Providing 10^{-16} Short-Term Stability of a 1.5-μm Laser to Optical Clocks

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***Abstract*—We report on transferring 10^{-16}-level fractional frequency stability of a "master laser" operated at 1.5 μm to a "slave laser" operated at 698 nm, using a femtosecond fiber comb as transfer oscillator. With the 698-nm laser, the $^1S_0 - {}^3P_0$ clock transition of ^{87}Sr was resolved with a Fourier-limited linewidth of 1.5 Hz (before: 10 Hz). Potential noise sources contributed by the frequency comb are discussed in detail.**

***Index Terms*—Atomic clocks, femtosecond frequency combs, frequency control, laser stability, optical phase-locked loops, stability transfer, transfer oscillator.**

I. Introduction

With fractional inaccuracies of 8.6×10^{-18} [1] and instabilities of $\sigma_y(\tau) = 4 \ldots 5 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$ [2], optical atomic clocks are the most precise instruments for measurements of time and frequency. Typically, a highly short-term stable interrogation laser is stabilized to a long-term stable optical transition of an atomic reference. While the stability of single-ion clocks is generally limited by quantum projection noise [3], optical lattice clocks with a large number of neutral atoms suffer from insufficient performance of the interrogation laser to exploit their full potential [4]–[6].

State-of-the-art clock lasers are often stabilized to high-finesse optical cavities with spacers made of Ultra-Low Expansion (ULE) glass. Minimizing the length sensitivity to environmental perturbations, fractional frequency stabilities of a few times 10^{-16} at a second [2], [7] have been demonstrated. However, thermal noise resulting from Brownian motion inside the high-reflection coatings hampers further improvements massively [8], [9], and novel low-noise coatings are not yet competitive. Nevertheless, a powerful approach for reducing the thermal noise floor of an optical cavity that uses standard coating technology has been recently demonstrated, employing a cryogenic cavity machined from single-crystal silicon [10]. Furthermore, alternative techniques that do not rely on dielectric mirrors such as stabilizing to spectral holes in doped crystals [11], [12] or whispering-gallery-mode resonators [13], [14] increasingly attract attention.

As many of these approaches only work at specific wavelengths, transfer of an outstanding stability to the wavelength of the optical clock is needed. Utilizing a broadband optical frequency comb to bridge the spectral gap between a highly stable "master laser" and a less stable "slave laser," transfers of stabilities in the range of 10^{-15} have been demonstrated [15]–[17]. In extension, this approach allows us to slave several clock lasers to one master laser simultaneously.

However, with lasers approaching sub-10^{-16} instabilities, it becomes important to investigate if the transferred stability is degraded by additional noise from the transfer oscillator. In this paper, this question will be addressed, utilizing a commercial femtosecond fiber comb to accomplish an octave-spanning transfer of 10^{-16} instabilities to a less stable slave laser. In Section II, we describe the master laser system providing such ultrahigh stabilities. In Section III, we present results of a series of noise measurements on the fiber comb to evaluate the performance of the transfer. On the example of the ^{87}Sr optical lattice clock at the Physikalisch-Technische Bundesanstalt (PTB), the increased stability of the slave laser is demonstrated in Section IV.

II. Ultrastable Master Laser System

The master laser system comprises a 1.5-μm fiber laser stabilized to an optical cavity machined from single-crystal silicon. The cavity is operated at the zero point of its thermal expansion at a temperature of 124 K. The low operating temperature and the superior thermomechanical properties of silicon set the thermal noise limit [8], [18] for the fractional frequency stability of the laser to a level of $\sigma_y \approx 6 \times 10^{-17}$. This value is lower by a factor of three compared to state-of-the-art resonators operated at room temperature [2]. In a three-cornered hat comparison with two conventional laser systems, the silicon cavity stabilized laser has demonstrated short-term stabilities of mod $\sigma_y = 1 \ldots 3 \times 10^{-16}$ between $0.1 \ldots 10$ s [10] (see Fig. 1).

Because of the absorption of the material, laser transmission is restricted to the infrared between 1 and 6 μm. We chose an operation wavelength of 1.5 μm, as the laser technology

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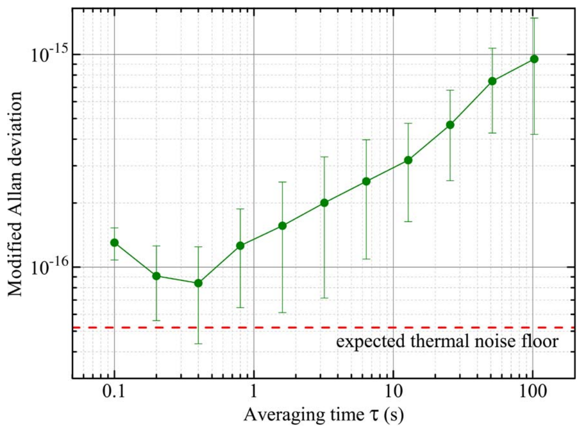

Fig. 1. Modified Allan deviation of the silicon cavity laser system derived from a three-cornered hat comparison with two conventional laser systems (data from [10]).

at this wavelength is rather mature and the stable light can be disseminated, e.g., to the femtosecond frequency comb, at low cost using standard telecom fibers [19].

III. Performance of Transfer Oscillator

The stability transfer from the infrared master laser to the spectral ranges of optical clock transitions is accomplished using a multiport Er:fiber femtosecond frequency comb. We exploited the correlations of the comb offset frequency $f_{\mathrm{CE}}(t)$ and repetition rate $f_{\mathrm{rep}}(t)$ with the fluctuations of frequency $\nu_n(t)$ of the n^{th} optical comb mode, i.e.,

$$\nu_n(t) = n \cdot f_{\mathrm{rep}}(t) + f_{\mathrm{CE}}(t) \quad (1)$$

which is forming the base of the transfer oscillator concept of Telle *et al.* [20]. This technique provides a transfer bandwidth in the megahertz range as it only relies on fast radio-frequency (RF) tracking electronics and no bandwidth restrictions caused by a limited response time of the mode-locked laser itself occur.

The requirements to the transfer are set by the performance of the master laser, which supports instabilities of mod $\sigma_y = 1\ldots 2\times 10^{-16}$ for averaging times between $0.1\ldots 3$ s (see Section II). Moreover, advanced clock comparison experiments reach residual instabilities of $\sigma_y \approx 1\times 10^{-17}$ [21]–[23] for long averaging times. These numbers trigger the question whether a multiport frequency comb is capable of bridging vast spectral gaps without adding noise to the comparison of the spectrally separated oscillators.

Equation (1), which is the very base of the transfer concept, is valid at the output coupler of the mode-locked fiber comb. However, before the light is superimposed with the connected continuous-wave (CW) oscillators, usually, the light is amplified, and its frequency is converted to the region of the CW oscillator. These subsequent processing steps might introduce an additional noise term $\delta\nu(n,t)$ to the right-hand side of (1) [24] and thus corrupt the transfer concept. A single broadened fiber oscillator already proved its capability of transferring stabilities at levels below 10^{-16} for averaging times > 1 s [25], [26]. However, in commercial fiber comb systems, the oscillator output is amplified and spectrally shifted or broadened to the

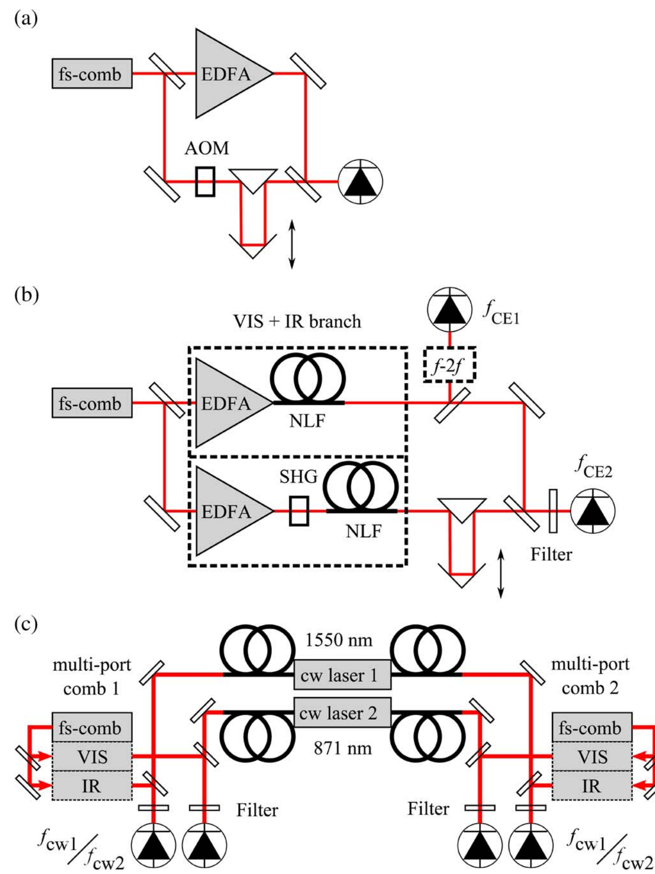

Fig. 2. Measurement setups for determining and identifying the noise generated in fiber comb conversion branches. (a) Interferometer for measuring the noise added in an EDFA (inner-branch noise). (b) Interbranch noise setup. SHG: second-harmonic generation; NLF: nonlinear fiber; Filter: monochromator with a filter bandwidth of about 0.1 nm. (c) Assembly to measure a frequency ratio of two CW lasers with two independent frequency combs (intercomb noise).

needed regions in multiple branches. Differential noise added in these branches would compromise the result of an interbranch frequency comparison [24], [27]. Therefore, prior to the stability transfer experiment itself, we have investigated and characterized the noise that is potentially added in conversion branches. In other words, we check to which level (1) is valid when using a multiport frequency comb.

The potential noise sources giving rise to excess noise $\delta\nu(n,t)$ were discussed in detail by Newbury and Swann [24], i.e., amplified spontaneous emission (ASE) during the amplification process, detection/technical noise, excess noise in the nonlinear frequency conversion, and environmental noise acting on the setup stemming from thermal or acoustic influences. Our investigation is divided into three measurements, increasing the number of noise sources stepwise. All three arrangements are depicted in Fig. 2.

a) *Inner-branch noise:* This setup addresses the noise generated in an erbium-doped fiber amplifier (EDFA). We fed the oscillator output into an interferometer with an EDFA in the test arm and an acoustooptic modulator (AOM) in the reference arm to allow heterodyn detection in order to trace back ASE and environmental noise contributions during the amplification process. In general, we minimized the spurious interferometer noise by building

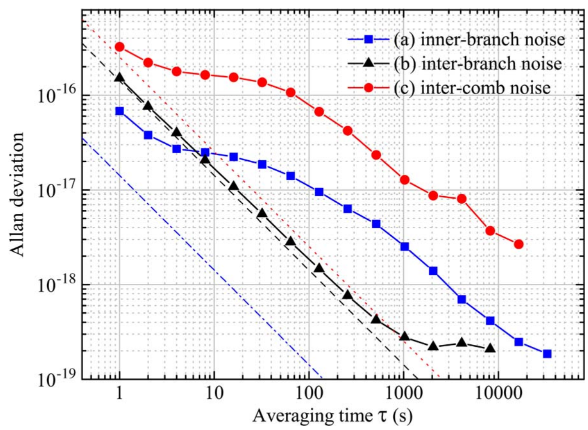

Fig. 3. Fractional frequency instability in terms of Allan deviation of the different noise measurements. (Straight lines) Detection limited instability of each measurement (assuming white phase noise; inner-branch: dashed-dotted blue; interbranch: dashed black; intercomb: dotted red).

setups that are as compact as possible and passively shielded. The beat signal was detected with a signal-to-noise ratio (SNR) of about 50 dB [resolution bandwidth (RBW): 100 kHz].

b) *Interbranch noise:* Going one step further, we added the frequency conversion step as potential excess noise source by comparing two branches that generate spectrally overlapping outputs. In detail, this was achieved by measuring the comb offset frequency f_{CE1} at about 1.1 μm in an octave-spanning IR branch ($\approx 1 \ldots 2.2$ μm) utilizing an $f - 2f$ interferometer [28]. The unused residual light is superimposed with the output of a frequency-doubled octave wide visible (VIS) branch ranging from $\approx 0.5 \ldots 1$ μm. The overlapping region at around 1 μm was filtered out and sent to a photo diode to again measure the comb offset frequency f_{CE2}. In each case, the comb offset frequency was measured with an SNR of about 30 dB (RBW $= 100$ kHz). The difference between both offset frequencies $f_{\mathrm{CE1}} - f_{\mathrm{CE2}}$ reveals the differential interbranch noise.

c) *Intercomb noise:* Finally, we built an almost fully symmetric setup sending two spectrally separated CW lasers to two completely independent multiport frequency comb systems located in different buildings. The difference in the measured frequency ratios $f_{\mathrm{cw1}}/f_{\mathrm{cw2}}$ contains all the noise sources that can compromise such frequency comparisons. The beat signals were detected with a SNR of about 25 dB (RBW $= 100$ kHz).

Each beat note was tracked with about 500-kHz bandwidth using a fast tracking oscillator due to the comb linewidth of about 100 kHz in the optical region. The instability of each measurement was evaluated in terms of the Allan deviation, and the results are depicted in Fig. 3.

The short-term stabilities of the all measurements are close to the requirements given by the best available optical oscillators (see Section II). The observed SNRs of the beat signals in the interbranch and intercomb measurements give on upper limit to white phase noise of -80 and -75 dBc/Hz, respectively. These values are converted to Allan deviations of $1 \ldots 3 \times 10^{-16}/(\tau/\mathrm{s})$ and are in agreement with the measured instabilities, proving the short-term performances of the interbranch and intercomb measurements are limited by white phase noise. The typical detected power of a single comb mode is about 1 nW yielding a shot-noise limited white phase noise floor at -97 dBc/Hz, which would support instabilities in the order of $2 \times 10^{-17}/(\tau/\mathrm{s})$. The difference reveals the presence of excess phase noise generated during the nonlinear broadening/shifting, as verified for Ti:sapphire combs [24] (and references therein). In the inner-branch measurement, most of the comb modes contribute to the signal, and the excess noise resulting from spectral broadening is absent. The SNR ratio is degraded only by dispersion in the EDFA yielding a white phase noise level of below -100 dBc/Hz, which converts to Allan deviations of $1 \ldots 2 \times 10^{-17}/(\tau/\mathrm{s})$, well below the observed instability. Hence, the amplification process adds considerable noise contributions that originate from ASE and environmental noise acting on the amplification fiber.

At intermediate observation times between $1 \ldots 100$ s, the inner-branch and intercomb noise measurements show pronounced instability plateaus. This signature is known to stem from environmental perturbations acting on fiber links [27], [29]. A single EDFA comprises about 15 m of fiber, and extra care is taken to isolate the fiber against environmental distortions. This explains the impressively low level of the plateau at low 10^{-17} in the inner-branch measurement. The fiber noise plateau in the intercomb experiment at $1 \ldots 2 \times 10^{-16}$ is presumably caused by a piece of about 20 m yet unstabilized fiber between a CW laser and one of the frequency combs. Thus, at this time scale, the measurement can be considered as a conservative estimate of relative noise between two independent multiport comb systems. In the future, the unstabilized fiber will be included in the active noise cancellation to provide a fully symmetric setup, and we are confident to substantially reduce the instability plateau to below 1×10^{-16}.

The interbranch performance does not seem to be affected by fiber noise. The reason becomes clear when looking at the branch layouts. Both conversion branches (VIS and IR) share the same environmental shielding so that most of the residual fiber noise is common mode. In conclusion, the intercomb performance can be further improved employing temperature stabilization or acoustic shielding to the entire fiber comb setups.

On very long time scales ($\approx 10^4$ s), the inter- and inner-branch measurements seem to level out in the 10^{-19} instability range. The reason for this is not fully understood. A possible explanation is the temperature dependence of the employed RF electronics that sets in and limits the measurements. However, this is about two orders of magnitude lower than what is currently achieved with the best clocks. Also, the intercomb experiment averages down to 3×10^{-18}, still surpassing the best clock comparisons by a factor of three [21]–[23].

IV. Spectroscopy and Clock Operation With ^{87}Sr

To demonstrate the feasibility and the usefulness of stability transfer from a extremely high-quality oscillator to the interrogation laser of an optical clock, we have used the PTB strontium

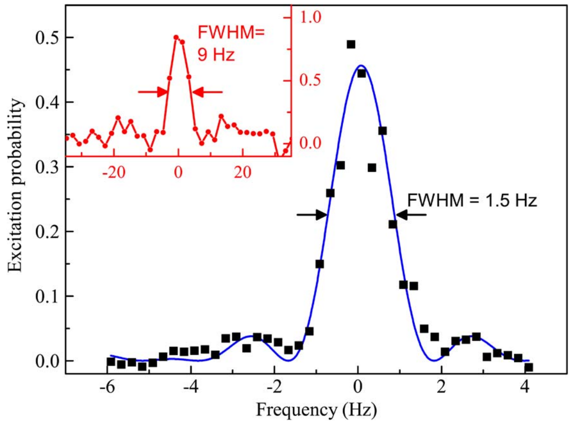

Fig. 4. Spectra of one Zeeman component of the ^{87}Sr clock transition with the strontium clock laser only (inset: 10-Hz linewidth; data from [22]) and with the stability transfer from the master laser stabilized to the cryogenic silicon cavity.

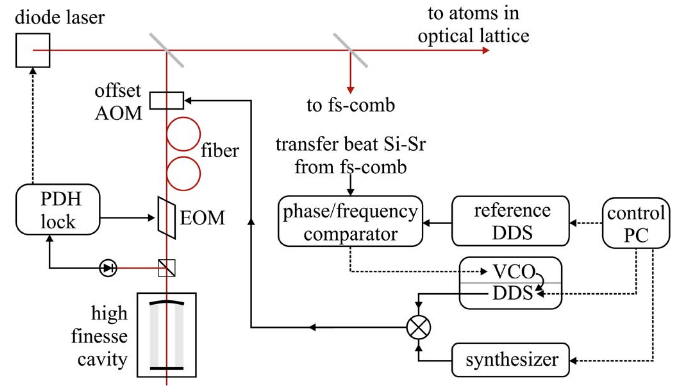

Fig. 5. Schematics of the lock of the Sr clock laser to (left) its reference resonator (PDH: Pound–Drever–Hall; EOM: electrooptical modulator) providing a short-term stability of $\sigma_y \approx 2 \times 10^{-15}$ at a few seconds. The RF driving the offset AOM is generated by mixing of two computer controlled sources. To phase lock the clock laser to the master laser, an error signal is generated in a phase/frequency comparator, to which the transfer beat from the fs frequency comb and a stable RF are fed.

lattice clock [22] as test system. The lattice clock setup and its clock laser have been described in some detail in previous publications [16], [30]–[32]. Thus, we focus here on the central aspects of the experiment only.

The strontium clock laser is stabilized to a reference resonator with a spacer made from the ULE glass to which mirrors with ULE substrates are optically contacted. The laser provides a fractional short-term stability of $\sigma_y \approx 2 \times 10^{-15}$ for averaging times of a few seconds. Using this laser, we typically observe spectra of the $^1S_0 - {}^3P_0$ clock transition at 698 nm in ^{87}Sr with a Fourier limited linewidth of 10 Hz and 90% contrast (see inset in Fig. 4).

To record the spectra, the atoms are loaded from a Zeeman-slowed optical beam into a magnetooptical trap (MOT) operated on the 462-nm resonance line of strontium. The temperature of the atomic cloud is reduced to a few microkelvins in a second MOT phase employing the intercombination line $^1S_0 - {}^3P_1$ (689 nm; 7-kHz linewidth). This temperature is low enough to load the atoms into an optical lattice operated at the light-shift cancellation wavelength for the clock transition.

To lock the laser frequency to the strontium clock transition we spin-polarize the atoms in the optical lattice to either one of the extreme Zeeman levels. They are probed in a Rabi-type interrogation on the low- and high-frequency half-width points of the lines in a weak magnetic field to separate the Zeeman transitions. For clock operation, the frequency of the clock laser is steered to the average of the two transition frequencies using an offset AOM (see Fig. 5), which cancels the linear Zeeman shift.

Previously, we have estimated the clock stability by interleaving two stabilizations and calculating the Allan deviation of the difference of the two steering frequencies applied to the offset AOM [22]. We found that the instability of this difference averages as $5 \times 10^{-15}/\sqrt{\tau/\mathrm{s}}$, meaning that this instability is available for the evaluation of, for example, systematic effects. In noninterleaved clock operation, the instability is expected to be a factor of at least two smaller because the cycle time, the twofold noise contribution, and the Dick effect [6] are reduced, provided the transition frequency does not show time-dependent shifts.

To make use of the superior stability of the master laser (see Section II), i.e., to improve the stability of the lattice clock, we have phase-locked the Sr clock laser (slave laser) with a bandwidth of about 500 Hz to the master laser using a femtosecond comb as transfer oscillator (see Section III). Due to the small bandwidth, the contribution of the white phase noise is suppressed, and the performance of the transfer is expected to be limited by acoustic and thermal influences on the fiber comb. The error signal derived from the phase comparison of transfer beat [16] with a stable RF reference is used to steer the RF driving the offset AOM between the clock laser and its ULE reference cavity (see Fig. 5). This RF is the sum of two oscillators [33] that independently provide a drift compensation for the ULE cavity using a direct digital synthesis (DDS) frequency generator and stepwise corrections to lock the laser to the clock transition via a conventional frequency synthesizer. The error signal of the phase lock acts on the voltage-controlled oscillator serving as local oscillator in the DDS generator. To scan the clock laser over or to lock it to the clock transition, the reference DDS of the phase lock is adjusted in addition to the conventional frequency synthesizer by the data acquisition system. The adjustment of the frequency synthesizer serves as feedforward to minimize the necessary adjustments of the drift-compensating DDS.

Activating the phase lock, we have recorded spectra of the clock transitions with linewidth reduced to below 2 Hz without loss of contrast (see Fig. 4). Longer interrogation times at reduced laser intensity did not provide narrower transitions and caused a considerable reduction of excitation probability. We did not observe an excitation probability close to unity for any interrogation pulse length since we employed an interrogation sequence that did not remove atoms remaining in other than the interrogated Zeeman levels after imperfect spin polarization. To estimate the clock stability, we locked the laser frequency to the average of the two Zeeman components $m_F = \pm 9/2$ and interleaved two stabilizations. For this measurement spin polarization was improved using a cleanup pulse [22]. With a probe time of 380 ms (corresponding to a Fourier-limited

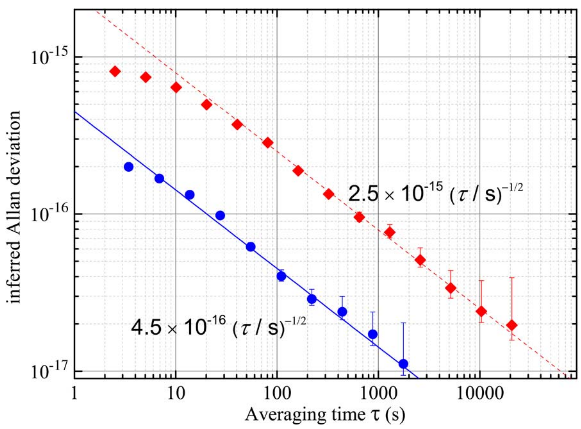

Fig. 6. Stabilities of the Sr lattice clock inferred from interleaved measurements (upper curve) using the stability of the ULE reference cavity of the Sr clock laser (data from [22]) and (lower curve) with the stability transfer from the silicon cavity stabilized laser system. Averaging times to achieve a desired statistical uncertainty are reduced in the latter case by a factor of 30.

linewidth of 2.1 Hz), a maximum excitation probability of 80% was observed. A single interrogation on one half-width point of a Zeeman component comprising the preparation and the detection of atoms required 860 ms with a duty cycle of 44%. We observe a significantly reduced instability (see Fig. 6): We infer a noninterleaved clock stability of $4.5 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$ that is similar to the best achieved values so far [2], [4]. This improvement of clock stability mostly reflects the improvement of the line quality factor (10/2.1 Hz). The cycle time T_C was not considerably increased in the current experiment (860 ms) compared with the previous ones (630 ms) since the loading and the preparation time could be significantly reduced. As the clock stability scales with $\sqrt{T_C}$ (neglecting the Dick effect), it is only slightly degraded by the increase in cycle time. In conclusion, it is obvious that the improved clock stability facilitates the clock operation enormously, as averaging times for many investigations are reduced by a factor of 30.

V. Conclusion and Outlook

Bridging the spectral gap with a femtosecond fiber comb, we have transferred the 10^{-16}-level short-term stability of a high-end cryogenic cavity stabilized laser (master laser) operated at 1.5 μm to a clock laser (slave laser) operated at 698 nm. We have investigated potential noise sources arising from independent signal processing in the different branches of the femtosecond fiber comb. Our measurements have shown that the short-term performance of the transfer is in a range of $\sigma_y \approx 1 \ldots 3 \times 10^{-16}$ at a second, which is already on the level of stability of the best current lasers. This is however not a principle limitation, as environmental perturbations can be reduced by temperature stabilization and acoustic shielding of the fiber comb setup.

Despite the current limitation of the setup, the stability of the slave laser has been significantly improved, resolving the $^1\mathrm{S}_0 - {}^3\mathrm{P}_0$ clock transition of ^{87}Sr with a Fourier-limited linewidth of 1.5 Hz. Inferred from two alternated stabilizations of the improved slave laser, we expect clock instabilities to average down with $4.5 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$, provided frequency shifts of the atomic transition are kept sufficiently stable in the long term. This compares with the best observed clock instabilities so far [2].

Enabling stability transfers across the full wavelength range covered by the frequency comb, this concept allows focusing efforts in the development of a single outstanding oscillator and providing its stability for simultaneous operation of multiple clocks.

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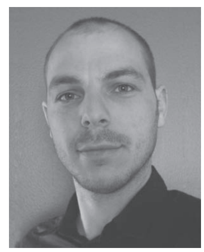

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