Ultra-low phase noise frequency-comb-based microwave generation and characterization

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***Abstract*—We report on the generation of ultra-low phase noise microwave signals at 12GHz by photodetecting the pulse train of an Erbium-doped fiber-based optical frequency comb phase locked to a ultra-narrow linewidth ultra-stable laser at 1.5µm. With advanced photodetection techniques and home-made phase noise measurement apparatus, our experiment demonstrates generation of a microwave source with absolute phase noise below -170dBc/Hz at 10kHz and above, and below -100dBc/Hz at 1Hz from a 12GHz carrier, which pushes even further the best results reported so far.**

Keywords—Optical frequency combs, opto-electronic microwave sources, ultra-low phase noise

I. Introduction

Many applications such as telecommunication, radar, deep-space navigation systems and precision microwave spectroscopy are calling for ultra-stable microwave signals. Photonic generation of such signals by help of an optical frequency comb is of particular interest because it allows transferring the unsurpassed spectral purity of ultra-stable continuous wave lasers to the microwave domain, potentially leading to record low phase noise microwave sources.

The conversion from optical to microwave is done by synchronization of the repetition rate of a femto-second laser with an ultra-stable optical frequency reference. The microwave signal is further extracted *via* fast photo-detection of the optical pulse train. However, the spectral purity of the opto-electronically generated microwave signal is limited by both the comb's repetition rate performance and the photo-detection process itself. Such limits on the photodetection part include the amplitude-to-phase conversion (APC) combined with intensity noise of the femto-second laser and the shot and thermal noise from the photodetector. We use a combination of frequency comb repetion rate multiplier by fiber-based interleavers combined with high linearity photodetector to minimize the later and we have developed an automatic measurement and servo setup to minimize APC to levels where it does not have a significant impact on the phase noise of the microwave signal we produce.

At the performance level reached here, the characterization of extremely low phase noise microwave is, in itself, an interesting challenge. We have developped a special setup based 4 optical frequency combs, 3 ultra-stable lasers, a high quality microwave circuitry and a home-made heterodyne FPGA-based cross-correlation to reach mesurement noise floors below -180dBc/Hz at Fourier frequencies >1kHz from a 12GHz carrier with very low amplitude noise sensitivity.

II. Experimental setup

Our experimental setup comprises several optical frequency combs and ultra-stable cw lasers. These ultra stable cw lasers are composed of semiconductor diode lasers at 1.5µm wavelength servo-ed by the Pound-Drever-Hall technique to high finesse (typically $\sim 10^6$) Fabry-Perot cavities in ultra-high vaccuum [1]. Although this is not essential for this work, one of them is continuously monitored by a separate frequency comb and loosely frequency locked to primary frequency standards (atomic fountains) to produce a low-noise and continuously operated constant optical cw reference. An Er-doped fiber-based optical frequency comb (OFC) with 250MHz repetition rate is phase locked to this reference [2] and its train of pulses are photodetected by a specifically designed highly linear photodetector. A fiber interleaver, followed by negative dispersion fiber patch cord for pulse

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recompression, allows external multiplication of the effective repetition rate to 4GHz before photodetection, so as to generate maximum power near 12GHz [3]. To minimize the effect of APC, which may transforms part of the comb's amplitude noise to excess phase noise, we add a zero-order acousto-optic modulator to servo-control the relative intensity noise of the comb down to lower than -150dBc/Hz (for Fourier frequencies <1MHz) and operate the photodiode at its "magic point" where non-linear saturation effect exactly cancel the amplitude-phase conversion for the considered repetition rate harmonics at 12GHz [4]. An active servo, based on a FPGA system, is used to keep the operation condition of the photodiode as close as possible to its "magic point". The resulting impact of amplitude-phase conversion is, in this way kept below -190dBc/Hz or better.

To measure the resulting microwave phase noise, we use a cross-correlation technique, where two extra similar systems (independent ultra-stable cw laser and independent OFCs) are used to implement a "three-cornered hat" configuration. Microwave mixing of the signal from the system which we want to characterize with the signals generated by each of these two extra systems produces two RF signals (near 10MHz each). These signals are sampled by fast analog-to-digital converters, digitally down-converted and computer processed to generate two time dependant phase comparisson data sets. Cross-correlation of these two phase data sets reveals the power spectral density of phase noise of the microwave signal at 12GHz that we want to characterize, assuming statistical independence of the two extra sources. Note that in this cross-correlation technique, the uncorrelated noise from the two extra systems is rejected and contributes only to the uncertainty of the estimates of the phase noise power spectral density of the system under test. This uncertainty averages down with the square root of the inverse of the measurement time. Less experimental effort is therefore required to set them up (no active servo-ing of the zero amplitude phase conversion point of the photodiodes,commercial grade photodiodes, less optimized combs pulses interleavers and optical power, etc...).

III. CURRENT RESULTS

Current esults of the full setup demonstrate the generation of microwave signals with <-100dBc/Hz at 1Hz, <-170dBc/Hz at 10kHz from the 12GHz carrier.

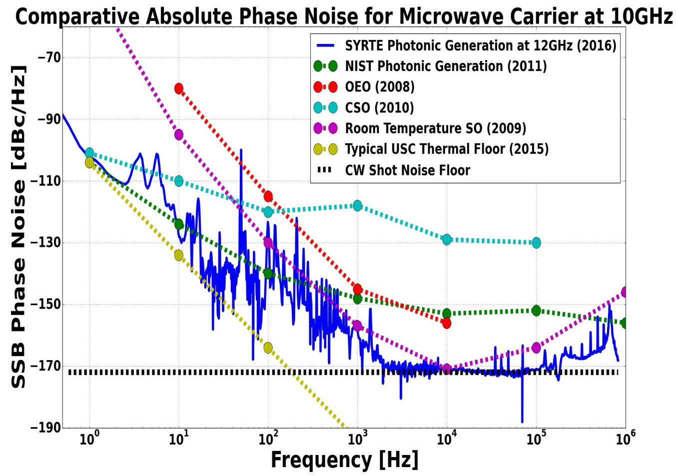

Fig. 1. Power spectral density of phase noise of the 12GHz signal generated by our optical frequency comb phase locked to an ultra-stable laser, as measure by heterodyne cross-correlation technique (red). For useful comparison with other systems, the phase noise has been rescaled to a carrier of 10GHz. The blue curve is the power spectral density of absolute phase noise of the system, measured by cross-correlation against two similar (but with reduced performance) accessory frequency comb based full systems. The dashed lines of various colors represent the typical results obtained for other sytems and technology, as reported in the available litterature. CSO: cryogenic sapphire oscillator, SO: Sapphire oscillator, OEO: opto-electronic oscillator USC: limit inferred from Ultra-Stable Cavity referenced laser phase noise measured in the optics domain, when mathematically transferred to the microwave domain, assuming a perfect noiseless frequency down conversion process.

This unprecedended level combines the performance of the best microwave sources both close to and far from the carrier, for a reasonably compact generation system (excluding the phase noise characterization apparatus), paving the way for field-deployable systems delivering record-low phase noise microwave signals.

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