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Optical frequency dissemination for metrology applications

Dissémination de fréquences optiques pour applications métrologiques

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ABSTRACT

With the progress in the development of optical frequency standards grows the demand for the dissemination of stable optical frequencies. To date, optical fiber links constitute the most promising medium to bridge large geographical distances while still maintaining a high degree of frequency stability and accuracy. We investigated the transfer of an optical frequency along different fiber links during the past years and achieved a fractional instability and uncertainty at a level lower than 10^{-19} using fiber links with lengths of up to almost 2000 km. We give an overview of different techniques and methods that can be used in combination with optical fiber links to achieve a stable frequency transfer. The results of different fiber links are summarized and an outlook of future links is given.

RÉSUMÉ

Avec les progrès réalisés dans le développement de standards de fréquences optiques, les besoins en matière de dissémination de fréquences optiques stables augmentent. À ce jour, la fibre optique constitue le moyen le plus prometteur pour relier de grandes distances géographiques tout en maintenant une haute exigence en matière de stabilité et de précision en fréquence. Nous avons étudié le transfert d'une fréquence optique par différentes fibres au cours des dernières années et avons atteint une instabilité fractionnelle et une imprécision à un niveau inférieur à 10^{-19} pour des fibres optiques couvrant une longueur de presque 2000 km. Nous donnons un aperçu de différentes techniques et méthodes qui peuvent être utilisées en combinaison avec des fibres optiques pour obtenir un transfert de fréquence stable. Les résultats obtenus pour différentes fibres optiques sont résumés et un aperçu des futurs développements du transfert par fibre est donné.

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1. Introduction

Precise frequency references constitute the corner stone for many precision measurements in modern science. This is due to the fact that no other physical quantity can be measured with a better accuracy than frequencies. To take advantage of this, the measurement variables of various experiments are converted into a frequency whenever possible, which is then determined by comparing it to a well-known reference. The most stable frequency references are generated by frequency standards that use atomic transitions as an oscillator. Nowadays, the precision and instability of these frequency references approaches 1×10^{-18} if an optical transition is chosen [1–6]. Experiments that require the highest degree of precision directly profit from these impressively stable and accurate references [7,8].

Some applications, as for instance in the telecommunication industry, require a relative frequency precision of $\approx 1 \times 10^{-8}$ for the synchronization of base stations [9]. These requirements are routinely met by commercial cesium or rubidium frequency standards that can be operated on site [10]. More stringent requirements to the frequency reference are set by high-precision experiments that demand a frequency uncertainty on the order of $\approx 1 \times 10^{-14}$ or below [11]. For these applications, commercial active hydrogen masers are often used that provide a frequency reference with an instability of about 1×10^{-15}. Due to the high costs of those devices, hydrogen masers are mostly found in major precision measurement laboratories. State-of-the-art optical clocks to date generate frequencies with fractional uncertainties of below 1×10^{-17} and instabilities of a few parts in 10^{18} [1–3]. Optical clocks as well as atomic fountain clocks are not commercially available and mostly require a laboratory environment due to their complexity and sensitivity. For the same reason, they can hardly be transported.

To still be able to take advantage of these stable oscillators, it is desirable to transfer the frequency information from the clock location to distant sites. With the availability of satellites and the invention of global satellite navigation, stable frequencies can be transferred to basically every point on the surface of the earth [12]. The microwave transfer between satellites and ground stations, however, is limited to an instability and accuracy of $> 10^{-16}$ [13]. It therefore supports most microwave frequency sources, but is inadequate for the dissemination of optical clock signals. In the past years, optical frequency transfer using fiber links has gained substantial attention due to the ability to deliver optical frequencies with instabilities and accuracies of a few parts in 10^{19} [14–17]. It should be pointed out, however, that despite this good performance, a comparison of optical clocks on the level of 10^{-18} first requires a precise determination of the gravitational potential difference between the clock locations to verify that potential deviations between the clock outputs do not originate from relativistic effects [7]. In this report, we give an overview of the principles and methods of carrier-wave-fiber-based frequency transfer. The fiber links investigated in our group are briefly reviewed, while the longest link is discussed in more detail. We also show a prediction for the expected frequency instability of future long-distance fiber links.

2. Principles of fiber based frequency transfer

For the last several years, experiments on the transfer of frequencies via optical fibers have been performed with ever-increasing performance and fiber lengths. Different methods using optical signals for the transfer of frequencies have been investigated. An optical signal provided by a continuous wave (cw) laser can be amplitude modulated before it is sent through a fiber link [18], thereby transferring a microwave frequency. A combined transfer of microwave and optical frequencies can be achieved by transmitting pulses from a mode-locked laser [19]. Femtosecond pulses can also be used in combination with an optical cross-correlation technique to deliver a stable timing signal to a remote location [20,21]. Furthermore, an optical carrier wave can be disseminated by transferring the light of a stable cw laser. While for short distances up to a few tens of kilometers, all four methods show formidable performances, the latter one has been demonstrated to achieve excellent results in long-distance frequency transfer, due to the high carrier frequency and since no dispersion management is required.

In addition to the higher oscillating frequency, it is nowadays possible to generate optical frequencies with extremely low fractional instabilities below 10^{-15} in 1 s [22,23]. Furthermore, the telecommunication industry did tremendous pioneering work by investigating the transmission of light through glass fibers. The well-developed countries in Western Europe feature a large and dense glass fiber network that is mainly used for Internet data traffic. Therefore, using glass fibers to coherently transmit an optical carrier is an obvious approach.

In contrast to sending light over free-space [20], light that is transmitted through fibers experiences less perturbations, which enables better performance. Nevertheless, deployed fibers are, to some extent, inevitably subject to the environment that can affect the properties of the light that travels through them. The most prominent perturbations on optical fibers are thermal fluctuations and acoustic vibrations. Those perturbations lead to variations of the physical fiber length and to fluctuations of the fiber's refractive index. This in turn changes the optical path length and causes phase shifts often referred to as Doppler noise. These phase fluctuations set limits on the achievable stability and accuracy of the transmitted signal. If an optical frequency of 194 THz is transmitted through a 1000-km-long standard single-mode fiber (as in our experiments) that is affected by a temperature variation of 1 K during the course of one day, a fractional frequency shift of about 4×10^{-13} is introduced. Consequently, the fiber-induced phase fluctuations have to be detected and compensated in order to achieve a high stability and accuracy of the transferred frequency.

A simplified setup for the optical-fiber-based frequency transfer is shown in Fig. 1. An optical oscillator that consists of a cw laser operating at a wavelength of 1542 nm generates a stable optical signal. The light of this laser enters a Michelson

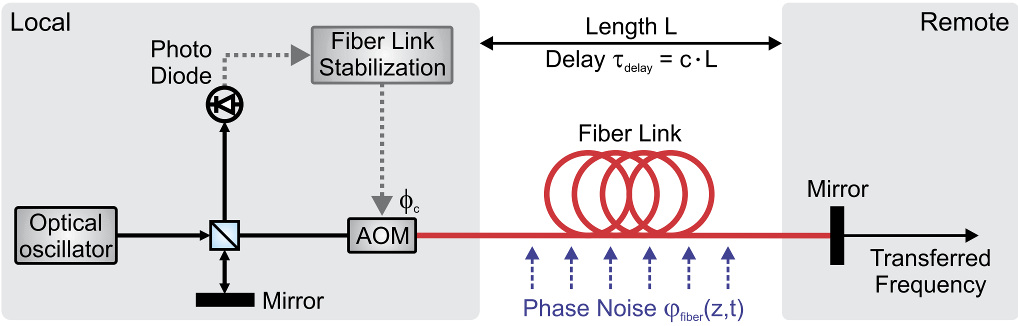

Fig. 1. (Color online.) Simplified setup for the optical fiber based frequency transfer. An optical frequency is sent through a fiber link. Environmental perturbations act on the fiber and introduce phase fluctuations in the optical signal. This fiber-induced phase noise is detected and compensated with an interferometric scheme. The fiber with length L introduces a signal delay τ_{delay} that determines the noise correction bandwidth. The fiber phase noise $\varphi_{\text{fiber}}(z,t)$ is a function of the position z and time t. AOM: acousto-optic modulator, ϕ_c: correction signal.

interferometer with a short reference arm and a long arm, which is the actual fiber link. At the end of the fiber link, a partially transparent mirror is used to retro-reflect a portion of the transferred light. The phase noise, φ_{fiber}, which is introduced by the fiber link, is detected by comparing the light from the two interferometer arms with each other. The heterodyne beat note that is generated on a photo diode is used to derive a correction signal, ϕ_c, to steer an acousto-optic modulator (AOM). This AOM shifts the frequency of the light in order to compensate for the fiber-induced phase noise. Since the round-trip light is used for the cancellation of the fiber-induced noise, this scheme also cancels the noise for the one-way signal, provided that the noise is identical for both propagation directions.

The finite velocity of the light in the fiber imposes a serious limitation on the achievable degree of phase noise suppression, as the presence of noise is detected only after the light traveled the entire fiber link twice. This directly affects the control bandwidth of the noise cancellation loop so that noise at higher Fourier frequencies cannot be suppressed. Another effect of the propagation delay, τ_{delay}, is that the light exits the fiber end before any correction can be applied. As a result, the fiber noise on the one-way signal cannot be suppressed entirely. As mentioned above, the phase noise cancellation system relies on the fact that the noise in the forward direction is identical to the noise in the backward direction so that the detected signal contains precisely twice the one-way phase noise.

The fast progress in the development of optical frequency standards accelerates the research on optical fiber links. To date, several countries around the world established links that reach from a few tens of kilometers up to almost 2000 km. Link lengths in excess of ≈ 100 km require the reamplification of the signals due to an optical attenuation in the fibers of about 0.2 dB/km for light around 1550 nm. There are different techniques for amplifying such optical signals. The most widespread one is an erbium-doped fiber amplifier (EDFA) that uses a section of active fiber to provide the gain for the signal to be amplified. This amplifier technique provides a moderate gain of up to 25 dB and a wide gain bandwidth covering ≈ 1530–1580 nm. Signal amplification can also be achieved by using stimulated Raman scattering (SRS) [24] in optical fibers. Such a Raman amplifier can provide gain comparable to that of an EDFA, while the gain bandwidth depends on multiple parameters like pump wavelength, pump power, fiber type, and others [25]. A third amplifier technique makes use of stimulated Brillouin scattering (SBS) [26] and, consequently, these amplifiers are often referred to as fiber Brillouin amplifiers (FBA) [27]. A total gain of up to 50 dB can be achieved with FBAs, while the gain bandwidth of just about 20 MHz is significantly narrower compared to the afore mentioned amplifiers. All of these amplifiers can be used to amplify a signal in both directions along the fiber. The fiber-induced noise cancellation relies on signals that travel in opposite directions in the fibers so that it has to be verified that all optical amplifiers offer bidirectionality.

In the meantime, a whole variety of different techniques have been employed as an alternative or an addition to the one shown in Fig. 1. Instead of delivering an optical frequency to a remote location, a two-way optical frequency comparison can be performed [28]. This method also allows the comparison of distant frequency standards, but in contrast to the technique shown in Fig. 1, no stable frequency is delivered to a remote location. Another interesting approach that is worth mentioning attempts to transfer a stable frequency to multiple remote locations simultaneously [29]. Here, a branching fiber network is used and the stabilization of the fiber link transfer is done at the remote end of the link instead of at the local end. This scheme allows a tree topology and a clear advantage of this technique is that in case of a malfunction of one of the link stabilization systems, all the other segments remain unaffected. This advantage comes at the cost of higher optical losses compared to the conventional technique described above. Delivering a stable frequency to more than one location can also be done by extracting a portion of the transferred signal at any point between the local and the remote end [30,16]. The signals traveling in the forward and in the backward direction between the two ends of the stabilized link can be used to derive a correction signal to extract a stable optical frequency. This way, many daisy chained locations along the actual fiber link can be served with an optical reference frequency. This approach comprises only one single fiber link stabilization control loop which reduces the complexity of the system. The extraction of the signal, however, introduces additional optical losses that have to be compensated.

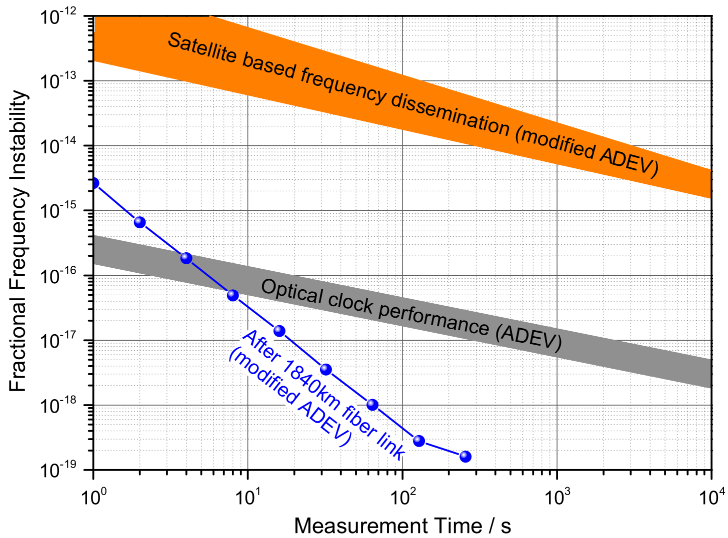

Fig. 2. (Color online.) Fractional frequency instability of satellite-based frequency transfer methods expressed as the modified Allan deviation (ADEV). Global navigation satellite systems or telecommunication satellites can be used to transfer a microwave frequency between ground stations [12,13]. The frequency instability (modified ADEV) after the longest fiber link investigated in our group demonstrates superior performance over the satellite links [15]. For comparison, the performance of today's best optical clocks is depicted [1–3].

Fig. 1 implies that the fiber link transfer has to be stabilized from the local to the remote site in one single step. However, this is not necessarily the case. It is also possible to cascade multiple fiber links by stabilizing each section individually [31]. The advantage of such a cascaded fiber link is an increase in fiber noise cancellation bandwidth due to a reduced propagation delay, τ_{delay}, and consequently a potentially lower instability of the transferred frequency. However, this configuration involves a more complex experimental setup due to the additional fiber stabilization systems.

3. Results and discussion

Throughout the past years, we investigated the transfer of a stable optical frequency via different fiber links through Germany. Our fibers are buried at least one meter below ground, which provides a good passive isolation against environmental perturbations. Additionally, all fibers exclusively carry the light that is used for the frequency transfer without any Internet data traffic. For the majority of experiments, we used a combination of EFDAs that are spaced by $\approx$ 90 km and FBAs located in the participating laboratories. All of our experiments were conducted by using a single-span stabilization.

The longest fiber link that we investigated so far formed a loop from the Max Planck Institute of Quantum Optics (MPQ) in Garching to the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and back to MPQ [15]. This fiber link had a total length of 1840 km, introduced an optical attenuation of about 420 dB and comprised 22 individual amplification stages. The propagation time of the round-trip light was close to 18 ms, thereby reducing the control bandwidth for the fiber noise cancellation to $\approx$ 27 Hz. We transferred a frequency of about 194 THz by sending the light of a cw laser through this link and coherently lock its returning phase. Despite the strongly reduced noise suppression bandwidth, we achieved a frequency instability of 3×10^{-15} in 1 s and 4×10^{-19} after only 100 s, as shown in Fig. 2. The transferred frequency has been measured with a high-resolution overlapping Λ-type counter and the frequency instability is expressed as the modified Allan deviation (ADEV) [32]. The comparison with the instability of today's best optical clocks sets this result into perspective. After 10 s, the fiber link noise averages down below the instability of even the best optical clocks. The demonstrated long-term optical clock instability of $1\text{–}2 \times 10^{-18}$ is about one order of magnitude above that of this long-haul fiber link. Fig. 2 clearly demonstrates the preeminence of the fiber link technology over satellite-based frequency transfer methods on distances up to a few thousand kilometers.

However, our aim is not only to deliver a stable optical frequency, but also the sent and transferred frequency should precisely match. In other words, the accuracy of the transferred frequency has to be verified independently as systematic frequency shifts are not revealed by the instability analysis. For this 1840-km fiber link, we compared the transferred frequency with the sent frequency over the course of three days. We could constrain any deviation between sent and received frequency to below 3×10^{-19}, which is less than 50 μHz for a frequency of 194 THz. We obtained similar results by transmitting clock signals over two independent fiber links between MPQ and PTB. Here, we compared a local optical oscillator at MPQ with a remote oscillator at PTB and vice versa. Again, with the lowest reported uncertainty for optical clocks to date of $1\text{–}2 \times 10^{-18}$ [1], the uncertainty of this fiber link is about one order of magnitude lower and therefore does not constitute any limitation for a remote comparison of such optical clocks.

Table 1
Investigated fiber links in our group for frequency transfer applications and the achieved performance. LUH: University of Hanover.

Link route	Link length	Instability	Uncertainty
PTB – LUH – PTB [34]	146 km	5×10^{-19} @ 10^4 s	1×10^{-19}
PTB – Cörmigk – PTB – LUH – PTB [27]	480 km	2×10^{-18} @ 10^4 s	2×10^{-18}
PTB – MPQ & MPQ – PTB [14]	920 km	7×10^{-18} @ 10^3 s*	4×10^{-19}
MPQ – PTB – MPQ [15]	1840 km	4×10^{-19} @ 10^2 s*	3×10^{-19}

* Modified Allan deviation.

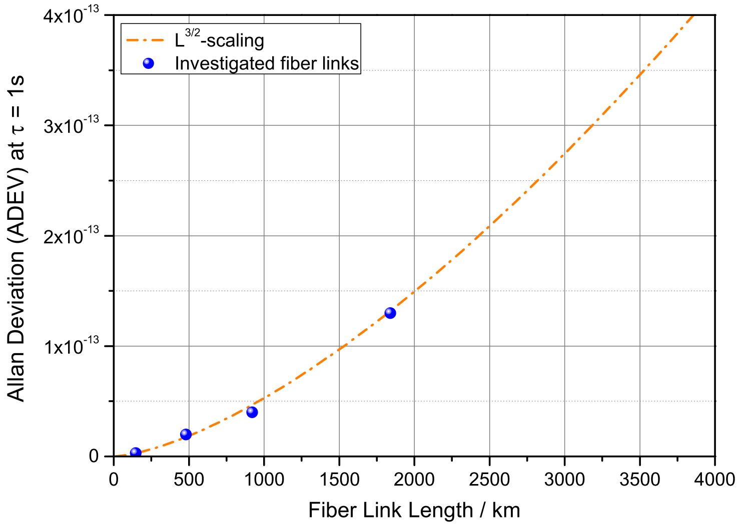

Fig. 3. (Color online.) Frequency instability expressed as the Allan deviation (ADEV) at a measurement time $\tau = 1$ s for fiber links that have been investigated in our group [34,27,14,15]. The achievable (short-term) instability scales with the fiber link length as $L^{3/2}$ as expected from [33].

Under the assumption that the fiber link has a spatial uniform noise distribution, it adds a certain amount of noise per unit length to the signal. At the same time, the one-way propagation time grows proportional to the fiber link length L. The triangle deviation of the transferred frequency measured with a high-resolution Λ-type frequency counter has a dependence from the measurement time τ of $\tau^{-3/2}$, while it scales with the fiber link length as $L^{3/2}$ [33]. The triangle deviation, the ADEV and the modified ADEV, come with the same scaling with L, whereas the ADEV has a dependency of τ^{-1} from the measurement time [32].

The different fiber links that we investigated during the past years are summarized in Table 1. Over the course of four years, we managed to increase the link length by more than a factor of ten, while maintaining or even improving the performance. The first fiber link characterized in our collaboration consisted of a fiber loop from PTB to the University of Hanover and back to PTB with a total length of 146 km [34]. A fractional frequency instability of the transferred frequency of 3×10^{-15} in 1 s was achieved. By taking this result as a reference, the $L^{3/2}$-scaling allows us to predict the achievable frequency instability for longer fiber links if a single-span stabilization is used. This prediction is shown as a dashed line in Fig. 3. For a 480-km link, the predicted 1-s frequency instability is $\approx 1 \times 10^{-14}$ and the actually achieved instability is 2×10^{-14} [27]. The achieved instability in the 920 km link is 3.8×10^{-14} [14] (prediction: 4.6×10^{-14}) and in the 1840 km link the achieved instability is 1.3×10^{-13} [15] (prediction: 1.3×10^{-13}).

The $L^{3/2}$ scaling technically only holds under the assumption that the fiber-induced noise is distributed equally over the entire fiber length and that the total noise scales linearly with increasing link length. The results demonstrate that the scaling is still valid for link lengths of up to $\approx$ 2000 km, even though entirely different fiber links were investigated. Fig. 3 also illustrates the evolution of achievable frequency instabilities for longer fiber links. As can be seen, even with a fiber link that would span all across Europe, highly stable frequency transfer could still be achieved, provided that the fiber noise is on the same order of magnitude compared to the links that we investigated so far.

4. Summary and outlook

Throughout the past years we dedicated our work to the transfer of stable optical frequencies via fiber links. With a demonstrated instability and uncertainty at the lower 10^{-19} level for a fiber link that measures close to 2000 km in length, we reached a performance that is sufficient to connect all the major precision measurement laboratories within Europe for the purpose of transferring highly stable optical signals without a significant degradation. Currently, the first international fiber links are under construction and expected to go in operation within the next years [35]. Most of the future fiber links in Europe will have a length of around 1000 km or less as, for example, PTB – SYRTE: ≈ 1200 km, MPQ – SYRTE: ≈ 950 km, SYRTE – NPL: ≈ 450 km and INRIM – LENS: ≈ 650 km. Given the progress in the development of optical frequency standards, it might be required to improve the frequency transfer performance of optical fiber links in a few years from now. This can be achieved by splitting the links into multiple sections as mentioned above to gain control bandwidth for fiber noise cancellation. Additionally, advanced loop filters or even digital phase locked loops can be implemented, which are designed for the unique noise and signal delay properties of fiber links. Therefore, it is expected to still be able to improve the frequency transfer performance.

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