Frequency dissemination with less than 2×10^{-18} fractional-frequency instability over 120 km of a commercial fiber infrastructure

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***Abstract*— This work presents frequency dissemination with fractional-frequency instability of 2×10^{-18} at a 100-second interrogation time on a single-mode fiber communication infrastructure, the system consisted of a Michelson interferometer over 120 km of optical fiber connecting the Weizmann Institute of Science and Tel Aviv University. We used optical add-drop multiplexers to incorporate the Michelson interferometer into an active communication infrastructure and used it to detect the phase noise accumulated on the fiber channel. A phase-locked loop controlling an acoustic optic modulator was used to correct it. This facilitated distributing a phase-stable frequency at the remote station.**

Keywords—Michelson interferometer, Acoustic optic modulator (AOM), Optical add-drop modulator (OADM).

I. Introduction

Frequency dissemination is an essential architectural element in optical-frequency metrology, enabling the dissemination of highly stable laser sources to various users [1,2] in fields such as atomic timekeeping, geodesy, and fundamental physics. These highly stable lasers facilitate high-precision measurements and atomic-clock comparisons between remote locations. As the laser light passes through the fiber, it encounters various phase noise sources caused by strain and temperature variation, which change the refractive index of the fiber and degrade the linewidth of the stable source. A leading approach to reducing these noise sources is by correcting the phase changes using the Michelson interferometer [3] for coherent phase measurement, accumulating the phase noise added in the fiber channel, and correcting phase variations with acoustic optic modulators (AOMs).

This paper presents an architecture implemented at the Weizmann Institute of Science (WIS) that uses a Michelson interferometer to transfer a stable laser to Tel Aviv University (TAU) and back for a total distance of 120 Km. The system was implemented on the institutional infrastructure using optical add-drop multiplexing (OADM), where TAU is the central station that could be connected in the future to other universities around the country. We present the full system, which uses a locking system to correct the accumulated phase noise in the fiber link. Chapter II will explain the frequency dissemination concept, Chapter III will introduce our system, and Chapter IV will present the system's characterization at the WIS by showing the Allan and modified Allan deviations with power spectral density, with and without phase noise cancellation.

ISF: National Quantum Metrology Network Equipment, Israeli Ministry of Science.

II. The Optical Frequency Dissemination Concept

Optical frequency dissemination refers to transferring a highly stable laser from a local station through a fiber link to a destination station, as seen in Fig. 1. The fiber link introduces frequency perturbations due to mechanical and thermal disruptions along the infrastructure. These frequency perturbations can be compensated using a Phase-locked loop (PLL) in conjunction with AOMs.

A. The Basic Phase Compensation Approach

Fig. 1 presents the compensation approach. A stable laser is passed into a Michelson interferometer with a reference arm and transmitted to the link by shifting the laser frequency using the AOMs. The laser is reflected from a Faraday mirror and interferes with the reference arm. The frequency perturbation is seen in Fig. 1 as a $\delta\varphi(t)$ phase change at position z. The various phase accumulations at the remote station and the round trip can be calculated as described below.

B. The Remote and Local Stations

As described above, the reflected light interferes with the local reference arm. The phase noise accumulated during the round trip is denoted by forward and backward phase perturbations at position z [3]:

$$\varphi_{fibe\_RT}(t) = \int_0^L \delta\varphi\left(z, t - \frac{z}{c_n}\right) + \delta\varphi\left(z, t - \frac{2L-z}{c_n}\right) dz \quad (1.1)$$

Where c_n is the light velocity in the fiber, and L is the fiber length. After spectral analysis, the local station spectral improvement depended on the gain $G(w)$ of the PLL [3]:

$$S_{local}(w) = \left|\frac{1}{1+G(w)}\right|^2 S_{fibe\_RT}(w) \qquad (1.2)$$

Where $S_{fibe\_RT}(w)$ is the round-trip phase noise accumulated in the fiber. As the gain of the PLL increases, the in-loop phase noise decreases, emphasizing the contribution of the noise cancelation.

For the remote station, which does not see the whole in-loop reduction because of its position in the fiber link, the phase noise accumulated along the forward line is in one direction only:

$$\varphi_{Remote}(t) = \int_0^L \delta\varphi\left(z, t - \frac{L-z}{c_n}\right) dz \qquad (1.3)$$

After spectral analysis using noise cancelation and as $G(w) \to \infty$ [3], the improvement that can be reached is:

$$\frac{S_{remote}}{S_{fiber}} = a(2\pi f \tau)^2 \qquad (1.4)$$

Where S_{remote} is the power spectral density with a noise cancelation system at the remote station, S_{fiber} is the phase noise accumulated in the entire fiber, a is 1/3 the uniformly distributed noise, τ is the line delay, and f is the spectral density frequency.

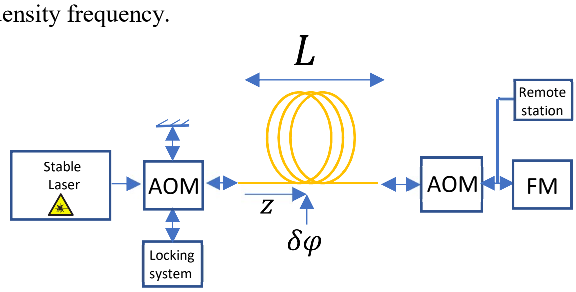

Fig. 1. A basic frequency dissemination diagram based on the Michelson interferometer.

III. System Architecture

The full system implementation is shown in Fig. 2, where a 1,560 nm stable laser passes through the free air Polarized Beam splitter (PBS) and creates the reference arm with a $\frac{\lambda}{4}$ plate and a mirror. The light enters the 120 Km fiber, passes to the OADM, is amplified, and is reflected to the remote station by a Faraday mirror (FM) while coupling a signal to the remote station, the interference with the original source let us evaluate the performance on the link transfer. The reflected signal interferes with the laser source. A 10 MHz signal is created from the frequency difference between the two AMOs. The signal entering the phase detector is compared to a Rubidium atomic clock. The phase difference is fed into a Proportional Integral Derivative (PID) and a frequency modulator to compensate for the radio frequency phase that reenters the AOM.

IV. Results

Fig. 3 shows the power spectral density of the phase noise accumulated in the fiber channel with and without noise cancellation, as described above. The figure shows that at an offset of 1 Hz, the improvement was about $\frac{S_{remote}}{S_{fiber}} \cong 50\ dB$,

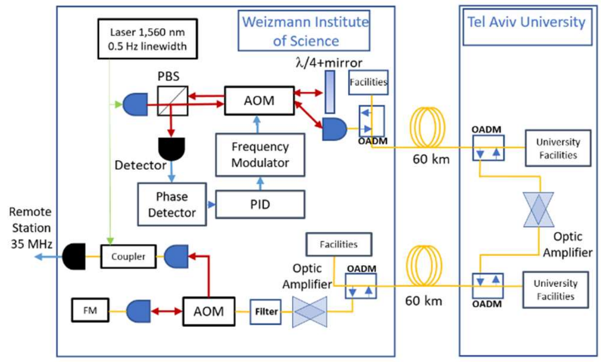

Fig. 2. Full system architecture connecting WIS to TAU. (FM: Faraday Mirror, Red lines: Air optical signal, Yellow: Fiber, Green: PM Fiber, Blue: Electric signal, the Blue shapes are coupling from air to fiber, the Black shapes are intensity detectors).

which conforms with equation 1.4 for $a = 1/3$, $f = 1\ Hz$, and $\tau = 1.2\ ms$. It led to a delay in performing a Π window for the Allan deviation and a Λ window for the Modified Allan deviation [4]. The Allan deviation shows a τ^{-1} characteristic

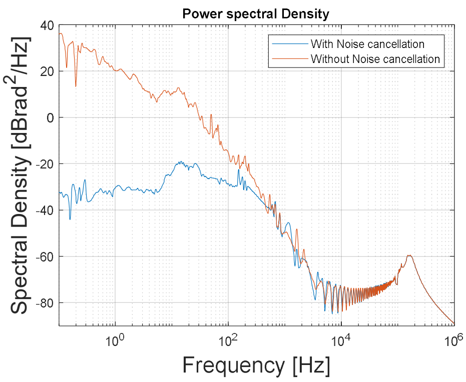

Fig. 3. There was a big improvement in the power spectral density of the phase noise when noise cancelation was used.

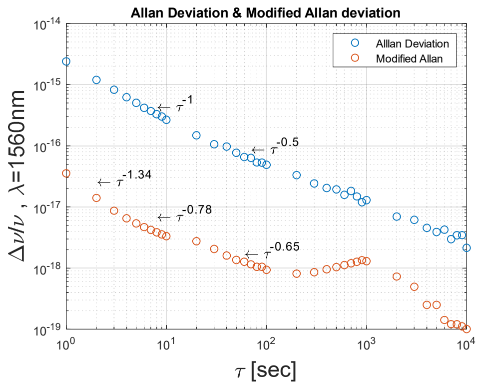

Fig. 4. Allan deviation and Modified Allan deviation, where the different slopes show the contribution of each noise characteristic.

slope that suggests a flicker and white phase noise [5], and a $\tau^{-0.5}$ for white frequency modulation. The modified Allan deviation shows that the flicker and white Phase Modulation

(PM) separate where the slope is $\tau^{-1.34}$, similar to the white PM ($\tau^{-1.5}$), the fiber link noise, $\tau^{-0.78}$ for the flicker PM (τ^{-1}) and $\tau^{-0.65}$ for the white FM. The modified Allan deviation shows a fractional frequency instability below of 1×10^{-18} after averaging for 100 s and 1×10^{-19} after $10{,}000$ s.

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