

# Transmission of an Optical Carrier Frequency over a Telecommunication Fiber Link

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**Abstract:** We investigated the transfer of an ultra-stable optical frequency via an optical fiber link. We achieved an instability below  $6 \times 10^{-18}$  for a distance of 86 km, and  $< 2 \times 10^{-17}$  over 211 km (integration time  $\sim 8000$ s).

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Fiber optic networks are an attractive option for the long distance transfer and dissemination of ultra-precise frequencies. Such transfer would enable the distribution of a reference frequency, e.g. from a standards laboratory, to any research lab connected by 1,5  $\mu\text{m}$  single-mode fiber [1]. Optical reference frequencies are required for spectroscopy, interferometry, and for their application in sensor systems and measurement instrumentation, including wavelength meters. The transmission of frequency information via optical fiber has received increasing attention over the last decade [2-4], since for the development of optical clocks, the direct comparison of clocks located in different laboratories, and often different countries, is necessary. Frequency transmission also allows the exploitation of optical clocks as *instruments*, e.g. addressing fundamental physics questions such as the variation of the fine structure constant over time, or using them as phase or frequency references to implement ultra-sensitive sensor systems.

Here we present experiments transferring an ultra-stable optical carrier over a 1,5  $\mu\text{m}$  metropolitan fiber optic network, spanning 86 km one-way, which we also extended to a total distance of 211 km using fiber spools. We directly transmit the frequency information as a stabilized optical carrier frequency, and use heterodyne detection followed by totalizing frequency counters to assess the frequency instability of the transmitted signal, as shown in figures 1 and 2, for a distance of 86 km and 211 km, respectively.

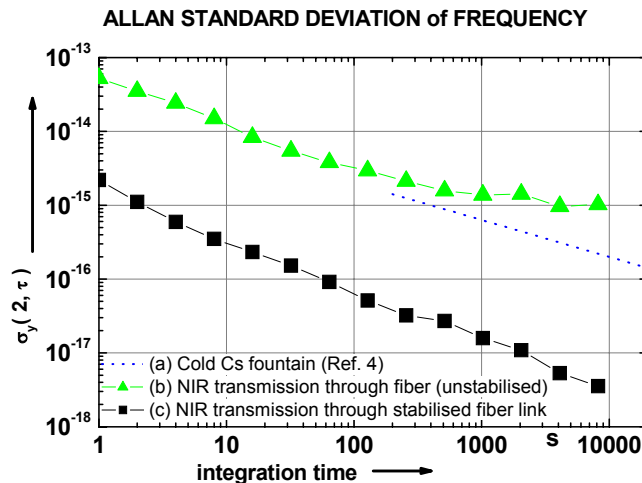


Fig. 1: Fluctuations as measured by the Allan standard deviation, for (a) the Cs fountain FO2, data from ref. [4], (b) the unstabilized metropolitan fiber link spanning 86 km (green triangles) and (c) the metropolitan fiber link spanning 86 km, with phase stabilization (black squares)

We stabilized a cw fiber laser (Koheras ADJUSTIK, denoted NIR) at 1542 nm to the clock laser of the strontium atomic lattice clock [5], operating at 698 nm, using a transfer scheme and a fiber-based femtosecond comb [6]. The resulting coherence length of the fiber laser exceeds 1000 km; its frequency fluctuations are shown as trace (a) in figure 2. Since the fiber laser is phase-locked to the optical reference, its stability is essentially that of the cavity stabilized Sr clock laser.

In a first experiment, we coupled approximately 1.5 mW of the stabilized 1542nm light into the 86 km fiber link. We then recorded the instability of the single-pass signal. We also detected the return signal, which had passed twice through 86 km, and used this to control an acousto-optic-modulator (AOM) at the fiber input. Similar to the well-known scheme first described by Ma [7], we thus actively stabilized the optical phase at the remote end of the fiber link. A continuous and simultaneous operation of the optical clock laser, the frequency comb, the cw-laser stabilization, and of the fiber stabilization over approximately half a day was achieved, reaching an instability below  $6 \times 10^{-18}$  for the stabilized fiber link.

In a second experiment, we extended the fiber link to a total length of 211 km single pass, by adding five fiber spools of 25km each. The total attenuation was approximately 50 dB single pass, or nearly 100 dB round-trip. We incorporated an erbium doped fiber amplifier, to amplify the optical signal before its return trip. The fluctuations of the single-pass signal as a function of integration time are shown in fig. 2. Taking an ensemble of 25000 1-second measurements, the mean of the transmitted frequency differed from the un-transmitted optical frequency by 3 mHz with an uncertainty for the mean of 4 mHz (or  $2 \times 10^{-17}$ ).

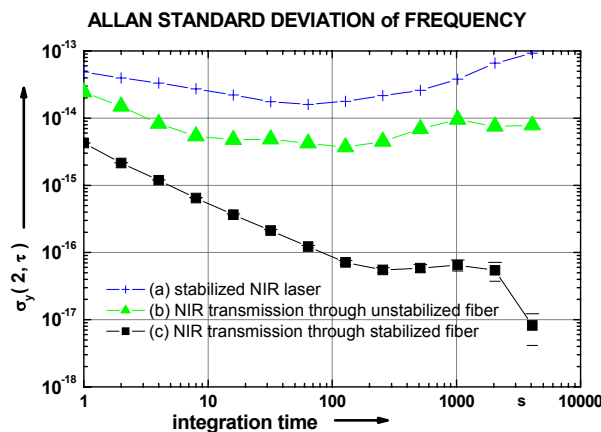


Fig. 2: Frequency fluctuations as measured by the Allan standard deviation, for (a) absolute optical frequency near 194 THz (1542 nm) as emitted by the stabilized NIR-laser (blue crosses); (b) fiber link of 211 km, including the metropolitan fiber optic network without phase stabilization of the fiber (green triangles) & (c) fiber link of 211 km, with fiber stabilization (black squares).

We have tested the transfer of a stabilized optical frequency over an existing metropolitan fiber link connecting two research laboratories in Paris. Reaching a link instability below  $10^{-16}$  at 100 s over a distance of 211 km, and an absolute accuracy around  $10^{-17}$  within a few hours, the transfer process outperforms most available clocks.

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## References

1. Masaki Amemiya, Michito Imae, Yasuhisa Fujii, Tomonari Suzuyama, Shin-ichi Ohshima, Shin-ichi Aoyagi, Yoshihiro Takigawa, Masami Kihara, "Time and Frequency Transfer and Dissemination Methods Using Optical Fiber Network", IEEJ Trans. FM, **126** (6) 458 (2006); G. Grosche, M. Eggert, D.A. Humphreys, C. Campbell, J.C. Petersen, J. Henningsen, B. Skipper, "Transmission of wavelength references via a commercial transparent optical network over 534 km", in: Technical Digest, Conference on Lasers and Electro-Optics, 2004. (CLEO). 16-21 May 2004, CTuH4.
2. B. de Beauvoir, F. Nez, L. Hilico, L. Julien, F. Biraben, B. Cagnac, J. J. Zondy, D. Touahri, O. Acaf and A. Clairon, "Transmission of an optical frequency through 3 km long optical fiber", Eur. Phys. J. D **1**, 227-229 (1998).
3. Jun Ye, Jin-Long Peng, R. Jason Jones, Kevin W. Holman, John L. Hall, David J. Jones, Scott A. Diddams, John Kitching, Sebastien Bize, James C. Bergquist, Leo W. Hollberg, Lennart Robertsson and Long-Sheng Ma, "Delivery of high-stability optical and microwave frequency standards over an optical fiber network", J. Opt. Soc. Am. B **20** (7), 1459 (2003); and references therein.
4. C. Daussy, O. Lopez, A. Amy-Klein, A. Goncharov, M. Guinet, C. Chardonnet, F. Narbonneau, M. Lours, D. Chambon, S. Bize, A. Clairon, G. Santarelli, M.E. Tobar and A. N. Luiten, "Long-Distance Frequency Dissemination with a Resolution of  $10^{-17}$ ", Phys. Rev. Lett., **94**, 203904 (2005).
5. R. Le Targat, X. Baillard, M. Fouché, A. Bruschi, O. Tcherbakoff, G. D. Rovera, and P. Lemonde "Accurate Optical Lattice Clock with  $^{87}\text{Sr}$  Atoms", Phys. Rev. Lett., **97**, 130801 (2006).
6. Phillip Kubina, Peter Adel, Gesine Grosche, Theodor W. Hänsch, Ronald Holzwarth, Burghard Lipphardt, Harald Schnatz; "Continuous Comparison of two Fiber based fs Frequency Combs", Optics Express, **13**, 904-909 (2005); Harald Schnatz, B. Lipphardt and G. Grosche, "Frequency Metrology using Fiber-Based fs-Frequency Combs", in: Technical Digest, Conference on Lasers and Electro-Optics (CLEO), 2006, CTuH1.
7. Long-Sheng Ma, Peter Jungner, Jun Ye and John L. Hall, "Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path", Opt. Lett. **19** (21), 1777 (1994).