Optical Frequency fiber dissemination at 10^{-19} uncertainty level in Italy

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Abstract—We describe the realization of a coherent optical fiber link for the metrological frequency dissemination on the national scale. This infrastructure will improve the frequency references used in radio-astronomy and in atomic physics and will benefit several laboratories in Italy involved in high resolution spectroscopy, matter physics and radioastronomy. The present infrastructure will be part of a forthcoming European network of optical links. This paper describes the haul implementation, the characterization and the future applications of this backbone.

Keywords—coherent fiber links, frequency metrology, optical fibers

I. INTRODUCTION

The advent of optical clocks, with unprecedented accuracy and stability opened the door to new applications in fundamental physics, geodesy and radio-astronomy [1,2]. On the other hand, these frequency standards are not transportable, and the resolution of state-of-the-art techniques for the frequency transfer, based on satellites, does not allow a full exploitation of these experiments [3]. In recent years, it has been demonstrated that the frequency dissemination via optical fiber can improve the remote comparison of optical frequencies by 5 orders of magnitude [4-6, and refs. therein].

The coherent transfer of optical phase is based on the transmission of a continuous wavelength laser with an ultra-narrow linewidth of few hertz along a standard telecom fiber. To avoid that temperature variations and acoustic noise deteriorate the phase stability during the transfer, a Doppler cancellation scheme is adopted, in which a double pass of light into the fiber is exploited [6].

The capability to transfer the optical phase over thousands of kilometers without deterioration is not only a crucial improvement for the remote clocks comparison and the fundamental physics experiments. It also opens the door to novel applications, such as the realization of giant optical gyroscopes [7,8], the synchronization of telescope antennas [9] and particle accelerators [10], and might benefit telecommunications as well. This is the reason why a great work has been done in Europe to develop a continental optical network for the frequency dissemination on optical fiber [11]. This topic found a lot of common issues and contact points with telecommunication, such as the sharing of the same hardware [12], the development of specific amplification techniques [13,14], and the adoption of existing apparatus [15].
The Italian National Metrology Institute (INRIM) in Turin, together with the European Laboratory of Non Linear Spectroscopy (LENS) in Florence, the Institute of Astrophysics (INAF) in Medicina (Bologna) started the LIFT project in 2012 and realized a 642 km coherent link over a commercial fiber that connects these laboratories, providing frequency dissemination at an unprecedented level of accuracy and stability on a national scale [16].

This paper describes the technique, the installation of the apparatus, and the characterization technique.

II. EXPERIMENTAL SETUP

The experimental setup for the ultrastable frequency transfer is shown in Fig. 1 (a). An ultra-narrow linewidth laser at 1542.14 nm is realized by frequency locking to an high finesse Fabry-Pérot cavity through the Pound-Drever-Hall technique. The resulting laser linewidth is < 30 Hz [17]. The laser is injected in the 642 km optical fiber and travels through the link, up to LENS in Florence, where it is extracted and used as a frequency reference. At LENS, part of the radiation is also reflected back through the same optical fiber, and reaches INRIM. To distinguish the coherent signal from the Rayleigh backscattering of the fiber, the radiation is frequency shifted by an acousto-optic modulator (AOM2) before reflection. At INRIM, an heterodyned beatnote can hence be performed between the original and the round-trip signal; this allows the detection of the link phase noise, and its active cancellation. This is done by pre-compensating the phase of the injected radiation through the acousto-optic modulator AOM1.

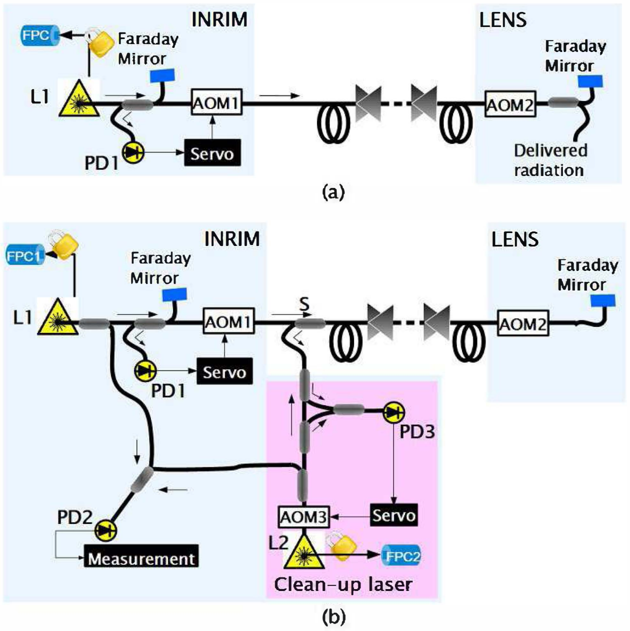

Figure 1 (a) The setup of the link Turin-Florence. The fiber laser L1 is frequency-locked to a Fabry-Pérot cavity (FPC1) and injected in the link. AOM1 and AOM2 are the local and remote acousto-optic modulators, respectively used for the noise cancellation and fixed frequency shifting. Photodiode PD1 is used to detect the fiber noise. 9 bEDFA are placed along the path (shown as triangles). (b) The setup of the doubled link. The laser coming back from LENS is extracted and regenerated through the clean-up laser L2. L2 is pre-stabilized on a Fabry-Perot cavity (FPC2) and phase-locked to the round-trip signal using AOM3 as actuator. A part of the radiation from L2 travels the double link in the backward direction, the remainder is phase-compared to L1 on photodiode PD2.

The link has 171 dB of optical losses, that are partly compensated by 8 bidirectional Erbium Doped Fiber Amplifiers (bEDFA) placed along the path. To permit the bidirectional operation of the haul, dedicated systems have been developed, which do not include optical isolators. Therefore, the large amount of direct and, most of all, backscattered Amplified Spontaneous Emission (ASE), saturates the gain of each amplifier of the chain and leads to strong oscillations of the systems. In few cases, the original performances of the amplifiers could be recovered by a strong optical filtering of the signal. The behavior of each amplifier when tested in field is a function of the position in the amplifiers chain and of the fiber and splices quality, hence each device was tested during installation. Fig. 2 shows the behavior of the bEDFA used in Piacenza.

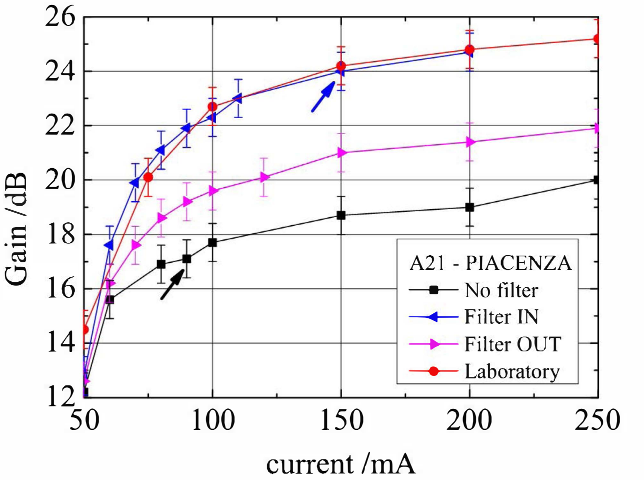

Figura 2: the gain of one of the bEDFA used in Piacenza, when used alone (red line, circles) or in the chain. The gain is reduced by about 5 dB if no filtering is used (black line) and the behaviur was strongly dependent on the filter placement (before or after the amplifier). The arrows indicate the threshold for the system's oscillations.

The link has been characterized by a looped configuration scheme that has both ends at INRIM. In this way, the total length is 1300 km. The setup for characterization is shown in Fig. 2 (b): at the remote station, a second ultrastable laser is phase-locked to the incoming radiation by using the acousto-optic modulator AOM3. A part of it is extracted, the remainder is injected in the fiber and travels the link in the opposite direction. This signal is used at the local station to perform the link stabilization, while the extracted fraction is directly compared to the original laser for characterization purpose.

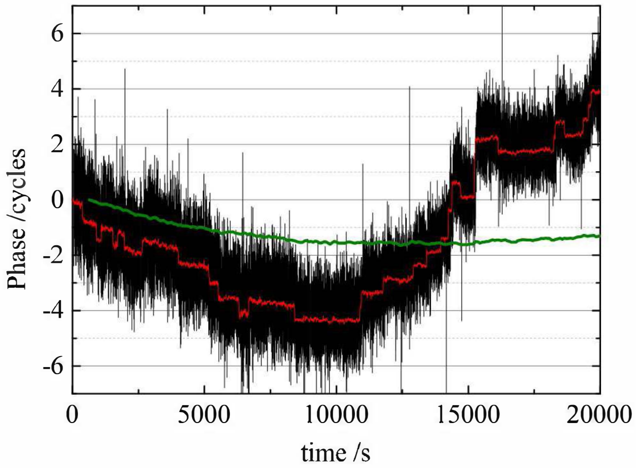

Fig. 3. The measured optical phase of the stabilized link. Black line: samples are filtered on a 1 Hz bandwidth; red line: samples are filtered on a 0.05 Hz bandwidth; green line: data are filtered on a 5 mHz bandwidth, and phase slips have been removed.

Figure 3 shows the measured optical phase of the compensated link after 1284 km. The phase samples have been subsequently filtered on a bandwidth of 0.05 Hz to detect any loss of coherence due to phase-slips of the Phase-Locked Loop (PLL) involved in the noise compensation apparatus.

These are statistical events that depend on the signal to noise ratio, and occur in multiples of $\pi/2$. Once removed, it can be seen that this setup allows the compensation of the fiber phase noise down to less than 2 cycles of excursions in several hours of operation. The phase noise of the doubled link before and after the fiber phase noise cancelation is shown in Fig. 4. The residual noise is limited by delay, as derived in [6], and is in good agreement with the expectation for this fiber.

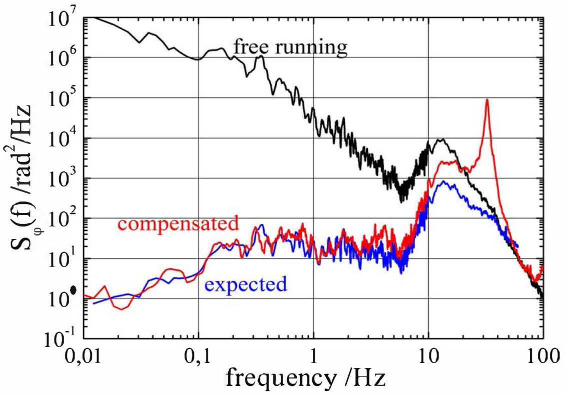

Fig. 4. The phase noise of the doubled link in free-running (black line) and phase-stabilized (red line) operation, and the expected residual noise (blue line).

LIFT exhibits a short term frequency instability of 1×10^{-14} at 1 s averaging time on a bandwidth of 1 Hz, and achieves an ultimate stability of 3×10^{-19} at few hours of averaging time. We attribute an ultimate accuracy on the frequency transfer of 3×10^{-19} , due to the repeatability of the results. This is also the level at which distant frequencies can be compared through this scheme, and encompasses the performances of state-of-the-art frequency references.

If compared to the 10^{-10} instability of common satellite techniques for T&F transfer, LIFT is $\sim10^5$ times faster for ensuring traceability of remote measurements to the SI time unit.

III. CONCLUSION

This work describes the realization and characterization of the Italian optical link for frequency dissemination. The realized infrastructure enables the delivery of optical frequency at the 5×10^{-19} level of accuracy in few hours of averaging time, and shows that the phase of an optical carrier can be delivered across thousands of kilometers without deterioration due to temperature, acoustic and seismic environmental noise; this opportunity opens the door to new experiments in the field of Length and Frequency metrology, fundamental physics and radio-astronomy, which the LIFT project will investigate in the near future.

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