Invited Paper

# Telecommunication fiber link for the remote characterization of a magnesium optical frequency standard

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## ABSTRACT

We have characterized the $^{24}$Mg optical frequency standard at the Institute of Quantum Optics (IQ), Hanover, using a clock laser at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, via a noise compensated 73 km fiber link and present preliminary results for the stability of the Mg standard. The stability of the clock laser ($\lambda$ = 657 nm) is transferred with a femtosecond frequency comb to a telecommunication laser at $\lambda$ = 1542 nm. The signal is then transmitted from PTB through the fiber link to IQ. A second comb at IQ (the remote end) is used to compare the transmitted laser frequency with that of the Mg clock laser $\lambda$ = 914 nm. The frequency ratio of the clock lasers $\nu_{Mg}/\nu_{Ca}$ shows a relative instability < $10^{-14}$ at 1 s. The upper limit for the contribution of the fiber link to the frequency instability is measured by connecting another optical fiber following the same 73 km route at Hanover computer center. The comparison performed at PTB between the local and the transmitted signal after a round trip length of 146 km showed a relative uncertainty below 1 x $10^{-19}$ and a short term instability $\sigma_y(\tau)$= 3.3 x $10^{-15}$/ ($\tau$/s).

**Keywords:** optical frequency transfer, stabilized fiber link, remote optical frequency measurement, optical frequency standard, frequency comb.

## 1. INTRODUCTION

Recently, cold atom or single ion clocks based on optical transitions have surpassed the performance of the best microwave clocks and have the potential to reach a relative uncertainty below $10^{-17}$ together with a short–term fractional frequency instability $\sigma_y$ of a few $10^{-15}(\tau/s)^{-1/2}$ [1, 2]. Such clocks are considered for a possible redefinition of the second. However, a prerequisite for a future redefinition is the ability to compare and disseminate optical frequencies at the corresponding level of uncertainty and stability of the optical clocks. Considering that optical clocks are not yet transportable due to their complexity, the use of optical fibers for the comparison of distant optical clocks has been discussed extensively [3, 4, 5]. Many other applications can also profit from the remote optical clock comparison such as the search for the change in fundamental constants, high precision test of the theory of general relativity, and GPS navigation. Additionally, the optical fiber link provides a novel way of calibrating the optical frequencies recommended for the practical realization of the meter.

In this paper, we characterize the Mg optical frequency standard at IQ, Hanover using the Ca clock laser and an H-maser referenced to a Cs fountain clock at PTB, Braunschweig via a 73 km fiber link. This approach takes advantage of the superior short-term stability of the Ca clock laser and the better long-term stability of the H-maser. The frequency stability of an ultra-stable optical frequency at 194 THz is transmitted over a noise compensated 73 km long underground fiber. We first describe the complete system used for the frequency measurement of a Mg frequency standard. Then we present some details of the fiber link and the optical phase stabilization system that compensates the phase fluctuations

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induced by the optical link. We characterize the stability of the frequency transfer through the fiber and finally present the first remote measurement of the frequency stability of the Mg frequency standard at IQ in Hanover.

the phase noise and frequency stability of an ultra-stable optical frequency at 194 THz transmitted over a noise compensated 146 km long underground fiber. The optical phase stabilization system that compensates phase fluctuations induced by the optical link is described. In the following section, using the stabilized link, we measured the stability of Mg-clock laser at IQ with respect to the Ca-clock laser at PTB and an H-maser referenced to a Cs fountain clock. This approach takes advantage of the superior short-term stability of the Ca clock laser and the better long-term stability of the H-maser.

## 2. CHARACTERIZATION OF THE MAGNESIUM FREQUENCY STANDARD

### 2.1 Setup for the frequency measurement

In this section we will present the setup used to measure the magnesium ($^{24}$Mg) frequency at IQ, Hanover, using the frequency standards at PTB, Braunschweig, over a distance of 73 km. The setup is shown in fig. 1. Since it is not possible to transmit the frequency of the Ca clock laser [6, 7] directly to Hanover using an optical fiber because of its high attenuation at 657 nm, we used a telecommunication laser (NIR) operating at 1542 nm. In order to transfer the stability of the Ca clock laser to the NIR laser, we used a transfer technique developed by Telle et al. [8] to establish a beat between the Ca clock laser at 657 nm and the NIR laser at 1542 nm without introducing additional noise from the comb.

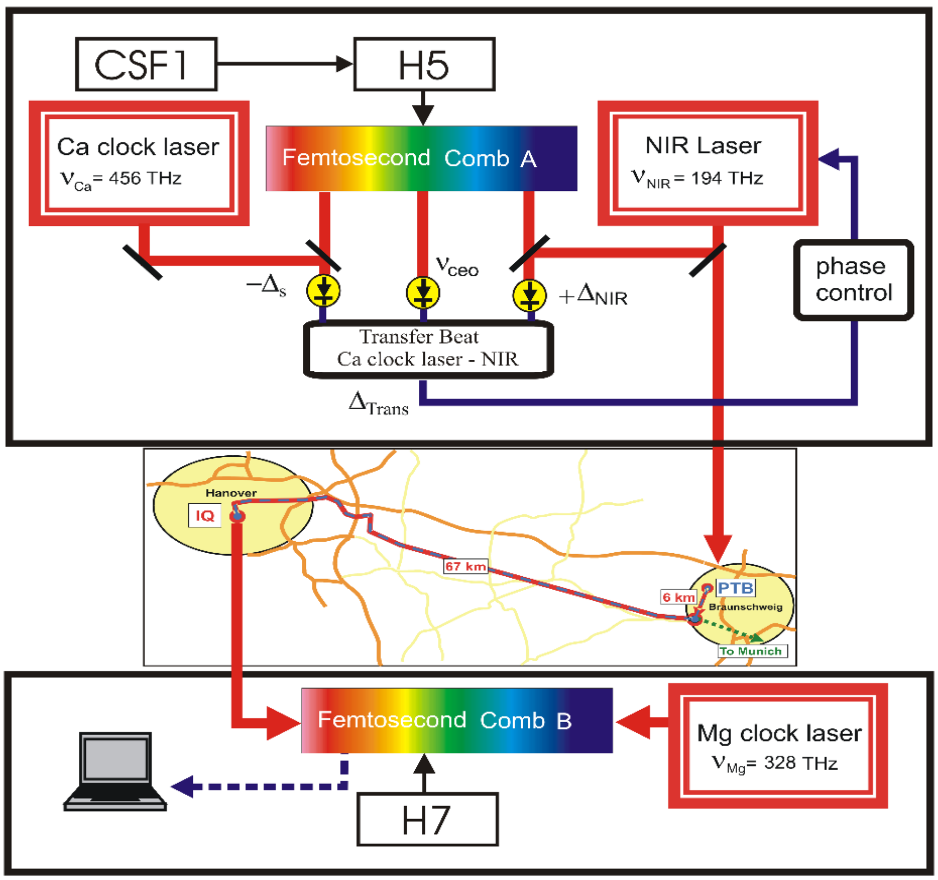


Figure 1: Setup for comparison of two optical frequency standards, comprising a Ca clock laser $\nu_{Ca}$ at 456 THz, a fiber laser $\nu_{NIR}$ at 194 THz, a $^{24}$Mg clock laser $\nu_{Mg}$ at 328 THz and two fs-frequency combs A and B. The PTB comb A was locked to a H-maser (H5) referenced to the Cesium fountain CSF1. The IQ comb is locked to an H-maser (H7). At the remote end the transfer beat was calculated from the measured individual beat signals.

A digital phase locked loop is used to compare the phases of the transfer beat and a local oscillator. Sending the control signal to a piezo-electric transducer (PZT) attached to the NIR laser, the laser is locked to the Ca clock laser. The control bandwidth of the loop is limited to approx. 10 kHz by a first PZT resonance at about 30 kHz. More details are described in [9]. The stabilized frequency of the NIR laser is then transmitted through the phase-noise compensated link of 73 km as will be discussed later in section 2.2.

At Hanover, a second transfer beat between the transmitted signal and the Mg clock laser is generated using the local frequency comb similar to the one at PTB, but stabilized to a transportable, passive H-maser (H7). The Mg clock laser is an extended cavity diode laser, which is stabilized to an ultra-stable optical resonator using the Pound-Drever-Hall scheme. More details about the Mg clock laser are found in Pape et al. [10]. With this setup, the short term stability of the Mg clock laser is measured against the Ca clock laser, while the long term stability of the $^{24}$Mg frequency standard is measured against the H-maser (H5) which is referenced to the Cs fountain CSF1, one of PTB's primary frequency standards.

### 2.2 Compensation of the fiber link noise

To link the optical clock lasers at PTB and IQ a dedicated pair of dark fiber with a length of 73 km was established in collaboration with the German Science Network DFN, GasLINE GmbH, and a local telecommunication provider in Braunschweig (EnBs). The fiber link comprises a commercial SMF-28 fiber according to the ITU-T G.652 standard, and about 16 splices and 10 connectors. It has an attenuation of about -23 dB. The selection of a fiber route in the side-strip of a gas pipe line assures that the fiber is well sheltered from environmental noise.

When a laser signal at 1542 nm (NIR) is transmitted through the 73 km fiber link, acoustic and thermal fluctuations along the fiber link introduce phase fluctuations. In order to detect and compensate these phase fluctuations, a fiber interferometer (fig. 2) based on commercial fiber components was constructed similar to a scheme described by L. Ma et al. [11]. At the input and the remote end of the fiber acousto-optic modulators (AOM-PTB) are installed. A Faraday mirror (FM) reflects part of the light back towards the input and rotates the state of polarization 90 degrees to passively compensate for any polarization changes occurring in the fiber link [12]. The acousto-optic modulator (AOM-IQ) at the remote end is used to discriminate the desired reflection from the Faraday mirror from the backscattered light within the fiber or reflections from connectors or splices.

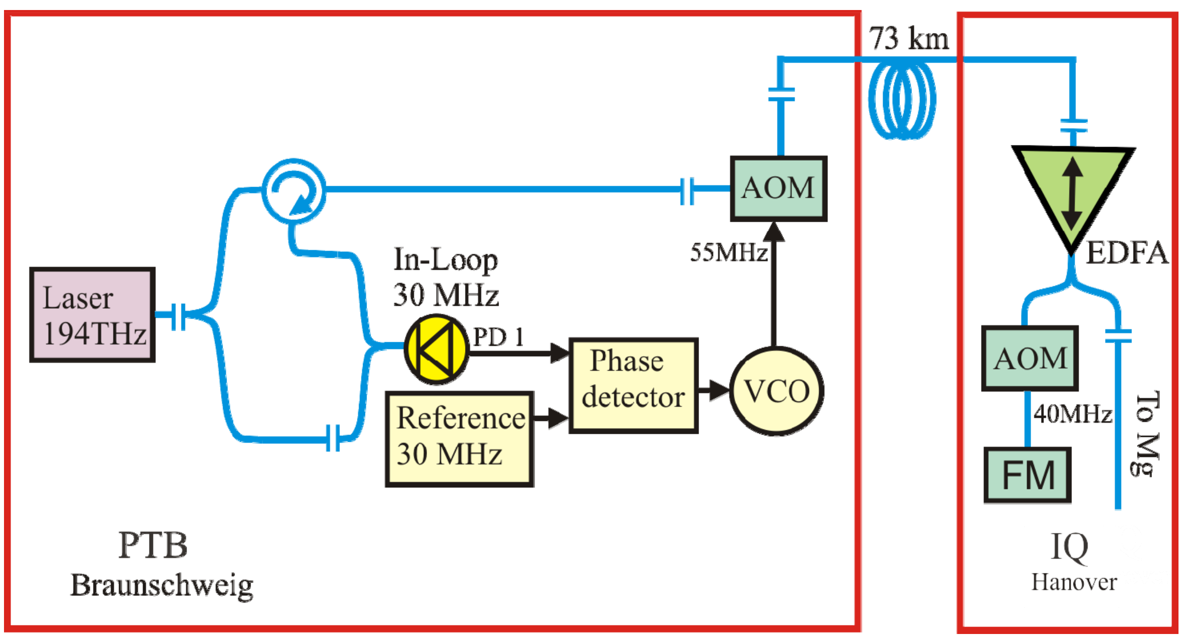


Figure 2: Setup for active fiber noise compensation. OC: optical circulator, AOM: acousto-optical modulator, VCO: voltage controlled oscillator, PD1: in-loop photo detector, EDFA: Erbium-doped fiber amplifier, FM: Faraday rotator mirror.

At the remote end the attenuation of the optical link is partially compensated using a bidirectional Er:doped amplifier (EDFA). After a full round trip, an interferometer measures the phase excursions accumulated along the link by comparing the light back-reflected from the remote end with the light from a short reference arm on a photodetector PD1. Phase stabilization is achieved by locking this beat signal to a local oscillator using a digital phase locked loop by feed-back of the control signal to AOM-PTB, which is located at the input of the fiber link. Analyzing the stabilized rf signal derived from photo detector PD1 provides an in-loop measurement of the residual phase noise. More details about the interferometer can be found in [13].

### 2.3 Characterization of the link stabilization

Both fibers linking PTB and IQ are located in the same strand and are affected by the same environmental conditions. To investigate an upper limit for the instability of the transferred signal at the remote end we connected both fibers at Hanover computer center (less than 1 km from IQ), forming a total length of about 146 km and placing remote end and reference arm at the same location (PTB). The signal measured is then an out-of-loop signal, which results from interfering the one-way light with the reference arm. It should be noted that in order to make this measurement or to stabilize the link, the laser coherence length must be much larger than the length of the fiber, which is 292 km for the round-trip signal, otherwise laser noise will degrade the measurement. The free running NIR laser line width is about 5 kHz, which corresponds to coherence length of about 20 km. However, when the laser is stabilized to the Ca clock laser it reaches a line width in the order of few Hz [9], which is completely sufficient to measure phase fluctuations introduced from the fiber link without introducing any additional noise from laser [14]. The Allan standard deviations (ADEV) of the stabilized and unstabilized out-of-loop signal are shown in fig. 3.

As Williams et al. pointed out in [14], the phase noise of the fiber link can't be fully compensated due to the delay introduced by the link. The residual noise due to the delay $\tau$ of a 146 km fiber is given by $S_D(f) = 6.6 \times 10^{-6} \cdot f^2 \cdot S_\phi(f)$, where $S_\phi$ is the noise introduced by the fiber, and $S_D$ is the residual noise after fiber link stabilization.

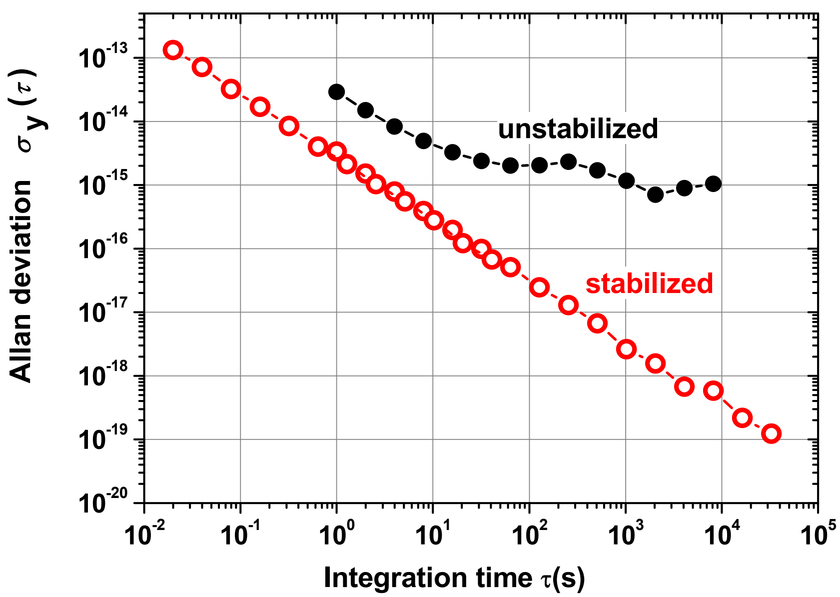


Figure 3: Relative frequency instability of the out-of-loop beat signal for the unstabilized (black dots ●) and stabilized (red open circles ○) link.

The compensation bandwidth is limited by 1/4τ, which is approx. 350 Hz for our 146 km link. The theoretical limit for the compensation is -52 dB at 1 Hz. From our measurement, we found that the compensation bandwidth is about 260 Hz, and a noise reduction of -45 dB at 1 Hz is achieved.

Beside the attainable stability, any small residual frequency offset between the frequency at the local site and that at the remote end is of fundamental importance. The accuracy of the transmitted frequency was checked by comparing the measured mean value of the out-of-loop signal with the expected value. Passing both AOMs (55 MHz (+1st order) and 40 MHz (-1st order)), the frequency at the remote end should be shifted by exactly 15 MHz with respect to the local end. The observed mean deviation of the transmitted optical carrier frequency given by the sample average of the full data set was $\Delta\nu = (-1.4 \pm 3.3)$ μHz. The statistical uncertainty of the mean was calculated from the standard deviation divided by the total number of data points, white phase noise, and it is found to be $1.7\times10^{-20}$. A more conservative estimate for the statistical uncertainty of the transmitted optical frequency is given by the last data point of the Allan standard deviation (see fig. 3), after 9 hours a relative frequency instability of $1.3\times10^{-19}$ is reached. More details are given in [15].

### 2.4 Stability of the $^{24}$Mg frequency standard

An earlier measurement of the absolute frequency of the $^{24}$Mg standard was limited by the stability of a portable Cs clock (black squares ■ in fig. 4) [16]. The short-term stability of the measurement could be improved using a transportable passive maser (H7). However, as indicated by the blue open circles ○ in fig. 4 the measurement of the $^{24}$Mg frequency standard is still limited by the stability of H7 and an even better frequency standard is required.

The fiber link allows us to benefit from frequency standards with superior stability at PTB; both in the microwave domain (active H maser) and the optical domain (Ca clock laser).

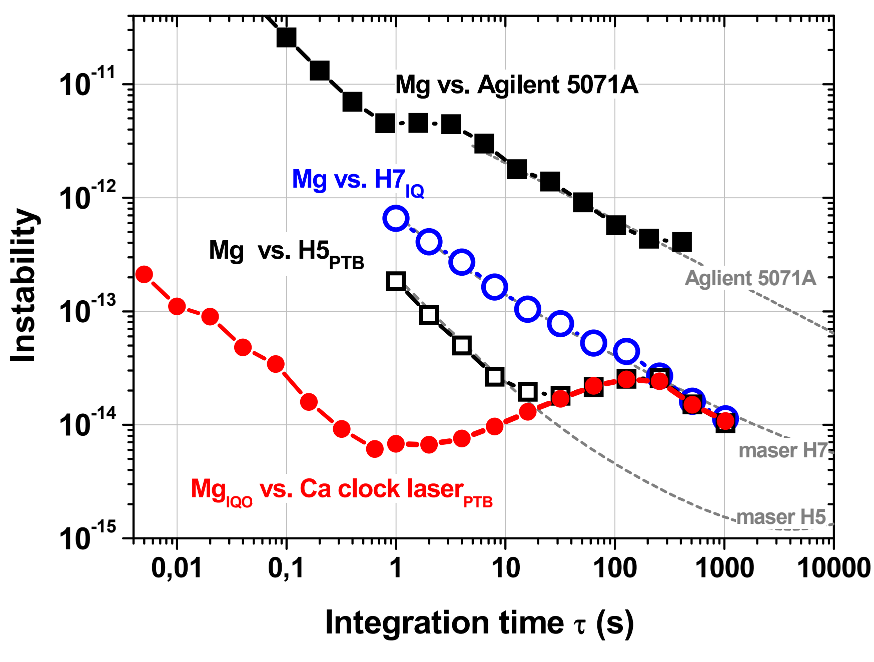


Figure 4: The stability of the $^{24}$Mg frequency standard measured against (H5-CSF1) at PTB is shown as open squares □, against Ca clock laser is shown as red dots ● (a small linear cavity drift was removed), against H7 at IQ is shown as blue open circles ○, and against a portable Cesium clock is shown as black squares ■.

Since the optical frequency comb at PTB is pre-stabilized to H5, the frequency of the NIR laser can be measured with respect to this microwave reference (and CSF1). Combining simultaneous measurements of the NIR-H5 frequency ratio at PTB ($\nu_{NIR}/\nu_{H5}$) and the NIR-Mg frequency ratio at IQ ($\nu_{NIR}/\nu_{Mg}$) allows us to eliminate the noise contribution of H7 and to relate the $^{24}$Mg frequency to a primary standard at PTB. The result is shown as black open squares □ in fig.4. Since the instability of H5 is lower than that of the remote Mg standard for $\tau > 20$ s, H5 can be used to evaluate the long-term performance of the Mg frequency standard.

However, to investigate the full performance of the Mg frequency standard at shorter time scales, the direct comparison with the Ca clock laser is indispensable. The red dots ● in fig.4 show preliminary results of the Mg standard for an integration time of $0.02\text{ s} < \tau < 1000\text{ s}$, derived from the measurement of the frequency ratio ($\nu_{Mg}/\nu_{Ca}$). For the analysis we removed a small linear drift of the Ca clock laser.

The advantage of using the fiber link is not only to provide short term characterization of clock lasers, it also allows to evaluate systematic frequency shift of the remote standard within several minutes. With the absolute frequency measurement of the clock transition currently performed and envisaged improvements the Mg standard can reach a level of $\sigma_y(\tau) = 1\times10^{-13}/(\tau/\text{s})^{1/2}$ in near future and provide a reference frequency at the $10^{-15}$ -level, that can serve as a secondary frequency standard for the dissemination of stable frequencies within the university of Hanover.

## 3. CONCULUSION

We have presented our capability of remotely comparing optical frequencies in a fully phase coherent way by using a carrier frequency in the optical telecommunication window. We used standard SMF28 fiber to connect the Ca clock laser at PTB, Braunschweig with the improved $^{24}$Mg standard at IQ, Hanover over a distance of 73 km. In order to analyze the instability limits of the fiber link we connected two similar fibers of 73 km at Hanover computer center to return light to PTB after crossing a distance of 146 km. We showed that a 146 km standard telecommunication fiber can be used to transmit an optical frequency standard with an instability of $\sigma_y(\tau) \leq 3.3\times10^{-15}/(\tau/\text{s})$ for $0.01\text{ s} < \tau < 30000\text{ s}$ and a relative frequency uncertainty below $1\times10^{-19}$, if we compensate the frequency fluctuations of the link. This enables the analysis of the frequency stability of the Mg clock lasers at IQ by using the Ca clock laser at PTB after a few seconds. Finally, the long term stability of $^{24}$Mg frequency standard at IQ was measured against the H-maser H5 referenced to the Cs fountain CSF1.

## 4. ACKNOWLEDGMENT

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