Optical Frequency Transfer with a 1284 km Coherent Fiber Link

D. Calonico, E. K. Bertacco, C. Calosso, C. Clivati, A. Godone, M. Frittelli, A. Mura, M. Zucco and F. Levi
Optics Division
Istituto Nazionale di Ricerca Metrologica (INRIM)
Turin, Italy

G. A. Costanzo,
Electronic Department
Politecnico di Torino,
Turin, Italy

N. Poli, D. V. Sutyrin, G. M. Tino,
Università di Firenze, LENS and INFN,
Sesto Fiorentino (FI), Italy

***Abstract*—We realized a coherent optical fiber link in Italy, with a fiber haul of 642 km. To characterize the link, we doubled the link to 1284 km, demonstrating a characterization technique based on the double round trip on a single fiber. The link is intended to significantly improve the frequency references used in radio-astronomy and precision measurements in atomic physics. The data analysis is based on the Allan deviation, whose expression is theoretically derived from the noise power spectrum. The demonstrated resolution is $3x10^{-19}$ in 1000 s and the uncertainty of the transfer is $5x10^{-19}$. The arming of a second fiber is avoided, and this could be rather beneficial to long hauls realizations for a continental fiber network for frequency and time metrology.**

Keywords—optical fiber link, frequency metrology, ultrastable laser

I. INTRODUCTION

Coherent optical fiber links have been demonstrated to be a unique mean to transfer time and frequency signals or compare remote optical frequency standards [1-11]. With respect to satellite techniques, the improvement is as large as four orders of magnitude [12]. For example, they are the only viable method to compare optical clocks, thus they are a key metrological technology in view of a possible redefinition of the second based on those new standards. Moreover, optical links could allow to realize a network of accurate clocks, especially in Europe. This network would establish a unique facility for testing fundamental physics, relativistic geodesy and for improving global navigation satellite systems [13-15]. Optical links would have even a larger impact on the fundamental research, as they could allow to improve the synchronization in VLBI radio-telescopes and particle accelerators [16-18].

In this Proceeding, we describe the optical fiber link of 642 km implemented in Italy, named LIFT (Italian Link for Time and Frequency) [19]. LIFT will connect the Italian metrological institute (INRIM) to different Italian scientific poles. In 2013 LIFT completed the connection to Florence, to the scientific pole of Sesto Fiorentino, where it will provide the frequency reference to the University of Florence, the European Nonlinear Spectroscopy Laboratory (LENS) and the National Institute of Optics of the National Research Council. In June 2014, it was completed the connection from INRIM to the radio-telescope of the Institute for Radio-Astronomy in Medicina (Bologna). In July 2014 it is expected the extension from Torino to the border Italy-France. This connection will be established within the Frejus tunnel, connecting INRIM to the Laboratorie Souterraine de Modane.

Fig. 1. Example of a figure caption.

The metrological performance of the link has been evaluated by looping the link so that the signal goes from INRIM to LENS and then comes back to INRIM, after traveling 1284 km in the optical fiber. This loop has been realized using a single fiber, thus avoiding the need of arming a separate twin link for the bare characterization purpose.

The link instability is evaluated using the Allan deviation as estimator. From the measured noise power spectrum density we have deduced an analytical expression for the Allan deviation. This approach is equivalent to the use of the Modified Allan deviation. The long term performance of the link was evaluated using a sharp digital filtering, that allowed also for cycle slips detection.

978-1-4799-5252-6/14/$31.00 ©2014 IEEE

II. EXPERIMENTAL SET-UP

LIFT is based on a mixed fiber architecture. It is mainly installed using a dedicated fiber, that connects Torino to Florence. The haul from Bologna to Medicina is implemented with DWDM multiplexing on a dark channel (ITU-44). The extension to the Frejus tunnel uses a mixed architecture DWDM and CWDM.

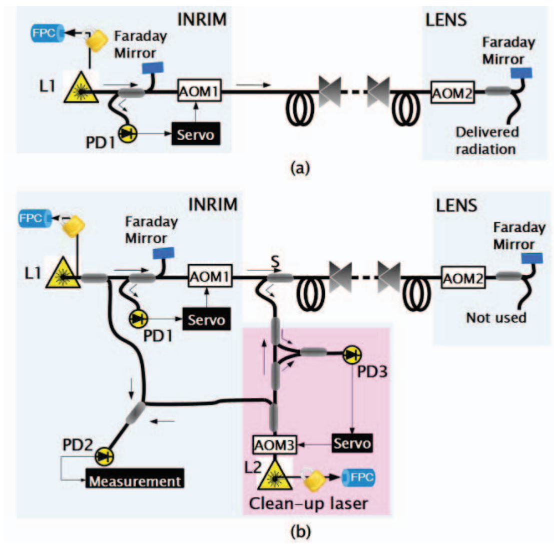

Fig. 2. Experimental set-up (see text for details).

The main connection has 172 dB losses, compensated by nine bidirectional Erbium Doped Fiber Amplifiers (bEDFA). The transfer laser is a fiber laser at 1542.14 nm, frequency-stabilized to an ultrastable Fabry-Perot cavity to obtain a linewidth <30 Hz [20]. The link is phase stabilized through the Doppler cancellation technique [21]. The set-up is shown in Figure 1(a). The ultrastable laser L1 is sent to LENS. In the remote laboratory a part of the signal is extracted and represents the delivered signal; the remainder is reflected back to INRIM using a Faraday mirror, which compensates the fiber birefringence. The acousto-optic fixed frequency shifted AOM2 is used to distinguish the reflected signal from undesired back-reflections along the fiber, that are not frequency-shifted. The round-trip signal is phase compared at INRIM to the local laser on photodiode PD1. This beat note contains the information about the noise added by the fiber on the roundtrip signal. It is used to stabilize the link with a phase locked loop (PLL) acting on the acousto-optic modulator AOM1. Usually, the characterization of optical links is pursued using a second fiber in the same bundle with an independent set of amplifiers [1,2]. In this work, we demonstrate a characterization technique that uses a single fiber and avoids the doubling of the infrastructure. The set-up is shown in Figure 2(b). The L1 radiation travels to LENS and is reflected back to INRIM, where it is extracted through the splitter S. A second independent ultrastable laser L2 works as a clean-up oscillator for the incoming signal and is phase-locked to it by acting on the acousto-optic modulator AOM3. The L2 radiation is injected in the link in the opposite direction, to provide a double-round-trip signal, needed for the 1284-km link stabilization. The clean-up laser is required due to the relevant wide band noise added by the optical amplifiers. L2 tracks the delivered radiation, hence the link performances are analyzed by comparing L2 to L1 on the photodiode PD2.

III. CHARACTERIZATION

The PD2 beat note phase noise spectrum is shown in Figure 3, (free running and the Doppler compensated link). The double link delay is 6.4 ms, so the loop bandwidth is about 39 Hz. The noise of the compensated link achieves the fundamental limit set by the round-trip delay [22].

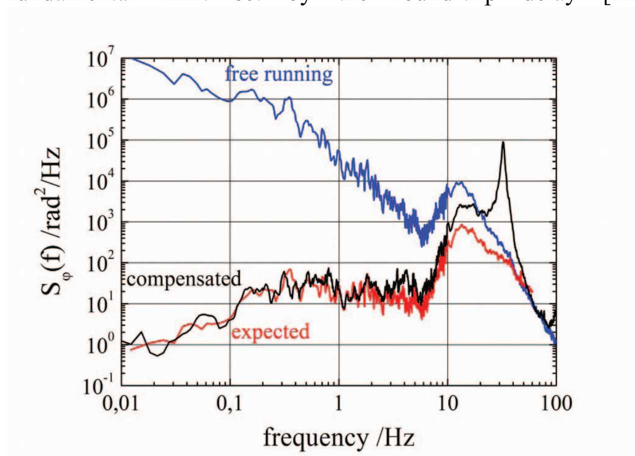

Fig. 3. Noise power spectrum density of the free running link, of the compensated link and of the expected delay limit..

The loss of phase coherence (cycles slips) [23] on the PLLs, that affects both the instability and the inaccuracy. The cycles slips rate mainly depends on the signal to noise ratio of the beat notes. In our set-up, the cycles slips are a few per hour, provided a polarization adjustment of the long arm every few hours.

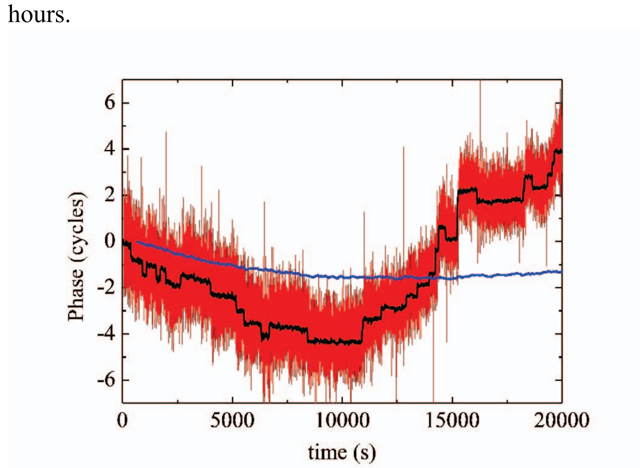

Fig. 4. Raw data (red), filtering with 0,05 bw (black line), re-alignement and further filtering (blue).

The phase of the beat note on PD2 is measured with a dead-time free digital phase recorder [24], at the sampling rate of 1 ms equivalent to a 500 Hz bandwidth filter. The cycles slips are barely visible on the raw data even when filtered at 1 Hz bandwidth, as shown in Figure 4 (black line). Filtering the data on a bandwidth of 0.05 Hz enables their detection (red line). Particular care is devoted to the filtering process: a Finite Impulse Response (FIR) filter [25] is applied to the raw data, with an out-of-bandwidth attenuation >70 dB between 10 and 100 Hz.

We realign the phase by subtracting an integer number of 0.5 cycles, i.e. the minimum slip amplitude. Finally, the phase data are further filtered (5 mHz bandwidth) and differentiated to obtain the instantaneous frequency.

To evaluate the frequency instability, the Allan deviation estimator is used [26]. From Fig. 3, the frequency noise spectrum of the link is modeled [27] by the relation $S_y(f)=h_3f^3$, that is quite uncommon in time and frequency metrology. Hence, we theoretically calculate the Allan variance from the frequency noise power spectral density, obtaining $Adev^2(t_a)=3f_h^2t_a^{-2}/(8Pi^2)$, for $t_a>1/2f_h$, where f_h is the measurement bandwidth set by a sharp filter. The measured instability is in good agreement with the prediction.

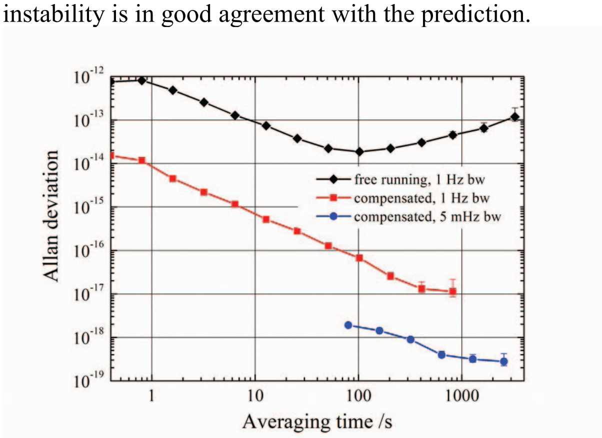

Fig. 5. Link instability. Allan deviation of uncompensated link (diamonds); compensated link with 1 Hz bw (squares) and 5 mHz bw (circles).

Figure 5 shows the Allan deviation of the free running and compensated optical link on a 1 Hz measurement bandwidth, together with the stability of the compensated link on a 5 mHz bandwidth. The link achieves a short term instability of $1x10^{-14}$ at 1 s in a 1 Hz bandwidth and an ultimate frequency resolution of $3x10^{-19}$ in a 5 mHz bandwidth.

We evaluate the accuracy of the link at $5x10^{-19}$ because a non-repeatable offset observed at this level exceeds the obtained frequency resolution. In spite of this, the present frequency dissemination accuracy is beyond the most challenging requirements of any application. If the Modified Allan deviation of the raw data is computed, we obtain the correspondence shown in Figure 6 The ModAdev is proportional to t_a^{-2} as evaluated in [3]. The Allan deviation has always a t_a^{-1} dependence, but reducing the bandwidth, the first relevant point, that is at $t_a=1/2f_H$, is always on the Mod Adev curve.

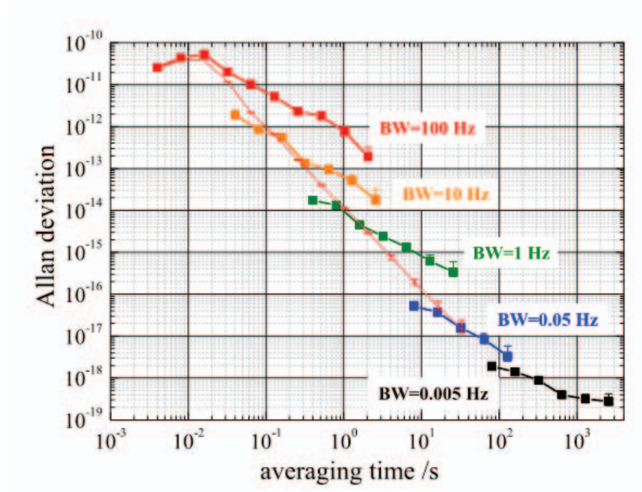

Fig. 6. Allan deviation with different bandwidths and Modified Allan deviation of the raw data (red line)

In conclusion, we have realized a coherent optical fiber link for frequency transfer over a 642 km haul, and doubling its length on the same fiber, we demonstrated the frequency dissemination over 1284 km. A short term Allan deviation of $1x10^{-14}$ at 1 s on the bandwidth of 1 Hz is observed with and an ultimate accuracy on the frequency transfer of $5x10^{-19}$ after about one hour of measurement. The LIFT project will now be extended to Medicina and the Frejus tunnel. We plan also to implement new techniques for taming the noise introduced by the fiber, in particular the optical Two Way method described in [28]

ACKNOWLEDGMENT

This work was supported by: the Italian Ministry of Research MIUR under the Progetti Premiali program and the PRIN09-2009ZJJBLX project; the European Metrology Research Program (EMRP) under SIB-02 NEAT-FT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

REFERENCES

[1] O. Lopez, A. Haboucha, F. Kéfélian, H. Jiang, B. Chanteau, V. Roncin, C. Chardonnet, A. Amy-Klein, G. Santarelli, "Cascaded multiplexed optical link on a telecommunication network for frequency dissemination," Opt. Express 18, 16849-16857 (2010).

[2] K. Predehl, G. Grosche, S. M. F. Raupach, S. Droste, O. Terra, J. Alnis, Th. Legero,T. W. Hänsch, Th. Udem, R. Holzwarth, H. Schnatz, "A

920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th decimal place," Science 336, 441-444 (2012).

[3] S. Droste, F. Ozimek, Th. Udem, K. Predehl, T.W. Haensch, H. Schnatz, G. Grosche, and R. Holzwarth, "Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link", Phys. Rev. Lett. 111, 110801 (2013)

[4] O. Lopez, A. Kanj, P. Pottie, D. Rovera, J. Achkar, C. Chardonnet, A. Amy-Klein, G. Santarelli "Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network," Appl. Phys. B 110, 3–6 (2013).

[5] L. Sliwczyński, P. Krehlik, A. Czubla, L. Buczek, M. Lipiński, "Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km," Metrologia 50, 133 (2013).

[6] B. Wang, C. Gao, W.L. Chen, J. Miao, X. Zhu, Y. Bai, J.W. Zhang, Y.Y. Feng, T.C. Li, L.J. Wang, "Precise and continuous time and frequency synchronization at the $5x10^{-19}$ Accuracy Level," Sci. Rep. 2, p. 556 (2012).

[7] G. Marra, R. Slavik, H. S. Margolis, S. N. Lea, P. Petropoulos, D. J. Richardson, P. Gill High resolution microwave frequency transfer over a 86 km long optical fiber network using an optical frequency comb", Opt. Let. 36, Issue 4, pp. 511-513 (2011).

[8] M. Fujieda, M. Kumagai, S. Nagano, A. Yamaguchi, H. Hachisu, and T. Ido "All optical link for direct comparison of distant optical clocks", Opt. Expr. 19, pp. 16498-16507 (2011)

[9] S-C. Ebenhag, P. O. Hedekvist, P. Jarlemark, R. Emardson, K. Jaldehag, C. Rieck, P. Löthberg "Measurements and Error Sources in Time Transfer Using Asynchronous Fiber Network," IEEE Trans. Instrum Meas. 59, 1918-1924 (2010).

[10] F.-L. Hong, M. Musha, M. Takamoto, H. Inaba, S. Yanagimachi, A. Takamizawa, K. Watabe, T. Ikegami, M. Imae, Y. Fujii, M. Amemiya, K. Nakagawa, K. Ueda, H. Katori, "Measuring the frequency of a Sr optical lattice clock using a 120 km coherent optical transfer" Opt. Lett. 34, 5, 692 (2009)

[11] J. Vojtech; V. Smotlacha; P. Skoda; A. Kuna; M. Hula, S. Sima, "Photonic services, their enablers and applications" Proc. SPIE 8516, Remote Sensing System Engineering IV, 85160H (October 23, 2012).

[12] A. Bauch, J. Achkar , S. Bize, D. Calonico, R. Dach , R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, P. Uhrich, "Comparison between frequency standards in Europe and the USA at the 10-15 uncertainty level," Metrologia 43, pp. 109–120 (2006).

[13] C. W. Chou, D. B. Hume, T. Rosenband, D. J. Wineland, "Optical clocks and relativity," Science 329, pp. 1630 (2010).

[14] J. Müller, M. Soffel. S. A. Klioner, "Geodesy and relativity", J Geod. (2008) 82:133–145

[15] G. Cerretto, N. Guyennon, I. Sesia, P. Tavella, F. Gonzalez, J. Hahn, V. Fernandez, A. Mozo, "Evaluation of the OD&TS System Noise in the GALILEO GIOVE Mission", Proc. of EFTF'08, April 2008,Toulouse, France.

[16] Y. He, B. J. Orr, K. G. H. Baldwin, M. J. Wouters, A. N. Luiten, G. Aben, R. B. Warrington "Stable radiofrequency transfer over optical fiber by phase-conjugate frequency mixing," Opt. Expr. 21, p. 18754 (2013).

[17] J. F. Cliche, B. Shillue, "Precision timing control for radioastronomy: maintaining femtosecond synchronization in the Atacama Large Millimeter Array," IEEE Contr. Syst. Mag. 26, pp. 19–26 (2006).

[18] J. Kim, J. A. Cox, J. Chen and F. X. Krtner "Drift-free femtosecond timing synchronization of remote optical and microwave sources," Nature Photonics 2, pp. 733–736 (2008).

[19] F. Levi, R. Ambrosini, D. Calonico, C. E. Calosso, C. Clivati, G. A. Costanzo, P. De Natale, D. Mazzotti, M. Frittelli, G. Galzerano, A. Mura, D. Sutyrin, G. M. Tino, M. E. Zucco, N. Poli, "LIFT: The Italian fiber Network For Frequency and Time Distribution," Proceedings of the Joint UFFC, EFTF and PFM Symposium (2013).

[20] H. Schnatz, D. Calonico, E. Dierikx, G. Grosche, P. O. Hedekvist, A. Kuna, G. Marra, M. Merimaa, A. Niessner, G. Santarelli, V. Smotlacha, C. Chardonnet, "Accurate Time/Frequency Comparison and Dissemination Through Optical Telecommunication Networks," Proceedings of the European Frequency and Time Forum (2012).

[21] C. Clivati, D. Calonico, C. E. Calosso, G. A. Costanzo, F. Levi, A. Mura, A. Godone, "Planar-waveguide external cavity laser stabilization for an optical link with 10^{-19} frequency stability," IEEE Trans. Ultrason. Ferroelectr. Freq. Contr., vol. 58, no. pp. 12, 2582-2587, Dec. 2011.

[22] P. A. Williams, W. C. Swann, and N. R. Newbury, "High-stability transfer of an optical frequency over long fiber optic links," J. Opt. Soc. Am. B 25, 1284-1293 (2008).

[23] Th. Udem, J. Reichert, T. W. Hänsch, M. Kourogi, "Accuracy of optical frequency comb generators and optical frequency interval divider chains" Opt. Lett. 23, 1387 (1998)

[24] G. Kramer and W. Klische, in Proceedings of the 2001 IEEE International Frequency Control Symposium and PDA Exhibition, Seattle, Washington, 2001 (IEEE, New York, 2001), pp. 144–151.

[25] S. K. Mitra, "Digital Signal Processing, University of California, Santa Barbara: TATA McGraw-Hill, 2006

[26] D. Allan, "Statistics of Atomic Frequency Standards", Proc. of the IEEE 54, p. 221-230 (1966).

[27] E. Rubiola, Phase Noise and Frequency Stability in Oscillators, 1st ed. (Cambridge University Press, 2009).

[28] C. E. Calosso, E. Bertacco, D. Calonico, C. Clivati, G. A. Costanzo, M. Frittelli, F. Levi, A. Mura, and A. Godone, "Frequency transfer via a two-way optical phase comparison on a multiplexed fiber network 39, 1177 (2014)