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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

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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 $1 \times 10^{-14}$ 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 at the link end 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. In contrast, the fiber transmission losses are not 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 different frequency references and atomic clocks signals. Links with lengths of one up to a few hundreds of kilometers have been realized with remarkable residual noise levels as low as $5 \times 10^{-19}$ 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 reference 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]).

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 $R_b = 2.5 \, \text{k}\Omega$ and $R_L = 1 \, \text{k}\Omega$. 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 $C_1$) 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 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 $\phi(t)$ 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 $-1/2$ 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 dataset [9]), grey filled circles: measurement setup (residual), red filled squares: E-R system with 100 m fiber link.

time the slope is steeper than $\sigma^{-1/2}$ but does not match with the expected slope in $\sigma^{-1}$. 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 $2 \times 10^{-15}$ at 1 s and in the low $10^{-16}$ range after 100 s. A floor at the level of $10^{-12}$ is reached at 10 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 Lacroït for careful reading of the manuscript.

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