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Swiss Fiber Network for Dissemination of Optical Frequencies in the L-band of a Telecommunication Network

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Abstract *We present a phase-stabilized metrological optical frequency dissemination network spanning over 456 km, multiplexed into the L-band ITU-T channel 7 of the Swiss academic data network. Our solution provides efficient shared use of existing fibers for ultra-precise time and frequency signals for scientific applications and beyond. ©2022 The Author(s)*

Introduction

Comparison and dissemination of stable and accurate frequency and time signals bear relevance in a broad spectrum of fields spanning from fundamental research in metrology[1], precision spectroscopy[2] and relativistic geodesy[3], to more applied aspects such as synchronization of large scale facilities[4]. Complementing the well-established satellite techniques[5], phase-stabilized fiber optic networks have become a state-of-the-art for metrological frequency dissemination with performances overcoming those imposed on the former.

The technical implementation of metrological frequency signals into fiber networks requires a dedicated fixed frequency channel, which is particularly challenging when dark fibers are not available. Recently, several phase-stabilized frequency metrology networks have been deployed in *C-band* ITU-T channel 44 (CH44), both in dark fibers and in networks shared with data traffic[4],[7]–[10]. Given the heavy data load and requirements of dynamic spectral allocation of modern telecommunication equipment, it is however desirable to push such an 'alien' fixed frequency channel out of the *C-band*. Here the *L-band* provides an obvious and versatile alternative.

In this paper we present the Swiss frequency dissemination network in the *L-band* ITU-T channel 07 (CH07), multiplexed into the academic fiber network of Switzerland provided by SWITCH. We extend on previous results and characterizations[6] and show how the setup can be used to read out and quantify antropogenic noise imposed on the fibers, and provide an evaluation the frequency stability in dependence of time.

Concept

Our fiber network consists of three segments of a total length of 456 km, connecting laboratories at the Swiss Federal Institute of Metrology METAS, the University of Basel and ETH Zurich (see Fig. 1 for the network layout). The main purpose of the network is to provide reference frequencies from METAS to precision spectroscopy laboratories in Basel and Zurich. To that end, at METAS, we prepare a laser source with an ultrastable and accurate frequency at ITU-T CH07 (190.07 THz), traceable to the the International System of units (SI) definition of the second via comparison to state-of-the-art atomic clocks. This frequency is injected into a fiber connecting the laboratory at METAS to the one at the University of Basel, using optical add-drop multiplexing filters on the 100 GHz DWDM grid. The spectral characteristics of these filters were measured using the setup described in[11] and shown in Fig. 2. Note that the isolation of the filters decreases for wavelengths below around 1400 nm, which has to be taken into account in the network design. In Basel, part of the light is coupled out for local use, while the rest is injected into the subsequent segment, connecting the University of Basel to Zurich. There once more part of the light is kept for local use, while the rest is sent through the network back to METAS to form a closed loop network topology allowing for end-to-end comparison of the disseminated frequency.

The stability and accuracy of the disseminated frequency is subject to noise processes imposed by the environment onto the fiber. We compensate these effects using the established Doppler noise cancellation scheme[12],[13] on each of the

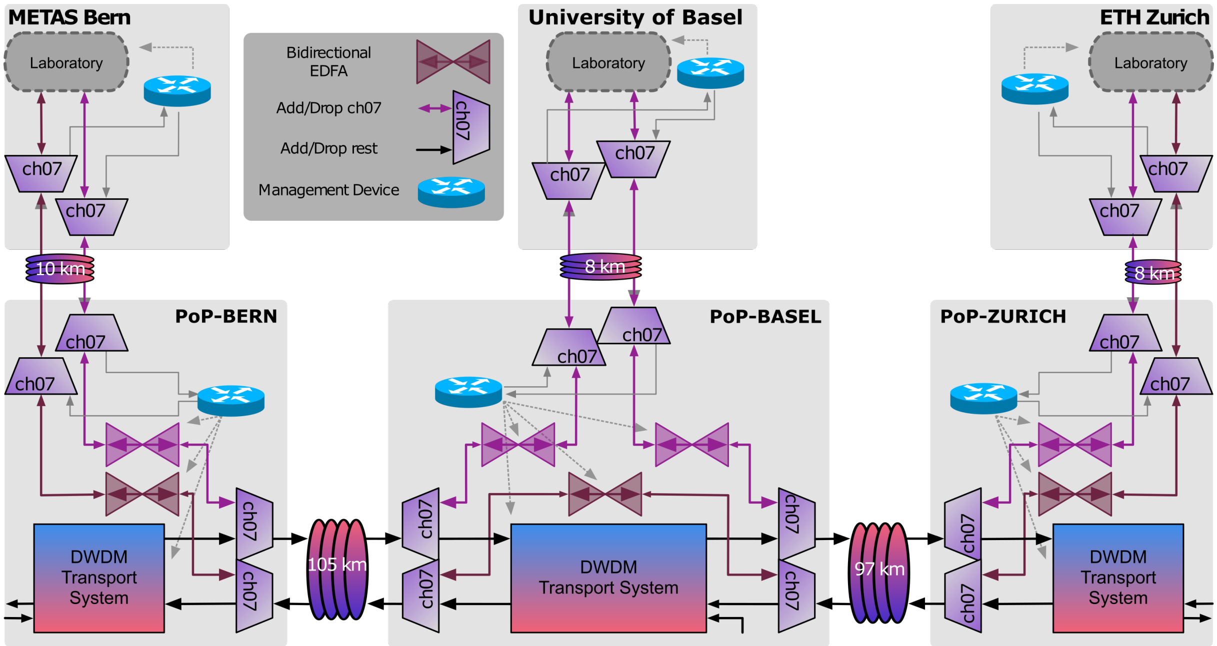

Fig. 1: Network layout. The metrological frequency signal is multiplexed into the DWDM transport system of the SWITCH network using 100 GHz OADM filters for CH07. Bidirectional EDFAs compensated power losses in the fibers. Each of the three segment Bern-Basel, Basel-Zurich and Zurich-Bern contains a phase noise cancellation setup on the laboratory side (not shown here). Network routers and switches (blue cylinders) enable communication to the EDFAs an between the laboratories. This figure is part of Fig. 1 in[6], adapted without modification.

three fiber segments. The link stability performance is quantified in terms of the residual frequency error $\Delta\nu(t)$ of the light arriving in Bern after traveling through the whole network. The frequency is measured by beating it with an original copy of the signal sent out, shifted by 120 MHz, and measuring the frequency of the beat signal with a frequency counter. The residual error is an accumulation of noise contributions along the whole 456 km fiber link. We use this observable to quantify the noise imposed on the fibers as a function of time of the day.

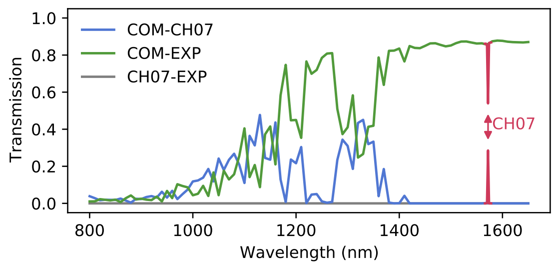

Fig. 2: Spectral transmission between individual ports of the ITU-T CH07 DWDM filters used in this project. Blue (Green): Transmission from COM to Ch07 (EXP) port, showing an isolated transmission peak (dip) at the CH07 wavelength of 1572.06 nm (marked in red). Gray: Transmission from CH07 to EXP, showing high isolation.

Results and Discussion

With the described network, we achieve an relative frequency instability of the disseminated light of around 4.7×10^{-16} for 1 s, and 3.8×10^{-19} at 2000 s integration time, as reported previously[6]. This renders the network suitable for the dissemination of state-of-the-art atomic clock signals.

On a day-to-day basis, we observe variations of $\Delta\nu$ depending on the weekday and the time of the day, with significantly reduced noise during the night, weekends and holidays. As an example, Fig. 3 shows a time trace of the residual frequency error measured over 17 days with 1 s sampling. In order to analyze these diurnal stability changes, we measure the standard deviation σ_ν from the nominal frequency as a function of time of the day. This is shown in Fig. 4, where we have calculated σ_ν in bins of 30 min. Here we see a striking manifestation of the diurnal fluctuations, with a sharp increase at around 5 am, and a steady decrease starting at around 3 pm, reaching the minimum at around 1 am. Further we see strongly reduced noise levels on weekends (red) as compared to workdays (blue). The pattern of noise variation with weekdays and the time of day coincides with traditional workday schedule and the related antropogenic noise originating from sources such a road and railway traffic.

To further analyze the non-stationary character of the noise, we calculate the Allan deviation σ_y of the fractional frequency uncertainty of this data set. The results is shown in Fig. 5, where we plot the Allan deviation for the full data (black), as well as the Allan deviation of smaller bins of 10^3 (red), 10^4 (blue) and 10^5 (green) data points. The latter

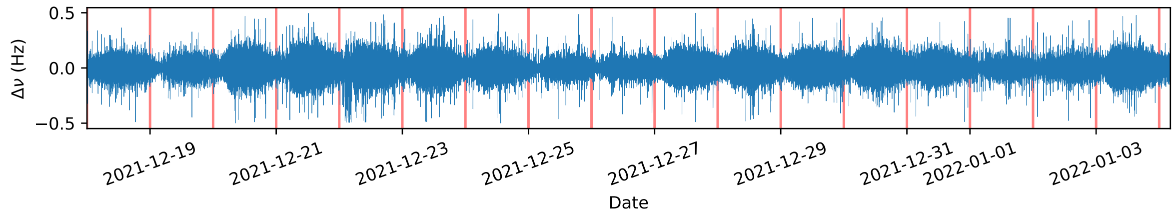

Fig. 3: Time trace of the residual frequency error $\Delta\nu$ of the full round-trip signal, measured with 1 Hz sampling. Red lines mark midnight for each day.

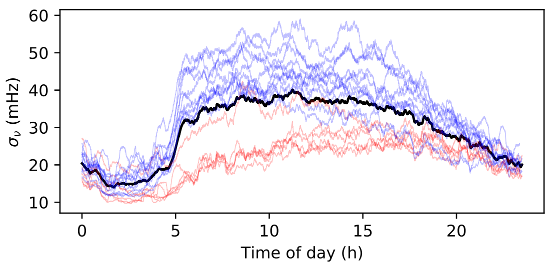

Fig. 4: Standard deviation σ_ν as a function of the time of the day, showing a manifestation of day-night fluctuations of noise levels in the fiber. Blue: work days. Red: weekend days. Black: average. The standard deviation is calculated from 30 min bins of data.

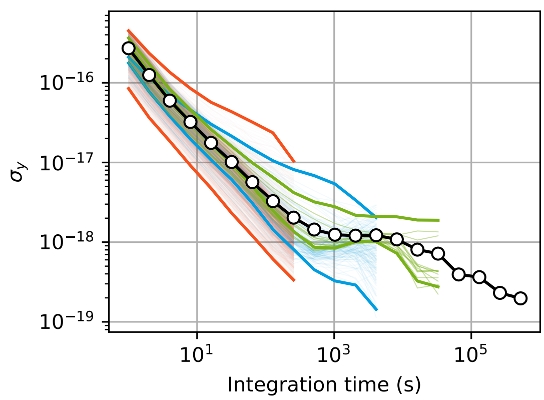

Fig. 5: Allan deviation of the disseminated frequency. Black: full data set. Green: re-sampling in bins of 10^5 points. Blue: bins of 10^4 points. Red: bins of 10^3 points.

yield sets of curves, for which we have marked two extreme curves with stronger bold lines to indicate the overall spread. The flattening of the curves for longer times is due to increasing probability of cycle-slips and hence loss of coherence with increasing measurement time. In addition, for integration times longer than half a day, there is a flattening of the curves due to diurnal variations. This evaluation can help on the choice of measurement window and time on the frequency receiver side.

Conclusion and Outlook

The results presented here underline the versatility of the *L-band* for the use of frequency dissemination for metrological applications. The shared architecture with multiplexing into an existing data network allows efficient use of fibers, while guaranteeing non-interference between the two applications. In addition, we can exploit the residual frequency fluctuations of the metrological signal in order to obtain intriguing information on antropogenic noise along the fiber link. Although compared to other established fiber sensing techniques such as distributed acoustic sensing, our technique does not allow for spatial resolution, here we can cover long fiber spans of hundreds of kilometers. This noise evaluation comes at minimal added effort to the standard operation of the metrological frequency dissemination networks, and provides valuable information for the user side on optimal performance of the frequency link.

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