Long-distance remote characterization of ultrastable lasers via commercial telecommunication fiber network

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We demonstrate a fully optical, remote characterization of independent ultrastable lasers separated by a geographical distance of more than 50 km via a 73 km long phase-stabilized fiber in a commercial telecommunication network. The phase-coherent comparison spans more than one optical octave and shows a fractional frequency instability between the independent ultrastable laser systems of \(3 \times 10^{-15}\) in 0.1 s. This enables future remote characterizations of the stability of 100 mHz linewidth lasers within seconds. © 2009 Optical Society of America

OCIS codes: 060.2360, 120.3940, 120.4800, 140.3425.

Optical atomic clocks have surpassed state-of-the-art microwave clocks in terms of accuracy and stability and allow targeting fractional inaccuracies of 1 part in \(10^{18}\) [1, 2]. This will have a wide range of physical applications, as e.g. the search for variations of fundamental constants or precision tests of general theory of relativity. A crucial element in achieving this performance are ultrastable lasers which currently limit the short term stability of state-of-the-art optical clocks [2]. Direct comparisons of such clocks are difficult, since today, the complex setup of an optical clock does not allow for transportation. Phase-coherent long-range dissemination and remote characterization of ultrastable optical frequencies have therefore become an important tool in frequency metrology triggering many activities worldwide. Early works demonstrated e.g. a remote characterization of an optical frequency standard using a microwave signal transmitted via a 43 km long optical fiber [3]. The most promising method with the highest demonstrated stability directly transmits the ultrastable optical carrier via phase-stabilized fibers [2, 4–6] and was applied to remote optical clock comparisons over distances of 3.5 km [2, 7]. Regarding the typical long-range distances between optical clocks and the costs, usage of commercial telecommunication fiber networks and transfer at 1.5 \(\mu\)m are recommended. Links with lengths of up to 251 km [6, 8–10] were demonstrated, even including simultaneous data traffic [11]. For these experiments, however, the local and remote end were located at the same position. Recently, an optical clock was compared to a microwave frequency standard via a 120 km telecommunication fiber link [12].

In this work we realize for the first time to our knowledge a remote comparison of 73 km-distant ultrastable lasers via a telecommunication fiber network. The demonstrated performance allows to characterize the stability of 100 mHz linewidth lasers within seconds.

Fig. 1. (Color online) Schematic setup. EDFA: erbium doped fiber amplifier, AOM: acousto-optic modulator, OC: optical circulator, FM: Faraday mirror, PD: photodiode, \(\phi\)-Det: phase detector, VCO: voltage-controlled oscillator.

With our setup we are able to reveal the flicker floor of our ultrastable lasers of \(3 \times 10^{-15}\) in only 0.1 s averaging time. This represents a real-time application of a long-distance fiber link at the performance-level of state-of-the-art optical clocks. In combination with sophisticated fiber stabilization systems [10], the results confirm the potential of long-distance telecommunication fiber links for comparing optical clocks at the level of \(10^{-17}\) or below in a few minutes.

The lasers compared here are separated by more than 50 km geographical distance and are used for the calcium and magnesium optical frequency standard located at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and at the Institute of Quantum Optics (IQ) at the University of Hanover, respectively. In Hanover, currently two ultrastable laser systems are in

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Fig. 2. (Color online) Fractional Allan deviation of the beat frequency between ultrastable laser systems in more than 50 km distant laboratories. L1-L2 local measurement, L1-TL and L2-TL via a 73 km stabilized fiber link; TL: transfer laser at 1542 nm. With (filled symbols) and without (open symbols) removal of linear drifts.

operation, L1 and L2. Both are diode lasers systems, which are stabilized to two independent ultrastable optical resonators. L2 uses a horizontal resonator (finesse $\mathcal{F} = 600,000$) mounted near the symmetry plane for reduced vibrational sensitivity. Since beat note measurements between two systems can only provide an upper bound for the combined stability, L1 and L2 are compared to an ultrastable laser (ML) located at PTB, whose stability is transferred via a 73 km long telecommunication fiber to IQ.

The experimental setup is schematically depicted in fig. 1. The stability of the ultrastable master laser (ML) at PTB at 657 nm - a diode laser system stabilized to a vibrationally insensitive optical resonator reaching a demonstrated linewidth at Hz level [13, 14] and a flicker floor of $\approx 2 \times 10^{-15}$ for $0.1 - 20$ s [15] - is transferred to a 1542 nm fiber laser (TL) by means of a femtosecond frequency comb [16]. We inject about 5 mW of the light of TL into the 73 km long fiber link to IQ, connected via the local computer center in Hanover (RZ-H). At IQ, the light is amplified in a bidirectional erbium doped fiber amplifier (EDFA), frequency shifted with an acousto-optic modulator (AOM 2) and afterwards partially reflected back to PTB, using a Faraday rotator mirror. At PTB, the back reflected light is used for active cancellation of phase noise of the fiber by servo feedback to AOM 1. The servo bandwidth of the noise cancellation loop is limited to $\approx 700$ Hz due to fiber length [8]. The single pass loss in the 73 km fiber is $\approx 23$ dB. Information about the stabilization system and the link between PTB and RZ-H can be found in [10, 15]. Part of the transmitted light at 1542 nm is coupled out at IQ and used for comparison to L1 and L2 at 914 nm by means of a second frequency comb. Both frequency combs are based on femtosecond erbium fiber lasers which are frequency doubled into the visible. Thus, the phase stable remote comparison via a transfer laser covers more than one optical octave.

The remote characterization of the ultrastable lasers is performed in the time and frequency domains. In the time domain, all frequencies are recorded simultaneously by using a multichannel frequency counter with synchronous readout and zero deadtime. This can be operated either as a $\Pi$ or an overlapping $\Lambda$ estimator [17]. The frequency of the transfer beat $\nu_2 = \nu_1 - \nu$ between the delivered cw light $\nu_1$ at 1542 nm and the 914 nm cw light $\nu_2$ of the local ultrastable lasers is calculated using the relation

$$\nu_2 - \frac{m_2}{m_1} \nu_1 = \left(2 - \frac{m_2}{m_1}\right) \nu_{\text{CEO}} - \frac{m_2}{m_1} \nu_{B_1} + \nu_{B_2},$$

by measuring the mode numbers $m_1, m_2$ of the frequency comb, the carrier-envelope offset frequency $\nu_{\text{CEO}}$, and the beat note frequencies $\nu_{B_1}, \nu_{B_2}$ between the cw frequencies and the corresponding comb modes.

The results of the characterization of the three independent laser systems are depicted in fig. 2. The Allan deviation (ADEV) shown is obtained by operating the counter as a $\Pi$ estimator. L2 shows a drift rate of several $10^{-15}$ s$^{-1}$ and L1 of $\approx 10^{-15}$ s$^{-1}$, which we attribute to temperature fluctuations of the ultrastable resonators. The drift rate of ML, and thus TL, was identified independently at PTB using a hydrogen maser as $\approx 10^{-16}$ s$^{-1}$. With linear drift correction, for $\tau \geq 0.05$ s TL is identified as the most stable laser, and L2 as more stable than L1 (fig. 2). From previous characterizations of the PTB-(RZ-H)-PTB fiber link with instabilities of $\sigma_\nu(\tau) = 3 \times 10^{-15}(\tau/\text{s})^{-1}$ [10, 15], we suspect that the link may limit the laser comparison up to $\approx 1$ s.

To overcome this limitation, we implemented a data evaluation based on the modified Allan deviation (ModADEV). The ModADEV is obtained (case (c) in [17]) by operating the counter as an overlapping $\Lambda$ esti-
A laser comparison is already revealed after 100 ms and the case of the ModADEV, the performance of the remote transfer beat note sizer and double-balanced mixers. The spectrum of the analog signal processing [16] using a direct digital synthesizer (with an internal gate time of 1 ms). While leaving the instability contributions of frequency modulation noise processes unaffected (within 30% error [17]), the contribution of white phase noise - which is typical for residual link fluctuations - falls off as $\tau^{-3/2}$. Fig. 3 depicts the ADEV and ModADEV for the L2-TL comparison. Also shown is the instability of the 73 km link, estimated [18] from independent round-trip measurements PTB-IQ-PTB. While the ADEV of the link falls off as $\sigma_y(\tau) = (2.1 \pm 0.5) \times 10^{-15}(\tau/s)^{-1}$, the ModADEV behaves as $\sigma_y^{\text{mod}}(\tau) = (7 \pm 1.8) \times 10^{-17}(\tau/s)^{-3/2}$. Thus, at 1 s measurement time, the link instability contribution is reduced by a factor of 30.

For both ADEV and ModADEV, the L2-TL traces coincide with the estimated link instabilities for very short time scales, i.e. no significant additional measurement noise or laser noise could be detected. Also, both traces eventually reach a flicker floor of a few $10^{-15}$. (The combined thermal noise contributions of the resonators of L2 and ML is calculated to be $1.1 \times 10^{-15}$.) However, in the case of the ModADEV, the performance of the remote laser comparison is already revealed after 100 ms and shows a flicker floor of $3 \times 10^{-15}$. The remote measurement results are close to the performance of state-of-the-art ultrastable lasers, as represented in fig. 3 by the previous results of the local comparison of ML to the ultrastable interrogation laser L(Yb$^+$) of the Yb$^+$ experiment at PTB [15].

For analysis in the frequency domain, we additionally implemented the operation in eq. (1) (divided by 4) by analog signal processing [16] using a direct digital synthesizer and double-balanced mixers. The spectrum of the remote transfer beat note $\frac{1}{T} (\nu_2 - \nu_3 - \nu_1)$, at 48.5 THz, between L2 and TL is depicted in fig. 4. It shows a linewidth of 1 Hz, limited by the spectrum analyzer used. By analyzing the spectrum of the remote beat signal, we optimized the laser system L2 in real-time. The beat signal also enables remote phase locking of a laser to the transferred light at the noise level of the stabilized fiber.

To conclude, we demonstrated a remote characterization of ultrastable laser systems on the $10^{-15}$ level on sub-second time scales. This displays the impressive potential of dissemination of ultrastable optical frequencies using long-distance telecommunication fiber networks for frequency metrology. Exciting applications are comparisons of optical clocks, remote high-precision spectroscopy or gravitational wave detectors. This work underlines the feasibility of expanding the distances bridged by the optical fiber links. Thus, the ultimate idea of a national [10] and European wide fiber network becomes a realistic scenario in the near future, which will strongly stimulate the field of fundamental physics and precision frequency metrology.

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