springer

Your article is protected by copyright and all rights are held exclusively by Springer-Verlag Berlin Heidelberg. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your work, please use the accepted author's version for posting to your own website or your institution's repository. You may further deposit the accepted author's version on a funder's repository at a funder's request, provided it is not made publicly available until 12 months after publication.

Author's personal copy

Appl. Phys. B (2013) 110:465–470
DOI 10.1007/s00340-012-5280-6

Applied Physics B
Lasers and Optics

Subhertz-linewidth infrared frequency source with a long-term instability below 5×10^{-15}

S. M. F. Raupach · T. Legero · C. Grebing · Ch. Hagemann · T. Kessler · A. Koczwara · B. Lipphardt · M. Misera · H. Schnatz · G. Grosche · U. Sterr

Accepted: 16 August 2012 / Published online: 23 December 2012
© Springer-Verlag Berlin Heidelberg 2012

Abstract Distributing a stable, absolute optical reference frequency via fiber network would serve research and development in academia and industry. Lasers stabilized to high-finesse Fabry–Pérot cavities can achieve fractional frequency instabilities of less than 10^{-15} for periods up to several seconds. Their instabilities increase for longer averaging times due to a variable frequency drift, with a linear drift component of the order of 10…100 mHz/s. Hydrogen masers, on the other hand, yield an instability floor of a few parts in 10^{-15}, but suffer from poor stabilities on short timescales. We demonstrate an infrared optical frequency source that combines a cavity-stabilized laser with a hydrogen maser to achieve a residual fractional frequency instability better than 5×10^{-15} for all averaging times from 0.4 up to 10,000 s. The frequency drift of the system over a period of 40,000 s is less than 30 μHz/s. For obtaining absolute frequency accuracy, the hydrogen maser is referenced to a primary frequency standard.

1 Introduction

For a wide range of applications, such as spectroscopy or laser development, it would be convenient to have a stable optical reference frequency available, which could be provided, e.g., by national metrological institutes via fiber networks [1].

S. M. F. Raupach (✉) · T. Legero · C. Grebing · Ch. Hagemann · T. Kessler · A. Koczwara · B. Lipphardt · M. Misera · H. Schnatz · G. Grosche · U. Sterr
Physikalisch Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
e-mail: sebastian.raupach@ptb.de

Lasers stabilized to Fabry–Pérot cavities have demonstrated short-term frequency instabilities of the order of 10^{-15} and below [2–4], making them a tool of pivotal importance in a variety of cutting-edge research fields in frequency metrology. Among these are precision spectroscopy of hydrogen [5, 6], and the development of optical atomic clocks, where narrow electronic transitions of ultracold, trapped atoms or ions serve as highly stable and accurate frequency references [7–11]. Pre-stabilized lasers locked to atomic references achieve a measurement uncertainty of 8.6×10^{-18} [9] and residual instabilities (Allan deviation) falling off as $3 \times 10^{-15}\ (\tau/\mathrm{s})^{-1/2}$ when averaging over times τ; recent measurements are even consistent with an instability of $5 \times 10^{-16}\ (\tau/\mathrm{s})^{-1/2}$ [3]. Narrow-linewidth lasers are furthermore applied in the characterization of fiber links dedicated to long-haul precision frequency dissemination [12].

On timescales above 10 to 100 s, a cavity-stabilized laser's frequency performance suffers from drifts of the order of 10…100 mHz/s or more, corresponding roughly to 10^{-16}/s. This restricts the lasers' application to experiments performed with averaging times of seconds or below. The drift can be attributed to, e.g., aging of the cavity spacer made of amorphous material such as ultralow expansion (ULE) glass [13], or to varying mechanical forces and residual temperature fluctuations.

To reduce a cavity-stabilized laser's frequency drift and slow frequency fluctuations, apart from using transitions in trapped ultracold particles as a frequency reference as in optical clocks, there exist different strategies: one possibility is to use cryogenically cooled cavities made of special material such as sapphire or silicon monocrystals. Here, long-term linear drift rates of less than 200 μHz/s at a wavelength of 1,064 nm (7×10^{-19}/s) were observed [14], and even lower rates seem achievable [4]. Another

Author's personal copy

way is to correct for the frequency drift in regular intervals by probing spectral holes burnt into a liquid-helium-cooled, doped crystal [15, 16]. Here, special care has to be taken to minimize any variations of the ambient temperature and pressure. In recent experiments, a drift rate of (5 ± 3) mHz/s was observed, and spectral holes were used to stabilize a laser to 6×10^{-16} for averaging times between 2 and 8 s [15, 16]. Unlike absorption lines of ultracold trapped particles, however, spectral holes cannot serve as absolute frequency standards.

In the microwave regime, hydrogen masers (H-masers) serve as a stable frequency source, where the H-maser can further be referenced to or steered towards a primary frequency standard [18]. The maser's performance can be transferred into the optical domain by locking a femtosecond frequency comb [17] to it. On short timescales, however, this leads to relatively high levels of instability typical of an H-maser.

We seek to develop a system, which can serve as an optical absolute frequency source. By combining an active H-maser and a cavity-stabilized laser, a performance superior to typical H-maser referenced frequency combs is achieved. When located in the appropriate infrared region, such a frequency can be distributed very accurately using long-range phase-stabilized fiber links [1, 19, 20].

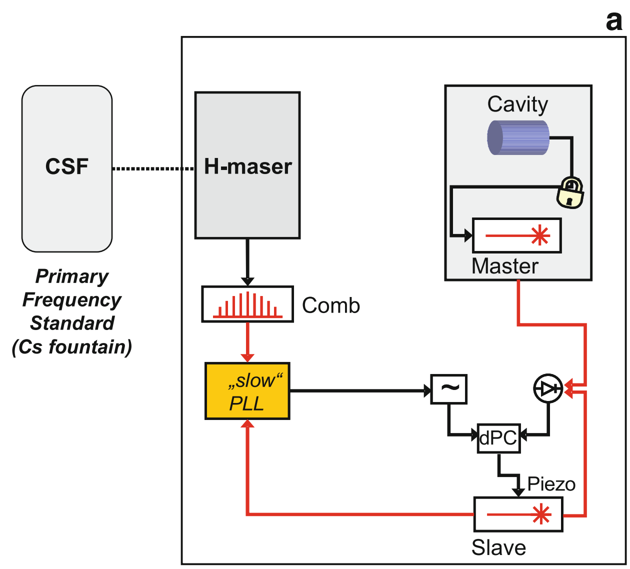
In the following, we present a tuneable optical frequency source at 1.5 μm, that traces the phase of an H-maser and displays its long-term stability for averaging times beyond 100 s, while at the same time offering a linewidth of less than 1 Hz and yielding a fractional instability below 5×10^{-15} also in the intermediate range. By referencing the H-maser to the SI second, e.g., via GPS, such a system provides absolute frequency accuracy.

2 Experimental setup

Our scheme links a cavity-stabilized laser and a long-term stable radio frequency (rf) reference equipment readily available at laboratories dealing with frequency metrology. The approach is similar to a scheme used for stabilizing the microwave interrogation oscillator for a cesium fountain clock at PTB [21]. Our setup, where a slave laser is locked to a cavity-stabilized master laser and, via a frequency comb, to an H-maser, is depicted schematically in Fig. 1.

To evaluate the system, two separate and largely independent setups were realized, as would also be the case for implementations in different institutes connected by a fiber link.

For evaluation, we wish to obtain three beat frequencies. To measure their relative frequency drift, we record the beat frequency between the cavity-stabilized master lasers. Secondly, to illustrate the relative stability of the hydrogen-maser



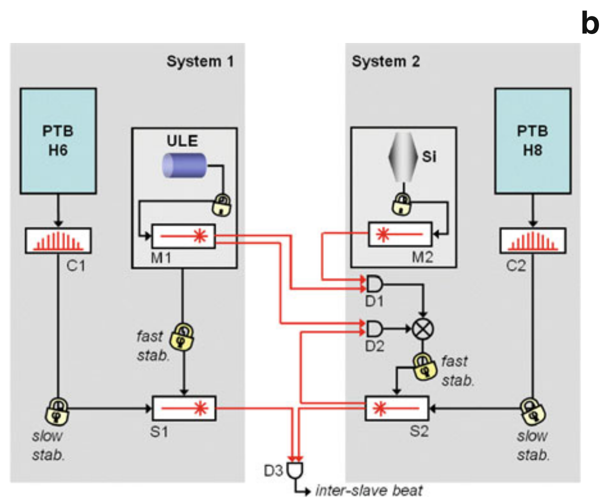


Fig. 1 Schematic sketch of the two setups used for the experiments described here. **a** The general setup is presented, **b** the dual implementation (without the reference to the cesium fountain). A slave laser (*S1*, *S2*) is stabilized simultaneously to a cavity-stabilized master laser (*M1*, *M2*), where the cavities are made from *ULE* glass and silicon, respectively, and an H-maser driven frequency comb (*C1*, *C2*). The low-pass filtered error signal of the stabilization to the comb slowly tunes the reference frequency used for the lock of the slave laser to its master laser. The experiment is set up twice, to allow for measurements of the signals' stabilities; *H6*, *H8* H-masers, *D1*, *D2*, *D3* photo detectors, *PLL* phase-locked loop, *dPC* digital phase comparator

referenced frequency combs, the beat frequency between two comb modes of the two frequency combs is obtained. To determine the overall stability obtained by simultaneous stabilization to the master lasers and—via the frequency combs—to the hydrogen masers, the beat frequency between the slave lasers is recorded.

Two infrared fiber lasers (194 THz), a distributed feedback (DFB) laser (M1; Adjustik/Koheras [30]) and a

Author's personal copy

distributed Bragg reflector laser (M2; Scorpio/NP Photonics [30]) with a free running linewidth of several Kilohertz are stabilized to Fabry–Pérot cavities made of ULE (M1; operating temperature 300 K, length 0.1 m) and silicon (M2; operating temperature 124 K, length 0.21 m) [4]. The output frequency of the lasers can be tuned by changing the temperature setpoint as well as mechanically using a built-in piezo-electric transducer (PZT).

The lasers act as master lasers providing the required short-term stability and exhibit a typical relative frequency drift of around 100 mHz/s.

The master lasers are located in the same room, where the inter-master beat frequency is measured locally. This radio frequency is tracked electronically and sent to a second room, where the slave lasers are located. Additionally, the light of one of the master lasers (M1) is transferred to the second laboratory via a short phase-stabilized fiber link.

A second DFB fiber laser is locked to each master laser as a slave laser (S1, S2; Adjustik/Koheras [30]) using the PZT for fast frequency control (10 kHz bandwidth). One of the slaves (S1) is locked directly to its master (M1) by obtaining the beat note of the optical signals $(\nu_{\mathbf{M1}} - \nu_{\mathbf{S1}})$. For the second slave laser (S2), its beat frequency against the same master laser $(\nu_{\mathbf{M1}} - \nu_{\mathbf{S2}})$ is measured and mixed electronically with the inter-master beat frequency $(\nu_{\mathbf{M2}} - \nu_{\mathbf{M1}})$ to obtain the beat frequency $\nu_{\mathbf{M2}} - \nu_{\mathbf{S2}}$ used for the lock.

Additionally, we measure the beat frequency between each slave laser and the closest comb mode of its respective frequency comb. The combs (C1, C2; FC1500/Menlo Systems [22, 30]) are based on Er^{+}-doped fiber ring lasers mode-locked via nonlinear polarization rotation.

The combs' repetition rates are locked to PTB's active hydrogen masers H6 and H8 (VCH-1003/Vremya CH [10, 18, 30]), and operate with a repetition rate of 100 MHz (C1) and 250 MHz (C2), respectively.

To suppress the frequency drift, these beat frequencies are used to stabilize the slave lasers to the masers via the frequency combs in a nested phase-locked loop, see Figs. 1 and 2, where a low-pass filter with a cutoff frequency of around 0.03 Hz suppresses the masers' noise.

The beat signal of each slave laser against its comb is compared to a rf reference in a digital phase comparator. It is a digital phase-frequency detector developed from the Alexander design [23], that discriminates not only phase deviations but also positive and negative frequency deviations to facilitate the initial acquisition of a phase lock. The phase comparator has integrated variable frequency dividers to extend the range of allowable phase excursions. Here, the frequencies are divided by 256.

The low-pass filtered error signal, after passing through an integrator, is used for slow tuning of the reference radio frequency of the second loop, that, in turn, is used for the lock to the cavity-stabilized master laser. Thereby the slow frequency variation of the cavity-stabilized master laser is compensated in the lock of the slave laser. The fast error signal remaining after the differential amplifier (Fig. 2) is digitized and controls the center frequency of a home-built direct digital synthesizer (v-DDS, Fig. 2), where the common mode rejection has to be tuned carefully. The control bandwidth of the voltage controlled DDS is roughly 4 kHz.

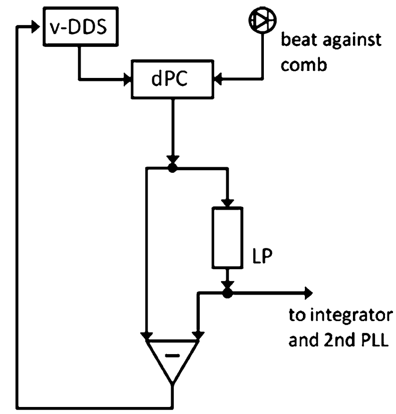


Fig. 2 Schematic sketch of the slow phase-locked loop deriving the slow error signal for correcting the laser drift against the comb. The residual part of the noise spectrum is directly fed back to the reference oscillator to cope with the high-frequency phase excursions caused by the maser, as they would be too large to maintain proper operation of the phase comparator. *v-DDS* Home-built voltage controlled direct digital synthesizer referenced to the maser, *dPC* digital phase comparator, *LP* RC low-pass filter (R = 5.1 kΩ; C =1,000 µF)

To determine the relative stability of the hydrogen maser-stabilized frequency combs, for both combs, we obtain the beat frequencies between slave laser S2 and the closest comb mode $(\nu_{\mathbf{C1}} - \nu_{\mathbf{S2}}, \nu_{\mathbf{S2}} - \nu_{\mathbf{C2}})$ and combine the time traces of these beat frequencies numerically to obtain $\nu_{\mathbf{C1}} - \nu_{\mathbf{C2}}$ (not depicted in Fig. 1).

3 Results and discussion

Figure 3 shows the stability curves of data taken with a gate time of 0.1 s on a dead-time-free frequency counter (FXE/K+K Messtechnik [24, 30]), operated in Π-mode, i.e., measuring the unweighted frequency average over the gate time [25]. The instability curves (overlapping fractional Allan deviation) calculated from the measured beat frequencies are shown. The cavity-stabilized master lasers (black squares) exhibit a relative short-term instability of the order of 10^{-15} for averaging times below 1 s, while for longer averaging times τ, the instability increases due to the cavities' drifts.

The beat note between the frequency combs (blue triangles) exhibits a complementary behavior, typical of

Author's personal copy

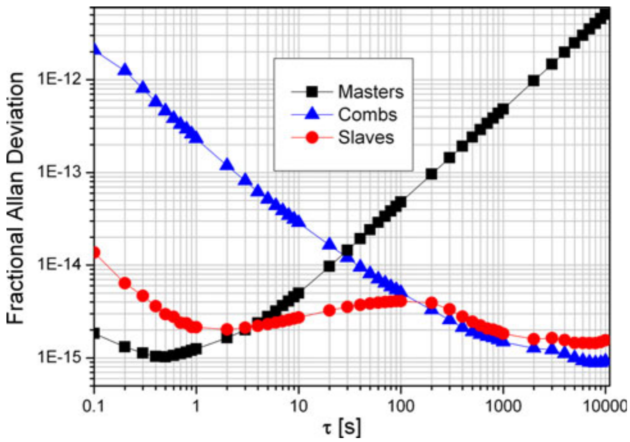


Fig. 3 Fractional overlapped Allan deviations $\sigma_y(\tau)$ of the beat frequencies between the cavity-stabilized master lasers, the H-maser stabilized frequency combs and the slave lasers, respectively, over averaging time τ; the values are given relative to the optical frequency of 194 THz; the data were taken simultaneously on a multi-channel frequency counter

H-masers. It starts at comparatively high levels of instability for short averaging times and initially falls off as $1/\tau$ to reach a stability floor of about 10^{-15} for averaging times around 1,000 s.

The instability between the stabilized slave lasers (red dots) is less than 5×10^{-15} for all averaging times from 0.4 up to 10,000 s. For shorter averaging times, while being two orders of magnitude smaller than that of the frequency combs, the slave lasers' relative instability does not quite achieve the master lasers' level. This behavior is observed to be independent of the slave lasers' lock to the hydrogen maser via the frequency comb. It is attributed mainly to the bandwidth when using the PZT for frequency control, as it is limited to around 10 kHz by mechanical resonances. Another contribution might arise from residual ground loops visible as weak 50 Hz—sidebands in the beat frequency's spectrum. For averaging times beyond 200 s, the stability curve of the slave lasers closely follows that of the frequency combs. For intermediate averaging times between 3 and 100 s, the stability of the slave lasers is slightly better than expected from the stability curves of the frequency combs and the master lasers alone. This indicates the deterministic behavior of the master lasers' frequencies in that the slow phase-locked loop provides a "good guess" of the linear frequency drift.

Figure 4 displays the time traces of the respective beat frequencies.

Both the beat frequencies between the master lasers as well as that between the slave lasers display frequency excursions every few hours caused by M2. The excursions last for about 30 s. A linear fit to the time trace of the inter-slave beat frequency after removing the frequency excursions inherited from M2 yields a slope of 28 μHz/s

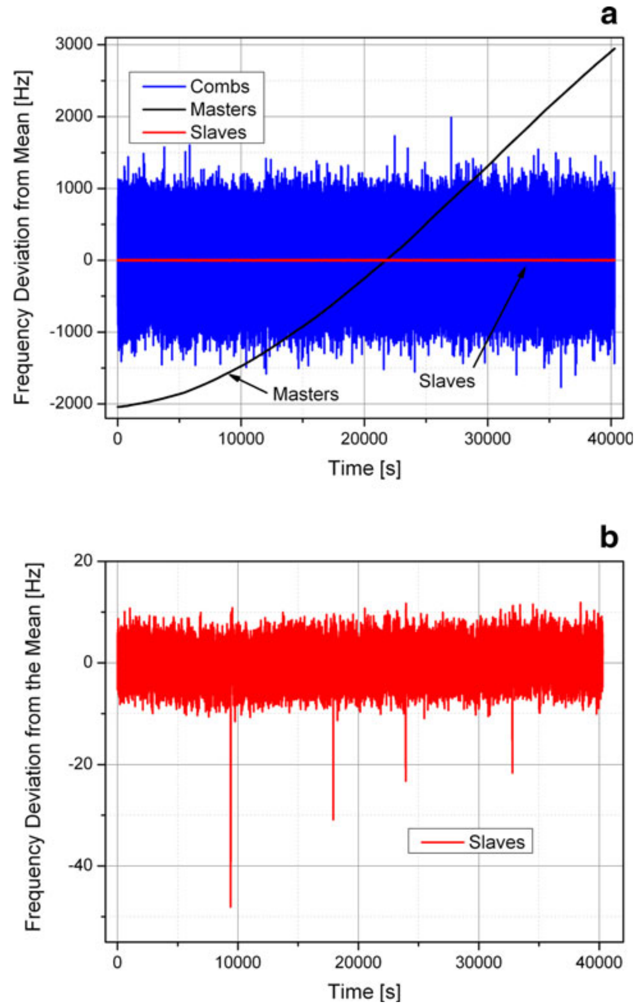


Fig. 4 Time traces of the beat frequencies used for the calculation of the stability curves in Fig. 3 (here: deviation from the respective mean value). The data were taken with a Π-type frequency counter with a gate time of 0.1 s. **a** Beat frequencies between the combs, between the master lasers and between the slave lasers; **b** enlarged view of the inter-slave beat frequency time trace. The frequency excursions are caused by master laser M2 and have been removed prior to calculating the Allan deviation in Fig. 3

corresponding to 1.5×10^{-19}/s, consistent with the last point of the slave lasers' stability curve. Comparing the time trace to the averaged time trace of the beat between the maser-stabilized combs reveals that the slightly visible "wiggling" of the frequency values is frequency flicker inherited from the masers.

Figure 5 shows the central part of the inter-slave beat spectrum, obtained from a rf spectrum analyzer with a resolution bandwidth of 1 Hz. It demonstrates that the slave lasers individually maintain a linewidth of less than 1 Hz and the system's potential for spectroscopic applications.

Over the measurement period of 40,000 s, from the measurement against the comb, each slave laser's mean frequency can be determined with a standard deviation of

Author's personal copy

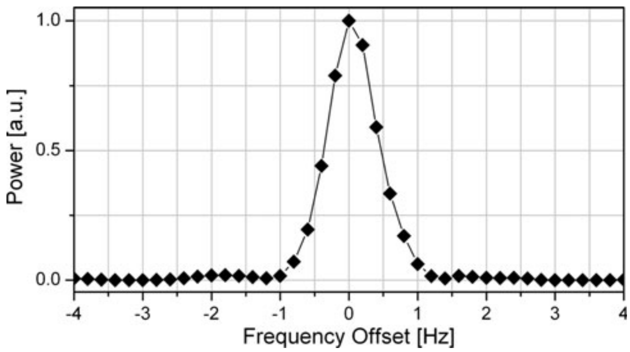


Fig. 5 Spectrum of the beat note between the slave lasers, obtained from a rf spectrum analyzer with a resolution bandwidth of 1 Hz (sweep time 4 s/100 Hz)

the mean of 396 mHz. Correcting the optical frequencies for the masers' drift against PTB's cesium fountain CSF1, we obtain an expected mean of the beat frequency of 83,689,891.236 Hz with a standard deviation of the mean of 547 mHz. Analyzing the direct beat frequency between the slave lasers over the same period of time yields a mean frequency of 83,689,890.875 Hz with a standard deviation of the mean of 4 mHz, illustrating the suppression of the masers' short-term noise, and hence the system's accumulation of frequency stability: At a calculated gate time of 1 s, the slave lasers' beat frequency values show a Gaussian distribution around the mean frequency, with a standard deviation of only 1.4 Hz, making it well suited as an optical reference frequency source.

One drawback of the current implementation is the direct tuning of the direct digital synthesizer's center frequency by the differential amplifier's voltage output in the slow PLL, as this in general causes a frequency offset in the phase lock that needs to be calibrated. Also, it makes the system susceptible to a possible drift of the differential amplifier's voltage, even though such an effect was not observed.

Compared to schemes involving a direct lock of a frequency comb to a cavity-stabilized laser [26, 27], the system described here largely suppresses the cavity's drift, without requiring the laser to be stabilized to an optical atomic reference. Using the frequency comb as a transfer oscillator, this performance can be transferred to other spectral regions as well. However, using light at frequencies around 194 THz has the advantage of being suited for long distance dissemination via phase-stabilized glass fiber links.

4 Conclusion

In summary, by stabilizing a slave laser to a hydrogen maser via a frequency comb, and to a Fabry–Pérot cavity via a master laser, we have realized an optical frequency source with instabilities below 5×10^{-15} for averaging times from 0.4 to 10,000 s. The current setup will be improved further particularly by increasing the bandwidth of the lock between the slave lasers and the master lasers using an acousto-optical modulator. Furthermore, instead of directly controlling the center frequency of the DDS, for future implementations, it is intended to rather control its phase.

We anticipate that due to its ease of implementation and the commercial availability of its components, the scheme will also be useful for existing experiments, e.g., experiments on delay-line stabilized lasers experiencing a pronounced frequency drift [28]. While not competing with the latest frequency standards currently under development, the scheme presented here formally allows for realizing an optical frequency with the highest precision available under the present definition of the SI second. It will be useful as an optical reference frequency source, which delivers a traceable absolute frequency if the H-maser is referenced to a frequency standard, e.g., via GPS. In view of the development of robust portable laser systems [29] and with masers being located, e.g., at remote radio telescope sites already, even field applications of the system could be envisaged. Alternatively, operating at 194 THz, the system output is well suited for distribution via fiber links.

A further application may be as a frequency safeguard for optical atomic clocks, insuring that frequency deviations during interruptions of an optical clock's operation remain within the limits set by microwave frequency standards.

Acknowledgments The authors would like to thank A. Bauch for providing the maser signals and for very helpful comments and discussions, as well as S. Weyers for providing the cesium fountain data and for helpful comments. This work was supported by the European Metrological Research Programme EMRP under SIB-02 NEAT-FT and IND 014. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. Support by the Centre of Quantum Engineering and Space-Time Research (QUEST) is gratefully acknowledged. Mention of specific products and trade names is for technical communication only and does not constitute an endorsement or recommendation by PTB.

References

1. K. Predehl, G. Grosche, S.M.F. Raupach, S. Droste, O. Terra, J. Alnis, Th. Legero, T.W. Hänsch, Th. Udem, R. Holzwarth, H. Schnatz, Science **336**, 441 (2012)
2. B.C. Young, F.C. Cruz, W.M. Itano, J.C. Bergquist, Phys. Rev. Lett. **82**, 3799 (1999)
3. Y.Y. Jiang, A.D. Ludlow, N.D. Lemke, R.W. Fox, J.A. Sherman, L.-S. Ma, C.W. Oates, Nat. Photonics **5**, 158 (2011)
4. T. Kessler, C. Hagemann, C. Grebing, T. Legero, U. Sterr, F. Riehle, M. J. Martin, L. Chen, J. Ye, Nat. Photonics **6**, 687 (2012)
5. J. Alnis, A. Matveev, N. Kochalevsky, Th. Udem, T.W. Hänsch, Phys. Rev. A **77**, 053809 (2008)
6. C.G. Parthey, A. Matveev, J. Alnis, B. Bernhardt, A. Beyer, R. Holzwarth, A. Maistrou, R. Pohl, K. Predehl, T. Udem, T.

Author's personal copy

Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, T.W. Hänsch, Phys. Rev. Lett. **107**, 203001 (2011)
7. T. Rosenband, D.B. Hume, P.O. Schmidt, C.W. Chou, A. Brusch, L. Lorini, W.H. Oskay, R.E. Drullinger, T.M. Fortier, J.E. Stalnaker, S.A. Diddams, W.C. Swann, N.R. Newbury, W.M. Itano, D.J. Wineland, J.C. Bergquist, Science **319**, 1808 (2008)
8. N.D. Lemke, A.D. Ludlow, Z.W. Barber, T.M. Fortier, S.A. Diddams, Y. Jiang, S.R. Jefferts, T.P. Heavner, T.E. Parker, C.W. Oates, Phys. Rev. Lett. **103**, 063001 (2009)
9. C.W. Chou, D.B. Hume, J.C.J. Koelemeij, D.J. Wineland, T. Rosenband, Phys. Rev. Lett. **104**, 070802 (2010)
10. St. Falke, H. Schnatz, J.S.R. Vellore Winfred, Th. Middelmann, St. Vogt, S. Weyers, B. Lipphardt, G. Grosche, F. Riehle, U. Sterr, Ch. Lisdat, Metrologia **48**, 399 (2011)
11. N. Huntemann, N. Okhapkin, B. Lipphardt, S. Weyers, Chr. Tamm, E. Peik, Phys. Rev. Lett. **108**, 090801 (2012)
12. O. Terra, G. Grosche, H. Schnatz, Opt. Express **18**, 16102 (2010)
13. P. Dubé, A.A. Madej, J.E. Bernard, L. Marmet, A.D. Shiner, Appl. Phys. B **95**, 43 (2009)
14. R. Storz, C. Braxmaier, K. Jäck, O. Pradl, S. Schiller, Opt. Lett. **23**, 1031 (1998)
15. Q.-F. Chen, A. Troshyn, I. Ernsting, S. Kayser, S. Vasilyev, A. Nevsky, S. Schiller, Phys. Rev. Lett. **107**, 223202 (2011)
16. M.J. Thorpe, L. Rippe, T.M. Fortier, M.S. Kirchner, T. Rosenband, Nat. Photonics **5**, 688 (2011)
17. J. Reichert, M. Nierung, R. Holzwarth, M. Weitz, Th. Udem, T.W. Hänsch, Phys. Rev. Lett. **84**, 3232 (2000)
18. A. Bauch, S. Weyers, D. Piester, E. Staliuniene, W. Yang, Metrologia **49**, 180 (2012)
19. O. Terra, G. Grosche, K. Predehl, R. Holzwarth, T. Legero, U. Sterr, B. Lipphardt, H. Schnatz, Appl. Phys. B **97**, 541 (2009)
20. A. Pape, O. Terra, J. Friebe, M. Riedmann, T. Wübbena, E.M. Rasel, K. Predehl, T. Legero, B. Lipphardt, H. Schnatz, G. Grosche, Opt. Express **18**, 21477–21483 (2010)
21. S. Weyers, B. Lipphardt, H. Schnatz, Phys. Rev. A **79**, 031803 (2009)
22. P. Kubina, P. Adel, F. Adler, G. Grosche, T.W. Hänsch, R. Holzwarth, A. Leitenstorfer, B. Lipphardt, H. Schnatz, Opt. Express **13**, 904–909 (2005)
23. J.D.H. Alexander, Electron. Lett. **11**, 541 (1975)
24. G. Kramer, W. Klische, in *Proc. IEEE Int. Symp. Time Freq*. 144 (2001)
25. S.T. Dawkins, J.J. McFerran, A.N. Luiten, IEEE Trans. Ultras. Ferroel. Freq. Control **54**, 918–925 (2007)
26. A. Bartels, C.W. Oates, L. Hollberg, S.A. Diddams, Opt. Lett. **29**, 1081 (2004)
27. Y. Nakajima, H. Inaba, K. Hosaka, K. Minoshima, A. Onae, M. Yasuda, T. Kohno, S. Kawato, T. Kobayashi, T. Katsuyama, F.-L. Hong, Opt. Express **18**, 1667 (2010)
28. F. Kéfélian, H. Jiang, P. Lemonde, G. Santarelli, Opt. Lett. **34**, 914 (2009)
29. D.R. Leibrandt, M.J. Thorpe, J.C. Bergquist, T. Rosenband, Opt. Express **19**, 10278–10286 (2011)
30. Mention of specific products and trade names is for technical communication only and does not constitute an endorsement or recommendation by PTB.