Ultra-low noise microwave extraction from fiber-based optical frequency comb.

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INTRODUCTION

Low phase-noise, microwave signals with high long term stability and reliability are of prime importance in a variety of scientific and technological fields, such as, for example, atomic frequency standards, radar and remote sensing, communications and navigation, high-speed electronics, very long baseline interferometry and high-precision timing distribution and synchronisation (see [1] and references therein). At present, the lowest noise microwave sources are based on cryogenic sapphire oscillators [2]. However these sources are not commercially available and have high maintenance costs. In recent times the stabilization of lasers to highly stable optical cavities has become a well established technology and reliable devices based around vibration-immune cavities show a fractional frequency stability that is routinely about $1x10^{-15}$ from 0.1s to 100s or better [3-5]. At the same time, femtosecond laser optical frequency combs have emerged as the ultimate low noise optical-to-microwave frequency divider delivering the potential for low noise microwave generation [6]. By combining an ultra-stable laser with this frequency division technique it should be possible to generate a signal with a phase noise performance that surpasses all existing microwave sources over a broad range of the Fourier spectrum. In this paper we demonstrate the development of a highly reliable all-fiber optical system that demonstrates low-phase noise microwave signal generation and low frequency instability. The NIST group have demonstrated outstanding results on Titanium-Sapphire-based Optical Frequency Comb (TSOFC), with residual phase noise as low as -107 $dBrad^2$/Hz at 1Hz for a carrier frequency of 10 GHz as well as a frequency instability of $6.5x10^{-16}$ at 1s [7, 8]. In addition the same group has investigated the mechanisms of excess noise in microwave signal extraction from optical pulse train (see [9,10] and references therein). Despite these outstanding results the TSOFC suffers from an insufficient long term operational reliability necessary for many applications. Fiber-based Optical Frequency Combs (FOFC), on the other hand, are suitable for continuous operation and have already demonstrated rather low phase noise signal generation for cesium atomic fountain clocks operation [11-13].

EXPERIMENTAL SET-UP

In our experiment we use of 250 MHz repetition rate (f_{rep}) FOFCs that include f-2f interferometers for measuring the carrier-envelope offset frequency (Menlo Systems GmbH, M-Comb +P250+XPS1500). A mode of the FOFC is phase locked to an ultra-stable cw laser , which allows synthesis of microwave signals through photodetection of the light pulses (which provides f_{rep} and its harmonics within the detector's bandwidth). Due to the phase lock loop, the repetition rate of the laser is phase-coherent with the optical reference signal but divided down in frequency by a large factor (~800000). It has the same frequency instability and time jitter as that of the optical reference, with a small unavoidable noise added by the division process. We investigate the impact of this added noise to the frequency instability as well as to the phase noise of the synthesized microwave signals. Our setup is described in Fig. 1: two quasi-identical FOFCs are independently phase-locked to a shared and common optical reference consisting of a cw fiber laser at 1542.14 nm stabilized onto an ultra stable cavity. The setup is tuned such that both FOFCs have the same f_{rep} (hence exhibiting exactly the same division factor from optical to microwave). Since the intrinsic noise of the optical reference is common mode, comparing the 2 microwave signals generated by the FOFCs completely characterizes the phase noise added by the optical to microwave division process. The lock technique used to stabilize the repetition rate of the FOFC, shown on Figure 1, is an improved version of the one described in [13]. The whole arrangement makes use of fiber pigtailed single mode optical components. Critical components, in particular power splitters and Optical Add and Drop modules (OADM), were selected to minimize phase noise.

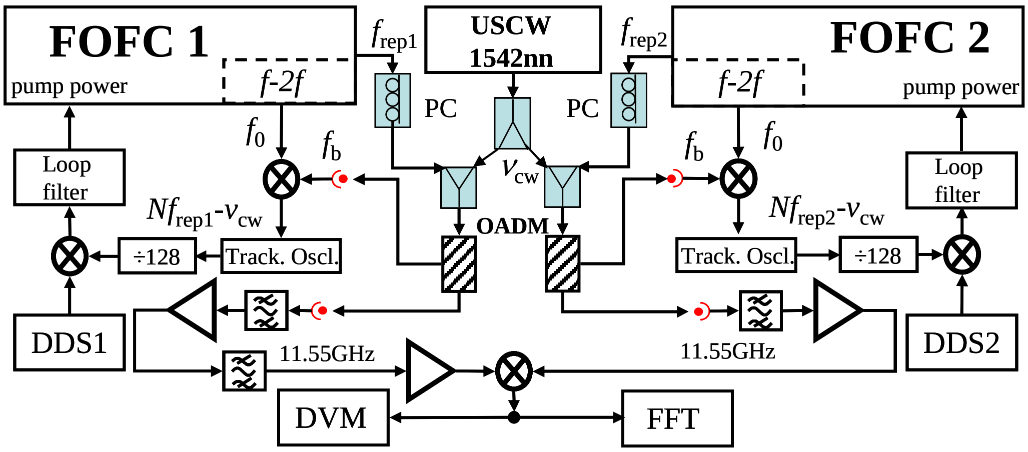

Figure 1: Set-up schematic (OADM: Optical Add/Drop Module, AOM: Acousto Optic Modulator, DDS: Direct Digital Synthesizer, USCW: Ultra Stable Continuous Wave laser, PC: Polarization Controller.

The 30 mW output (100 fs duration pulses) from the mode-locked laser oscillator was sent through a polarisation controller to an OADM (three port interference optical filter centered at 1542.14 nm with bandwidth 0.8 nm). The spectrally narrow filtered output is combined with the CW light from the ultra stable laser (of optical frequency ν_{cw}). The resulting beat-note signal $f_b = \nu_{cw} - Nxf_{rep} - f_0$ (where N is a large integer and f_0 is the carrier envelope offset frequency) is detected on a *InGaAs* photodiode. From the *f*-2*f* built-in interferometer we obtain a signal f_0 which is mixed with f_b and filtered to produce a frequency signal $\nu_{cw} - Nxf_{rep}$ independent of f_0. This signal is filtered by a tracking oscillator and then digitally divided by 128. Finally this divided signal is compared to a reference synthesized with a direct digital synthesizer (DDS1 see Fig. 1) to produce a phase error signal. This signal, processed in a simple analog loop filter, then controls the pump power of the femtosecond laser. The servo bandwidth is about 120 kHz, which allows robust and reliable phase locking to the reference cw laser.

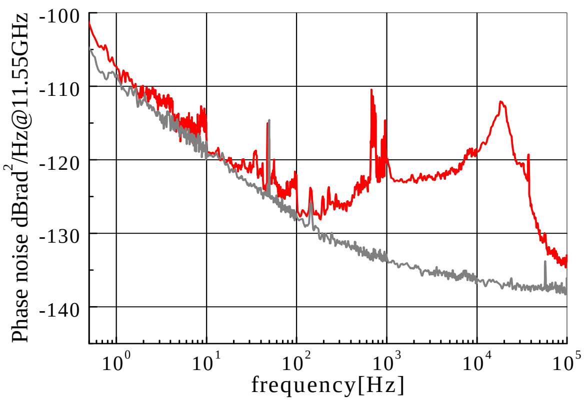

Fig. 2: Phase noise power spectral density of the difference of the two 11.55 GHz microwave signals (solid red line), measurement floor (photodetection+amplification) (grey line).

To generate a signal at the repetition rate (and its harmonics) the other output of the OADM, which contains nearly all of the mode-locked oscillator power (~10mW), is injected into a high-speed InGaAs pigtailed photodiode (Discovery model DSC40S, 20 GHz bandwidth). The second FOFC is locked with a similar technique but due to the lack of a fast pump power control port the bandwidth is limited to 20-30 kHz.For both FOFC systems, the low level output signal (about -30 dBm) of the microwave extraction photodiode is filtered by a very low insertion losses microwave filter centered at 11.55 GHz and amplified using very low flicker phase noise amplifiers. One of the outputs is further filtered and amplified up to a power of 5 dBm to saturate the LO port of a double balanced microwave mixer.

The RF port is driven with -8 dBm from the other FOFC system. Figure 2a shows the measured relative phase noise of the microwave signals at 11.55 GHz for two independent systems (black solid line) as well as the noise level of the readout system (photodetection,amplifiers and mixer) (dashed grey line). The detection floor was measured by driving both detection photo-diodes with the same FOFC. The residual phase noise of the amplifiers is slightly below that of the complete readout system. As can be seen on Figure 2 the measured noise is limited by the measurement system below ~100Hz Fourier frequencies. Nevertheless we achieve an very low phase noise level of about -108 log(f) dBrad^2/Hz for 1 Hz<f<100 Hz for the two systems.

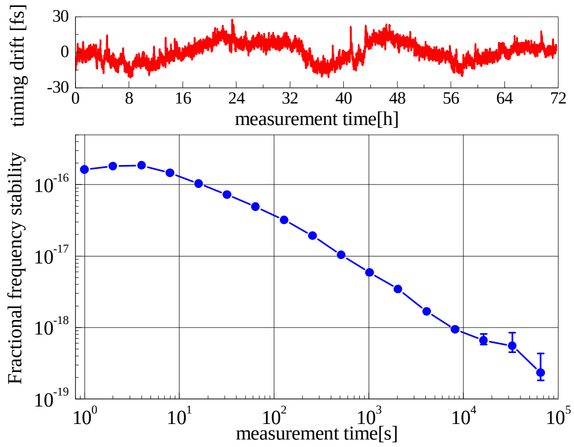

Figure 3: Top plot: relative timing jitter between the two microwave signals at 11 11.55 GHz over 72h (26300, 10s samples). The measurement is performed by sampling the voltage DC output of the microwave mixer (measurement bandwidth 5 Hz). Bottom plot : residual fractional frequency stability of the generated microwave signal scaled to one system (overlapping Allan deviation, 263000 1s samples).

It is also important to note the very low level of spurious peaks in the spectrum and that no post-data processing or filtering has been used to produce this result. Beyond 100 Hz the limited control bandwidth of one of the combs does not allow us to investigate the ultimate lower limit to the microwave generation process.

We have evaluated the fractional frequency stability (FFS) of the generated microwave signals by sampling the low pass filtered (5 Hz) voltage output of the microwave mixer. The top plot of figure 3 shows the relative timing jitter of the generated microwave signals over 72h. The bottom plot of the same figure shows FFS (overlapping Allan deviation) against the measurement time from a 74 hours dataset of continuous operation. The FFS for a single system is about $1.6x10^{-16}$ (at 1 s-10 s) scaling down to about $3x10^{-19}$ at 65536 s. To evaluate the accuracy of optical to microwave generation we have used the standard technique of deducing the frequency offset from the timing drift (top of fig. 3) The data shows a conversion accuracy of $2x10^{-20}$, which is compatible with zero within the error bars defined by the FFS shown in Fig. 3 [14].

ADVANCED NOISE REDUCTION TECNIQUES

To explore the ultimate performance of our optics to microwave division system, we need to use an ultra-high sensitivity phase comparison scheme which we realize with a carrier suppression noise measurement system (CSNMS) [14] as shown on Fig. 4. The electric signals resulting from pulse trains photodetections are directed to the two input ports of a 180-degrees hybrid junction through microwave isolators preventing unwanted feed-back effects on the photodiodes. A variable attenuator in front of one of these ports allows amplitude equalization of the signals. When phase matching is realized for a given carrier frequency, the difference output port of the hybrid junction exhibits destructive interference and every remaining signal near the carrier frequency is resulting from phase or amplitude differential noise at the input ports. Note that phase matching can conveniently be adjusted by changing the phase of the RF reference in one of the FOFC's phase-lock loops. The sum and difference output ports of the hybrid junction are filtered near 11.55GHz with the same filter used in the previous experience. The difference signal is afterward amplified and sent to the RF port of a microwave mixer. The sum signal passes through a variable phase shifter, is amplified and saturates the LO port of the mixer. The output of the mixer is low-pass filtered, amplified by a low-noise DC amplifier and sent to a fast Fourier transform (FFT) analyzer or digital voltmeter as in Fig. 4. Since no carrier is present on the dark port (difference output of the hybrid junction), the associated amplifier and the mixer operate in small-signal regime where flicker noise is greatly reduced [14]. Optimal phase and amplitude tuning produces at least 70dB of carrier suppression in the dark port leading to a power lower than -100dBm before amplification.

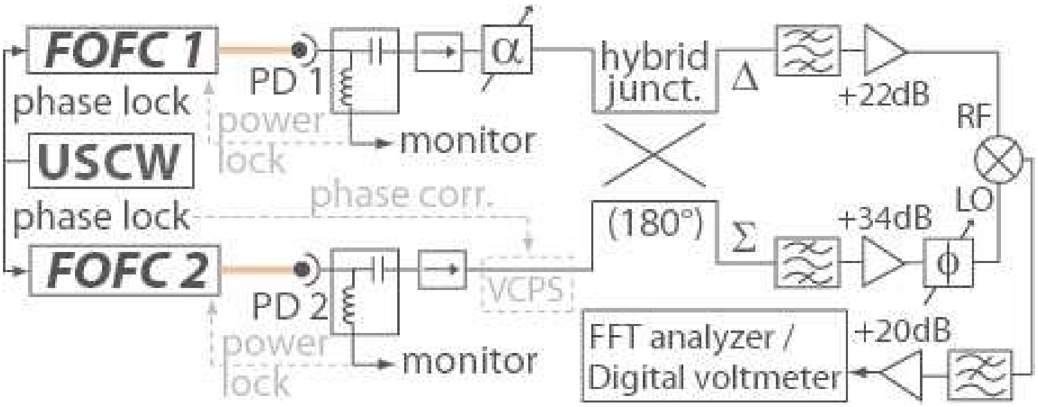

Figure 4: Set-up schematic which highlights the CSNMS, and the power lock.
FOFC: Fiber-based optical frequency comb; USCW: ultra-stable continuous wave laser ;VCPS: voltage-controlled phase shifter ; FFT: fast Fourier transform.

The bright port (sum output of the hybrid junction) is used to synchronously demodulate the dark port at the carrier frequency, thanks to the mixer and low-pass filter. Depending on the relative phase between the dark and bright port, the near-DC output of the mixer is proportional either to the phase or amplitude difference between the 11.55GHz harmonics at the input of the hybrid junction. The phase noise added in the bright port is common mode and does not impact the final measurement. The readout noise is measured by replacing the input of the dark port by a 50Ohm termination (see figure 5 curve 3). The FFT is used to measure phase noise power spectral densities of the microwave generation process. For the long timescales, we use the Allan standard deviation, measured by recording the phase at the output of the CSNMS with a digital voltmeter over extended period of time. The carrier suppression system is perfectly stable over several hours of continuous measurement. We emphasize that we didn't use any kind of active stabilization (automatic or human-based) of the amplitude or phase matching of the CSNMS.

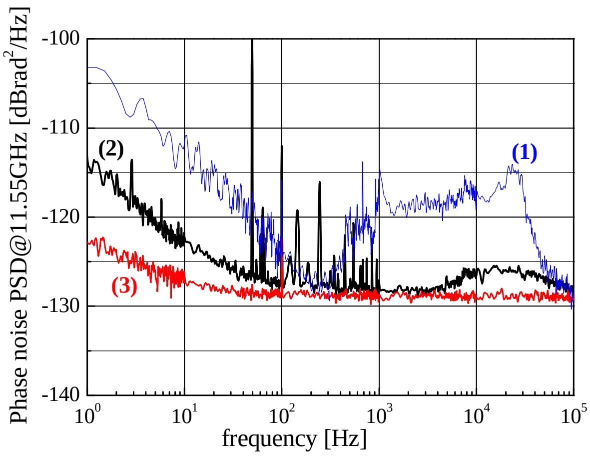

Fig. 5: Phase noise power spectral density (PSD) of the difference of the two 11.55GHz microwave signals extracted from FOFCs. Curve 1: No noise reduction technique was applied; Curve 2: with VCPS phase correction (see text) and stabilization of the optical power incident on the microwave generating photodiode (both AOM and pump power feed-back give the same result). Curve 3: readout system floor.

We initially realize a phase comparison between microwave signals directly generated by two FOFCs (see figure Fig.5 curve 1, basically identical whether we implement the CSNMS or a classical detection described above). A first striking figure is a relatively large noise bump between 300 Hz and 80 kHz. This figure is due to the limited servo-bandwidth (20kHz) available on one of the FOFCs. We have addressed this issue by implementing, on this FOFC, a phase correction on the microwave using the residual in-loop error signal of the phase-lock-loop. A voltage controlled phase shifter (VCPS) is inserted after the fast photodetector PD 2 associated with the low correction bandwidth FOFC. The control input of the VCPS is driven by a signal derived from the in-loop residual error through a simple voltage divider resistive network. The division ratio is chosen so as to realize a phase ratio between the phase-lock loop residual error signal and the microwave VCPS correction equal to (194THz/64)/11.55GHz, with 194THz and 11.55GHz being respectively the optical and microwave frequencies, the factor 64 being due to the frequency divider in the phase-lock loop. This corrects from residual noise due to insufficient gain in the main phase-lock loop. In a sense, this technique is an analog equivalent to the "transfer oscillator" scheme, developed by the PTB group, which uses direct digital synthesizers (DSS) to digitally realize the correct division factor. It proved useful to considerably reduce the phase noise spectral density above 300Hz as can be seen in figure 5 curve 2.

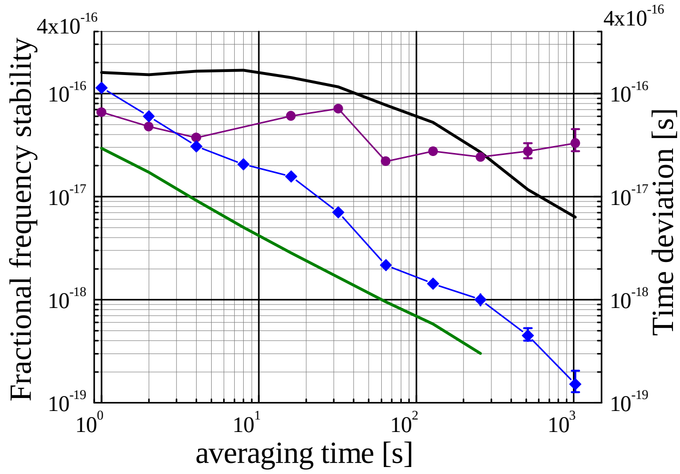

Fig. 6. Fractional frequency stability (FFS, measured by Allan standard deviation) and time deviation (TDEV) for a single optics-to-microwave FOFC system. Top continuous line: FFS with power stabilization on AOM; diamonds and circles: respectively FFS and TDEV with power stabilization on pump current control ; bottom continuous line: FFS floor of the measurement system.

A second feature of the noise spectral density in figure 5 (curve 1) is the 1/*f*-noise behavior between 1Hz and 200Hz. Studies on Titanium Sapphire based optical frequency combs at NIST [7-10] demonstrated that this behavior near carrier was due to AM-PM conversion in the photodetection process. We have implemented two different power stabilization techniques. In both cases, the DC output of the bias-tee following the fast photodiode is compared with a stable voltage reference and sent to an integral analog corrector. In the first technique, the correction signal is applied to the RF-power driving an acousto-optic modulator (AOM) which we added in front of the photodiode (the AOM is not represented on fig. 4 and was installed only for this specific experiment). In the second technique, the correction is applied to the pump power controller of the FOFC laser oscillator (which is possible because the main phase-lock correction is taken care of by the PZT below a few kHz). With both techniques, the power servo bandwidth is larger than 1kHz and is measured (in a separate out-of-loop measurement) to provide more than 20dB noise rejection at 1Hz Fourier frequency.

Both power stabilization schemes improved substantially the 1/*f*-noise behavior (as seen on figure 5 (curve 2)). We reach an unprecedented phase noise of -117dBrad^2/Hz (for a single system) at 1Hz from the 11.55GHz microwave carrier. On longer timescales, the FFS were, however, different for the two power stabilization techniques. The AOM-based scheme flattens out up to 10s (see figure 6) On the contrary, the pump-power-based technique averages down quickly, almost following the τ^{-1} slope expected for 1/*f*-noise limited phase coherent systems. We believe that the power stabilization of the optical pulses in the oscillator itself has a collateral stabilization effect on their spectral phase (which can be coupled to pulse energy by, for example, Kerr effect or temperature changes), as well as decreasing amplitude to phase conversion in the carrier-envelop offset measurement unit. In the pump-power stabilization case, the FFS reaches 1.5x10^{-19} at 1000s (for a single system), residual frequency offset compatible with zero at this level. The synchronization stability between the optics (i.e. the USCW laser) and one of the microwave signal is characterized by the time deviation associated with these phase measurements. We find it to be consistently below 100 attoseconds between 1s and 1000s (see figure 6) [16].

CONCLUSIONS

In conclusion, we have used two FOFC-based optical-to-microwave division frequency synthesizers referenced to a common optically source to create 11.55 GHz microwave signals with a relative frequency stability of 1.6×10^{-16} at 1 s. The relative phase noise spectral density at a 1 Hz offset from the 11.55 GHz carrier is measured at −111 $dBrad^2/Hz$, limited by the readout system noise floor. Long term stability and accuracy down to 3×10^{-19} at 65536 s was also demonstrated from a set of 3 days continuous measurement. These results are obtained with classical double balanced mixers measurement scheme. By using a noise measurement system based on the carrier suppression method and advanced noise reduction techniques we are able to improve the results down to a phase noise spectral density at a 1 Hz of −117 $dBrad^2/Hz$ and a FFS is of 1.5×10^{-19} at 1000s (for a single system).

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