A simple-architecture fibered transmission system for dissemination of high stability 100 MHz signals.

Ahmed Bakir, Cyrus Rocher, Baptiste Marechal, Emmanuel Bigler, Rodolphe Boudot, Yann Kersalé, Jacques Millo

To cite this version:

Ahmed Bakir, Cyrus Rocher, Baptiste Marechal, Emmanuel Bigler, Rodolphe Boudot, et al.. A simple-architecture fibered transmission system for dissemination of high stability 100 MHz signals.. Review of Scientific Instruments, 2018, 89 (5), pp.054703. hal-02366758

HAL Id: hal-02366758
https://hal.archives-ouvertes.fr/hal-02366758

Submitted on 16 Nov 2019

A simple-architecture fibered transmission system for dissemination of high stability 100 MHz signals

A. Bakir, C. Rocher, B. Maréchal, E. Bigler, R. Boudot, Y. Kersalé and J. Millo

We report on the development of a simple-architecture fiber-based frequency distribution system used to transfer high frequency stability 100 MHz signals. The system exhibits a residual fractional frequency stability of 1×10^{-14} at 1 s integration time and in the low 10^{-16} range after 100 s. These performances are suitable to transfer the signal of frequency references such as those of a state-of-the-art hydrogen maser without any phase noise compensation scheme. We demonstrate the dissemination of such a signal through a 100 m long optical fiber without any degradation. The proposed setup could be easily extended for operating frequencies in the 10 MHz - 1 GHz range.

Introduction: Hydrogen masers (HM) or cesium beam clocks, widely-used in metrology laboratories as frequency references, usually deliver a useful ultra-stable 10 MHz or 100 MHz signal to be distributed and used in a large number of experiments. Moreover, a wide variety of commercial devices require a 10 - 100 MHz external reference signal to be driven and synchronized. Consequently, the proper dissemination and transfer of high stability radio-frequency (RF) signals is a critical element in laboratories and industries where high-precision experiments and measurements are performed.

For this purpose, the most common option to distribute reference RF signals consists to use long coaxial RF cables and dedicated distribution amplifiers. However, coaxial cables suffer from high transmission losses preventing them to be used on long distances, are highly sensitive to temperature variations, vibrations and are not immune to electromagnetic perturbations. Hence, the phase of the reference signal is significantly affected and there is no simple and efficient system allowing for the compensation of this excess noise.

An alternative and efficient option for the dissemination of ultra-stable RF signals consists in the use of optical fiber links. Such links are appreciated for their low-insertion losses, immunity to electromagnetic spurious effects and high-reliability acquired thanks to the growth of telecommunication systems. Such systems are based on the combination of an emitter stage, an optical fiber link for propagation of the signal and a detection stage at the link end. In the emitter station, the intensity of a laser wave is modulated by the RF signal to be transmitted and injected into an optical fiber. In the detection stage, the signal is detected, demodulated by a high-bandwidth photodiode and amplified using a low noise amplifier (details given in [1, 2]).

Over the last decade, the transfer of optically-carried ultra-low noise RF signals has been strongly stimulated by the need of comparisons between distant frequency references and atomic clocks signals. Links with lengths of one up to a few hundreds of kilometers has been realized with remarkable residual noise levels as low as 5×10^{-19} at one day averaging time [3, 4, 5]. The transfer of RF reference signals with a high frequency stability over shorter links is also of great interest in large scientific facilities scale such as in the very long base line interferometer (VLBI), Deep Space Network stations or X-ray free electron lasers [6]. Dissemination of signals is also an important issue in time and frequency laboratories where low noise RF references can be generated using cavity-stabilized lasers [7] and optical frequency combs [8]. In fiber links, the phase of the signals to be distributed can also be significantly affected by environmental perturbations. This excess noise can be compensated by tuning the phases of the guided waves through a fiber stretcher (piezo-actuated based system) and by heating a spool of fiber placed before the link [1]. However, despite this servo system which allows to reduce greatly the fiber link-induced excess noise, the absolute stability level of the transmission system remains limited in this case by the excess noise added by the modulation and the demodulation of both the diode laser and photodiode.

In this letter, we present the design and demonstrate the validation of a simple-architecture emitter-receiver (ER) system compatible with the low noise transfer in the laboratory of ultra-stable 100 MHz signals. A dedicated selection of optical components (diode laser, photodiode) was performed in order to ensure simplicity, low-cost (less than 600 € for all the opto-electronic components) and easy implementation while keeping high-stability specifications. The transfer of the 100 MHz signal from a HM over a 100 m link inside the laboratory is reported. A residual fractional frequency stability at the level of 10^{-14} at 1 s and a few 10^{-16} after 100 s is demonstrated without the need of any noise compensation system.

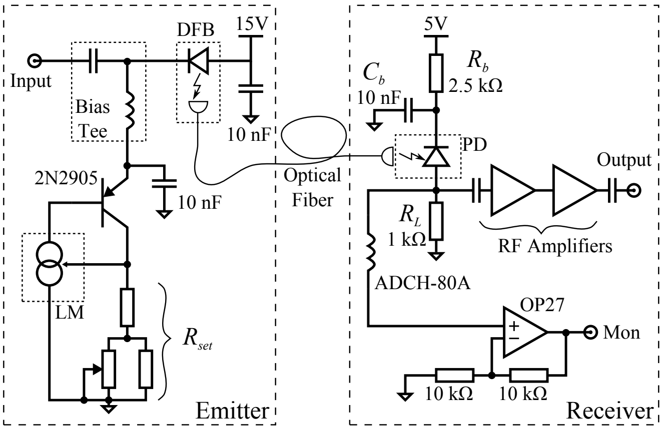

Fig. 1 *Schematic of the emitter-receiver electronic circuit. DFB: diode laser, PD: photodiode, LM: voltage control current source (LM134, Texas Instruments), Mon: Monitoring output.*

Description of the emitter and receiver stages: The emitter is based on a commercial pigtailed distributed feedback diode laser (FOL1xxxMWIx-OH2 series, FITEL). The latter is housed in a coaxial physics package integrating an embedded optical isolator. The diode laser emits an output optical power of 9 mW at 1.55 μm for a dc bias current of 100 mA. The intensity modulation is achieved by direct modulation of the diode laser current. No temperature control of the diode laser is implemented. The electronic circuit used to drive the laser is shown on Fig. 1 (left part). The diode laser current driver is based on a LM134 (Texas Instruments) voltage controlled 1 mA current source. A bipolar transistor (2N2905) is used to amplify the current and reach approximately 100 mA. The diode laser current is tuned using the potentiometer in the R_{set} resistance network between $0.5\ \Omega$ and $10.5\ \Omega$. In the small-signal regime, relevant for the modulation signal, the laser anode is grounded by the capacitor while the cathode is disconnected from the current source and connected to the modulation port through the bias tee (TCBT-14+, Mini-circuits).

The receiver (Fig. 1, right part) is based on a high-speed InGaAs PIN photodiode (FGA01FC, Thorlabs). Its packaging allows for direct input connection of an optical fiber with FC/APC connectors. The typical photodiode input optical power is 1 mW, yielding a bias current tuned to be about 1 mA using $R_b = 2.5\ \mathrm{k}\Omega$ and $R_L = 1\ \mathrm{k}\Omega$. The detected RF signal is amplified by about 40 dB using two amplifiers (based on ERA-5+, Mini-circuits). Since the inductance (ADCH-80A, Mini-circuits) is equivalent to an open-circuit in the small-signal regime and the RF amplifier input charge ($50\ \Omega$) is about 20 times smaller than R_L, most of the photo-current goes from the cathode (grounded by the capacitor C_b) to the input charge of the RF amplifier. An additional operational amplifier (OP27G, Analog Devices) allows to monitor the DC current from the photodiode proportional to the average optical power.

Fractional frequency stability results: A phase noise measurement setup, shown on Fig. 2, was implemented to measure the residual excess noise of the emitter-receiver system. This setup is driven by a commercial 100 MHz RF source. A phase shifter is placed in the first arm of the setup while the second arm contains the ER-system under test. A double-balanced mixer, used as a phase detector, delivers an output voltage signal with a typical sensitivity of about $0.2\ \mathrm{V/rad}$. The latter is recorded with a low noise digital voltmeter with a sample period of about 1.5 s. Acquired voltage data are converted in phase using the mixer coefficient, normalized by the carrier frequency and then converted to fractional frequency fluctuations $y(t)$ using a time derivative.

Blue diamonds on Fig. 3 plot the residual fractional frequency stability (FFS) of the ER-system estimated using the Allan deviation. It is measured to be 10^{-14} at 1 s integration time. After 8 s, a $\tau^{-1/2}$ slope, signature of a white frequency noise is obtained. For lower integration

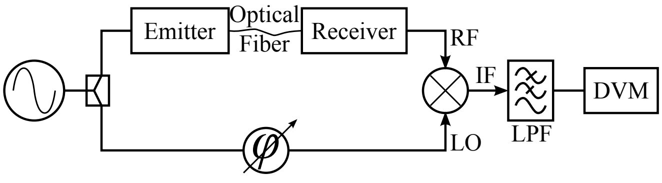

Fig. 2 *Residual fractional frequency stability measurement setup. DVM: digital voltmeter, LPF: low-pass filter.*

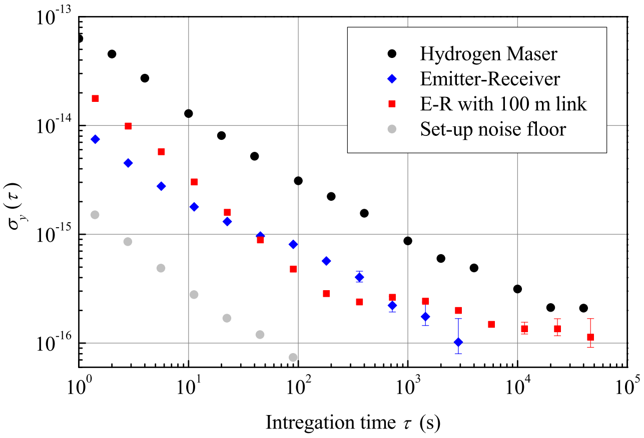

Fig. 3 *Fractional frequency stability of key signals in the experiment. Blue diamonds: ER system (residual), black filled circles: hydrogen maser (absolute stability taken from the datasheet [9]), grey filled circles: measurement setup (residual), red filled squares: E-R system with 100 m fiber link.*

time the slope is steeper than $\tau^{-1/2}$ but does not match with the expected slope in τ^{-1}. Further investigations would be required to find the origin of this noise and thus improve the FFS. Between 90 s and 400 s averaging times, we suspect the bump to be caused by environmental temperature fluctuations due to the air conditioning system (1.5 K peak-to-peak). However, the measured level is well below the fractional frequency stability of a HM (black filled circles data) and demonstrates that this extremely simple system is suitable to transfer the signal of a HM [9] without stability degradation.

The noise floor of the measurement set-up has been measured by replacing the ER-system by a cable and the equivalent attenuation. The result, shown on Fig. 3 (grey filled circles data), indicates clearly that the noise of the measurement set-up does not limit the FFS of the ER system. Moreover, the Allan deviation plot exhibits here FFS of $2 \times 10^{-15}\tau^{-1}$ for short integration time. Note that all the results described above have been obtained in a relatively quiet environment. Fibers were attached to the optical breadboard and passively protected from direct air flow.

In a third step, we have added 100 m of SMF28 optical fiber between the emitter and the receiver in order to estimate the noise of an uncompensated link. The fiber starts from a closed storage bay in a room dedicated to the distribution of reference signals and makes a round trip in the building following the wire path without any particular protection. The measurement setup is now driven by a HM from the laboratory. Similar measurements to the one described above were performed during 7 days. The corresponding FFS is shown on Fig. 3 (red filled squares data). The FFS is measured to be 2×10^{-14} at 1 s and in the low 10^{-16} range after 100 s. A floor at the level of 10^{-16} is reached at 10^4 s. In the latter measurement, with respect to the measurement previously reported, the improved thermal environment could explain the reduction of the FFS result around 200 s while the presence of a longer fiber could explain the excess noise around 1 s.

Conclusion: We have developed a simple-architecture and low-cost distribution system allowing to transfer ultra-stable 100 MHz radio-frequency signals over a fiber link. A careful selection and design of key components, including the telecom diode laser and the current source, was performed. The emitter-receiver-system exhibits a residual fractional frequency stability at the level of 10^{-14} and a few 10^{-16} at 1 s and after 100 s respectively. These performances are one order of magnitude better than the fractional frequency stability of 100 MHz signal from a state-of-the-art hydrogen maser. This signal was successfully disseminated over a 100 m long optical fiber, without implementing any fiber noise compensation techniques. The proposed setup could be easily extended to operating frequencies in the 10 MHz - 1 GHz range.

Acknowledgment: The work has been realized in the frame of the ANR project "Projets d'Investissements d'Avenir (PIA) Equipex Oscillator-Imp". The authors would like to thank the Council of the Région de Franche-Comté for its support to the PIA and to the Labex FIRST-TF for funding. The authors also want to thank Clément Lacroûte for careful reading of the manuscript.

A. Bakir, C. Rocher, B. Maréchal, E. Bigler, R. Boudot, Y. Kersalé and J. Millo (*FEMTO-ST, Univ. Bourgogne Franche-Comté, CNRS, ENSMM 26 Rue de l'Épitaphe, 25030 Besançon cedex, France*)

E-mail: millo@femto-st.fr

References

1 Foreman, S. M., Holman, K. W., Hudson, D. D., Jones, D. J., and Ye, J.: 'Remote transfer of ultrastable frequency references via fiber networks', *Rev. Sci. Instrum.*, 2007, **78**, p. 021101
2 Narbonneau, F., Lours, M., Bise, S., Clairon, A., Santarelli, G., Lopez, O., Daussy, C., Amy-Klein, A. and Chardonnet, C.: 'High resolution frequency standard dissemination via optical fiber metropolitan network', *Rev. Sci. Instrum.*, 2006, **77**, p. 064701
3 Wilcox, R., Byrd, J. M., Doolittle, L., Huang, G., and Staples, J. W.: 'Stable transmission of radio frequency signals on fiber links using interferometric delay sensing,' *Opt. Lett.*, 2009, **34**, 20, pp. 3050-3052
4 Lopez, O., Amy-Klein, A., Lours, M., Chardonnet, C., and Santarelli, G.: 'High-resolution microwave frequency dissemination on an 86-km urban optical link', *Appl. Phys. B*, 2010, **98**, 4, pp. 723–727
5 Śliwczyński, L., Krehlik, P., Czubla, A., Buczek, L., and Lipiński, M.: 'Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km', *Metrologia*, 2013, **50**, 2, p. 133
6 Xin, M., Safak, K., Peng, M. Y, Kalaydzhyan, A., Wang, A.-T., Mücke, O. D., and Kärtner, F. X: 'Attosecond precision multi-kilometer laser-microwave network', *Light Sci. Appl.*, 2017, **6**, 12, e16187
7 Matei, D. G., Legero, T., Häfner, S., Grebing, C., Weyrich, R., Zhang, W., Sonderhouse, L., Robinson, J. M., Ye, J., Riehle, F. and Sterr, U.: '1.5 μm Lasers with Sub-10 mHz Linewidth', *Phys. Rev. Lett.*, 2017, **118**, p. 263202
8 Xie, X., Bouchand, R., Nicolodi, D., Giunta, M., Hänsel, W., Lezius, M., Joshi, A., Datta, S., Alexandre, C, Lours, M., Tremblin, P.-A., Santarelli, G., Holzwarth, R. and Le Coq, Yann: 'Photonic microwave signals with zeptosecond-level absolute timing noise' , *Nat. Photonics*, 2017, **11**, pp. 44-47
9 *https://www.t4science.com/products/imaser3000/*