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which should be used for any reference to this work

Ultra-low noise microwave generation with a free-running optical frequency comb transfer oscillator

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We present ultra-low noise microwave synthesis by optical to radio-frequency (RF) division realized with a free-running or RF-locked optical frequency comb (OFC) acting as a transfer oscillator. The method does not require any optical lock of the OFC and circumvents the need for a high-bandwidth actuator. Instead, the OFC phase noise is electrically removed from a beat-note signal with an optical reference, leading to a broadband noise division. The phase noise of the ~15 GHz RF signal generated in this proof-of-principle demonstration is limited by a shot-noise level below–150 dBc/Hz at high Fourier frequencies and by a measure-mentnoise floorof–60 dBc/Hz at 1Hzoffset frequencywhen performing 1,100 cross-correlations. The method is attractive for high-repetition-rate OFCs that lead to a lower shot-noise, but are generally more difficult to tightly lock. It may also sim-plify the noise evaluation by enabling the generation of two or more distinct ultra-low noise RF signals from different optical references using a single OFC and their direct comparison to assesstheir individual noise.

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Optical frequency combs (OFCs) from mode-locked lasers provide a direct and phase-coherent link between optical and microwave frequencies through their two degrees of freedom, the repetition rate f_{rep}, and the carrier-envelope offset (CEO) frequency f_{CEO}. The most advanced applications of OFCs today are as optical-to-microwave frequency dividers. In the traditional implementation, one comb mode is tightly locked to an optical reference (ultra-stable laser) whose noise is divided by a large factor to the radio-frequency (RF) domain [1,2]. This has enabled the generation of the microwave signals with the lowest phase noise to date, below −173 dBc/Hz for a 12 GHz carrier [3]. This is lower than that for other well-established methods such as optoelectronic oscillators [4], which achieved around −160 dBc/Hz at 10 kHz offset from a 10 GHz carrier [5]. The ultimate noise level of the RF signal corresponds essentially to the frequency-divided noise of the reference laser within the OFC locking bandwidth. Therefore, this approach requires a fast actuator for the optical lock of the OFC and is most often done with megahertz range repetition rate OFCs for their ease of development and tight stabilization. Intra-cavity electro-optic modulators (EOMs) with megahertz bandwidths are most commonly used, but make the system more complex and costly, even though many comb systems today are equipped with such EOMs [6,7]. Higher f_{rep} in the gigahertz or multi-gigahertz range are attractive for low-noise RF generation, as the shot-noise limit in the generated signal resulting from the photodetection of the comb pulse train is reduced when lowering the number of harmonics of f_{rep} detected in the photodiode bandwidth [1,8]. Methods have been proposed to multiply the repetition rate of megahertz-range OFCs using fiber interleavers [8] or a set of filtering optical cavities [2], but the direct use of an OFC with a large repetition rate may simplify the overall setup and make it more compact. The price to pay is that the phase noise of gigahertz OFCs is generally higher, making them more challenging to properly phase-stabilize [9].

In the traditional approach of locking the OFC to an ultra-stable laser, the achieved phase noise of the generated microwave directly depends on the properties of the optical lock. Moreover, the OFC is dedicated to the RF signal generation, meaning that each low-noise RF signal to be generated requires a specific OFC. To characterize such a system, a second fully independent setup is needed for a cross-comparison, which involves its own ultra-stable laser and OFC locked to it, making the evaluation setup fairly sophisticated [3]. In this Letter, we show a proof-of-principle demonstration of ultra-low noise microwave generation realized in a different approach, where the OFC used for optical-to-RF division acts as a transfer oscillator (TO). Hence, it does not require an optical lock of the comb, which can be fully free-running or locked to an RF reference, providing numerous advantages. In our experiment, optical-to-RF division is demonstrated with an old generation Er:fiber OFC that is only equipped with a slow piezo-electrical transducer (PZT) for f_{rep} locking. The TO method circumvents the demanding optical lock and its associated bandwidth limitation in the division of the phase noise of the optical reference, leading to intrinsically broadband noise division. As the OFC is not phase-locked to the optical reference and remains fully independent, the same OFC can be used to downconvert different optical references to generate distinct RF signals. This makes the microwave signal generation setup more flexible, less complex, and more cost-efficient in comparison to the standard approach. The implemented scheme is inspired by the initial work of Telle *et al.* in Ti:sapphire mode-locked lasers [10] and by a method that we previously developed to characterize the CEO frequency in an OFC without directly detecting it by traditional f-to-$2f$ interferometry [11]. It basically consists of cancelling out electrically the phase noise of the OFC in a judicious combination of signals involving the beat-note with the optical reference to be downscaled, as outlined in Fig. 1(a). In contrast to our former implementation where only the noise of f_{rep} was removed to access the frequency noise of f_{CEO}, the noise of both degrees of freedom of the OFC, f_{CEO} and f_{rep}, needs to be cancelled here so that the resulting output RF signal only contains the downscaled phase noise of the ultra-stable laser without degradation by the OFC.

The experimental setup is detailed in Fig. 1(b). A beat-note signal f_{beat} between a mode ν_N of the OFC and an ultra-stable laser of frequency ν_{CW} is detected in a fast photodiode PD-2 (model DSC40S from Discovery Semiconductors Inc.). The signal centered at 14.95 GHz has a power of –80 dBm and a signal-to-noise ratio (SNR) higher than 50 dB in a 100 kHz resolution bandwidth (RBW). The continuous-wave (CW) reference laser (model ORION, RIO Inc.) emits at 1557.4 nm and is locked to a high finesse ultra-low thermal expansion (ULE) Fabry–Perot cavity using the Pound–Drever–Hall locking scheme [12], resulting in a linewidth of a few hertz. The OFC is an Er:fiber comb with a 250 MHz repetition rate mode-locked by nonlinear polarization rotation (FC1500 from Menlo Systems), which is significantly noisier than state-of-the-art modern fiber combs such as those based on a nonlinear amplifying loop mirror [6,13] or on difference frequency generation for passive phase stabilization [14]. The repetition rate can be locked via a slow PZT with a typical loop bandwidth lower than 1 kHz, and f_{CEO} via the pump current with a bandwidth in the range of 10 kHz. The beat-note signal f_{beat} is filtered with a narrowband RF cavity filter (3 dB bandwidth of ~70 MHz centered at 14.95 GHz) and is amplified to ~15 dBm in a set of four low-noise amplifiers (GNA-157F, RF-Bay Inc.). They have a negligible contribution to the phase noise of the final RF signal as their additive phase noise is orders of magnitude lower than the noise of the ultra-stable laser present in the beat signal. The frequency of the CW laser and the comb repetition rate are tuned so that the beat frequency corresponds to $f_{\text{beat}} = \nu_N - \nu_{\text{CW}} = N \cdot f_{\text{rep}} - |f_{\text{CEO}}| - \nu_{\text{CW}}$ with a comb mode N in the order of 768,000. The sign of f_{CEO} in this expression results from its negative value which was experimentally determined. In parallel, the CEO beat is detected at 20 MHz with a 40 dB SNR in a 100 kHz RBW using a standard f-to-$2f$ interferometer and is amplified to ~15 dBm. A single-sideband (SSB) mixer (model SSB-0618LXW, Marki Microwave Inc.) is used to subtract f_{CEO} from f_{beat} and produces a CEO-free beat signal $f_{\text{beat}}^{\text{CEO-free}} = N \cdot f_{\text{rep}} - \nu_{\text{CW}}$ centered at 14.97 GHz. Similar to our previous implementations [11,15], the resulting CEO-free beat signal needs to be frequency-divided by a large fractional number $n_2 = N/N_1$ (where N_1 defines the approximate output microwave frequency and we chose here $N_1 = 60$ for an output signal of ~15 GHz). We replaced the combination of cascaded frequency pre-scalers that we used before which led to a fixed integer division factor of $N_2 = 12,800$ by a direct digital synthesizer (DDS, model AD9915, Analog Devices) to get a finer division. As the input frequency range of the DDS is limited to 2.5 GHz, the CEO-free beat frequency is first divided by a factor of 6 using a pre-scaler (FPS-6-15, RF-Bay Inc.). The DDS is adjusted to output a signal matching its input frequency divided by a factor of $\sim 12,800/6 \approx 2,130$, leading to a downscaled CEO-free beat signal at 1.17 MHz. The residual OFC noise in this signal corresponding to ~60 times the phase fluctuations of f_{rep} is removed in a subsequent stage by mixing it with the 60th harmonic of f_{rep}, separately detected with another fast photodiode PD-1. This signal is bandpass filtered using a narrowband RF cavity filter (~70 MHz bandwidth centered at 15 GHz) and amplified. Even with the use of an SSB mixer, multiple peaks appear in the output signal at $15\text{ GHz} \pm k \cdot 1.17\text{ MHz}$ due to the high difficulty to filter out the only peak of interest (15 GHz – 1.17 MHz in our case). Hence, the resulting signal is affected by strong spurious noise peaks at high Fourier frequencies (at harmonics of 1.17 MHz; see Fig. 2, 1-DDS gray curve). We circumvented this issue by the use of the so-called 2-DDS scheme depicted in Fig. 1(b). Here, the second division

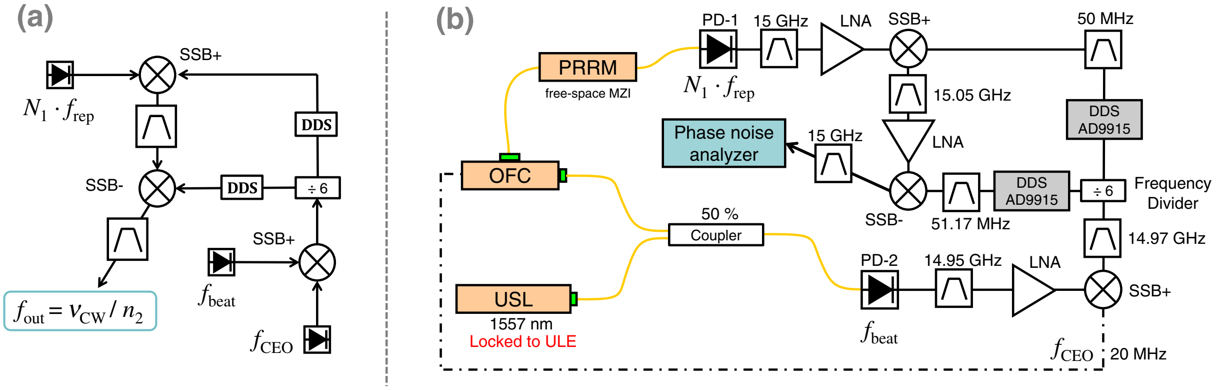

Fig. 1. (a) Scheme of principle of microwave synthesis by optical-to-RF division using an OFC as a transfer oscillator. PD, photodiode; SSB±, single sideband mixer (upper/lower sideband); DDS, direct digital synthesizer. (b) Detailed implementation of the 2-DDS scheme that improves the filtering of the generated microwave signal at 15 GHz and suppresses spurious peaks. USL, ultra-stable laser; LNA, low-noise amplifier; PRRM, pulse repetition rate multiplier (free-space Mach–Zehnder interferometer, MZI). The yellow lines represent single-mode fibers.

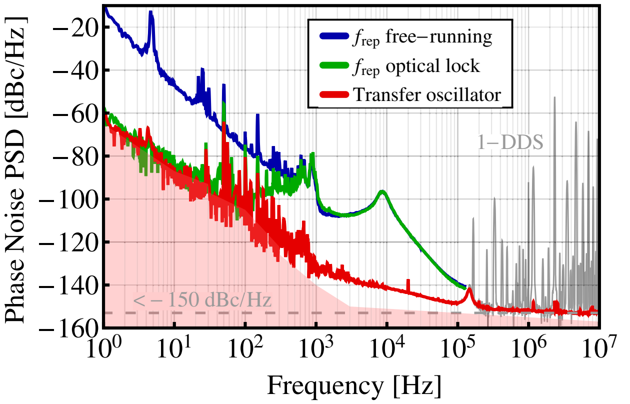

Fig. 2. SSB phase noise power spectral density (PSD) of a 15 GHz RF signal ($60 \cdot f_{\mathrm{rep}}$) generated by different means with a self-referenced OFC: free-running f_{rep} (blue), f_{rep} optically locked (green), and OFC used as TO with the 2-DDS scheme (red). The phase noise obtained with the 1-DDS scheme is shown for comparison at high frequency (gray). The red area shows the instrumental noise floor.

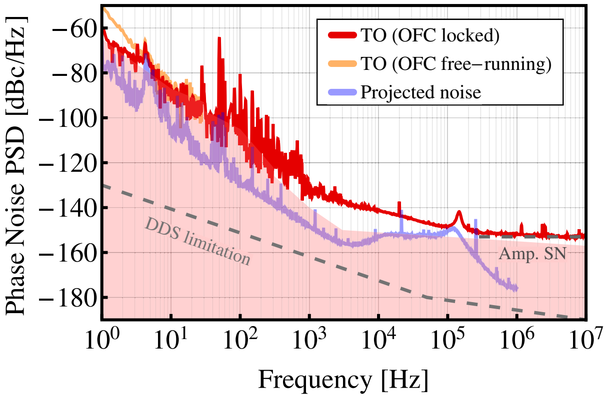

Fig. 3. Measured phase noise PSD of the 15 GHz signal generated by the TO method with f_{rep} locked to an RF reference (red curve) and free-running (orange curve). In both cases, f_{CEO} is free-running. This is in comparison to the projected noise spectrum obtained for a perfect down-scaling of the noise of the optical reference (purple). The additive phase noise floor induced in the two branches of the setup is also displayed (dashed lines): amplified shot-noise (Amp. SN) in the photodetection of $60 \cdot f_{\mathrm{rep}}$ and from the DDS frequency division process. The red area indicates the instrumental noise floor.

stage of the CEO-free beat signal at ∼2.5 GHz is realized using two DDSs in parallel delivering signals at 50 and 51.17 MHz so that their difference (1.17 MHz here) matches the output frequency corresponding to the targeted division factor n_2. The signal of the first DDS is mixed with $60 \cdot f_{\mathrm{rep}}$ using an SSB+ mixer to produce an intermediate signal at ∼15 GHz + 50 MHz where spurious components of the DDS signal can be easily filtered out using a narrowband RF filter (∼70 MHz bandwidth centered at 15.05 GHz). Another SSB mixer is used to cancel out the residual noise contribution of f_{rep} by combining the previous signal at ∼15.05 GHz with the output of the second DDS (51.17 MHz). The resulting signal at 14.99883 GHz is efficiently isolated owing to the 51.17 MHz separation of spurious peaks. This output signal contains the phase noise of the ultra-stable laser electrically divided by a factor of $n_2 \approx 12,800$ without any locking bandwidth limitation as the OFC remains fully independent from the optical reference. The contribution from the OFC noise is efficiently removed by the TO setup. The implemented 2-DDS scheme leads to a clean signal without undesirable noise peaks occurring when performing the frequency division using a single DDS (see Fig. 2).

As a first proof-of-principle demonstration of the proposed optical-to-RF division, we characterized the phase noise of the generated signal using a cross-correlator phase noise analyzer (Rohde & Schwarz FSWP26). We performed more than two hours of measurement corresponding to 1100 cross-correlations at 1 Hz offset frequency and up to 10^7 above 100 kHz. However, the measurement is still instrument-limited below 300 Hz. A higher number of cross-correlations might be used to lower the noise floor, but increasing it up to 10,000 at 1 Hz offset frequency would only bring an improvement of ∼5 dB and would last for more than 24 h, which is still insufficient to reach the projected noise level of the optical reference (Fig. 3). Hence, we restricted the evaluation to this cross-correlation measurement in this proof-of-principle demonstration, but this result does not constitute an absolute assessment of the ultimate performance of the method.

We compared the phase noise of the generated RF signal to the traditional method of optically locking the OFC in the same conditions and using the same OFC, where the optical lock was achieved with the cavity PZT. The results are displayed in Fig. 2. Both curves are limited to the same level at Fourier frequencies below ∼100 Hz, which matches the instrumental noise floor. From 100 Hz up to more than 100 kHz, the benefit of the TO method is clearly visible. The noise of the ultra-stable laser is not transferred to the generated microwave signal with the traditional optical lock, as it is out of the limited locking bandwidth of the OFC. In contrast, the noise of the optical reference is downscaled up to a much higher Fourier frequency using the TO method, even if some excess flicker phase noise seems to be present between 1 and 100 kHz, whose origin has not yet been identified. Notably, the servo bump of the CEO stabilization that couples to the noise spectrum of the repetition rate [16] at around 10 kHz is strongly suppressed, demonstrating the high rejection of the OFC noise. In our initial measurements, we noticed an imperfect cancellation of the OFC noise, especially visible at this servo bump. The reason is that the two signals f_{beat} and $60 \cdot f_{\mathrm{rep}}$ are detected with two different photodiodes and using two distinct outputs of the OFC. With the subsequent use of several electronic devices (filters, dividers, mixers), a time delay may occur between the two signals, leading to incomplete noise compensation when they are combined. The most detrimental element was identified to be the 15.05 GHz bandpass filter between the two DDSs. A higher noise rejection was reached by minimizing the relative delay between these two signals by adding a 4.8 m long SMA cable at the output of the second DDS, which led to the result displayed in Fig. 2.

We investigated the ultimate phase noise limit arising in the 2-DDS TO setup by measuring the additive phase noise induced in the two branches of the scheme shown in Fig. 1(b): (1) the detection of the high harmonic of the repetition rate (upper branch) and (2) the frequency division of the optical beat-note signal (lower branch). The results displayed in Fig. 3 show that the frequency division performed with the DDSs is by far not a limitation with the present projected noise of our ultra-stable laser. This could become a limitation at some Fourier frequencies if an improved optical reference with a noise reduced by at least one order of magnitude was used. The detection of the high harmonic of f_{rep} in the other branch constitutes the main limitation at Fourier frequencies above 100 kHz. It results from the amplified shot-noise in the photodetection of the pulse train and is similarly present in the traditional method with the optical lock of the OFC [1,8]. To reduce this high frequency noise, we used a pulse repetition rate multiplier (PRRM) composed of a 2-stage free-space in-loop Mach–Zehnder interferometer (MZI) [8,17]. This increased the RF power of the 15 GHz harmonic signal detected by PD-1 by 10 dB, reaching –20 dBm for 4 mW incident optical power. This signal was further amplified by ~25 dB using a low-noise RF amplifier. As a further improvement, we minimized the amplitude to phase (AM-to-PM) noise conversion in the photodetection. The AM-to-PM conversion factor highly depends on both the incident optical power and the photodiode bias voltage [18] and is strongly reduced at specific values of these parameters. With the used fast photodiode and Er:fiber OFC, we found a high rejection at 4 mW incident power and 9 V bias voltage. The results displayed in Figs. 2 and 3 were obtained in these conditions. Only the shot-noise of the photodetection of the comb pulse train in PD-1 constitutes a limitation in the generated microwave signal, which lies at a level below –150 dBc/Hz in the present configuration. The shot-noise in the detection of the laser-comb beat signal in PD-2 is not limiting as this signal is subsequently divided by the larger number n_2. The shot-noise level could be further lowered by sending more optical power to the photodiode PD-1, or by adding other PRRM stages and generating the microwave signal at 16 GHz instead of 15 GHz.

The frequency difference between the two DDSs must be precisely adjusted to fully cancel out the phase noise of the comb repetition rate. By slightly tuning one of the DDSs and minimizing the relative time delay between the two signals as previously mentioned, the point of maximum comb noise rejection was found within a tolerance of ±10 kHz on the generated 1.17 MHz signal (i.e., ~1% relative). This enables cost-efficient DDSs with a lower resolution to be used, making the method fairly easy to implement. Within this range, a proper rejection of the comb f_{rep} noise was achieved at all Fourier frequencies in the generated 15 GHz microwave signal when f_{rep} was locked to an RF reference. We also implemented the optical-to-RF division with the TO method using a free-running OFC (see Fig. 3). Very similar results were achieved above 5 Hz Fourier frequencies at the present level of evaluation, despite the much higher noise of the comb, which demonstrates the proper noise rejection obtained by the TO method. Only the slow drift of f_{rep} occurring below 5 Hz was more difficult to properly compensate, leading to a slightly higher resulting noise.

Besides the low-noise RF synthesis shown here, the 2-DDS TO scheme can also be used to characterize the phase noise of a free-running CW laser, even with a narrow linewidth, without a lower noise reference laser, but by employing any type of OFC (even free-running). It can also circumvent the main limitation at Fourier frequencies higher than ~10 kHz in our initial implementations of a method to analyze the noise of the free-running CEO signal in an OFC without using f-to-$2f$ interferometry [11,15].

In conclusion, we have reported a proof-of-principle demonstration of ultra-low noise RF synthesis realized by frequency downconversion of an optical reference using a TO frequency comb. In contrast to the traditional approach of tightly locking the OFC to the ultra-stable laser, the proposed method does not make use of any optical lock and circumvents the need for a high-bandwidth actuator. Therefore, it can be implemented with any type of frequency comb. The only constraint, e.g., when using frequency combs with a higher timing jitter, is that the beat signals (CEO and optical beat) have a sufficient SNR to ensure a proper frequency division and a moderate drift so that they remain within the bandwidth of the filters (~±30 MHz is acceptable with the present filters). It is particularly attractive with the use of high-repetition-rate combs, e.g., produced from mode-locked, diode-pumped solid-state lasers [9] or from micro-resonators [19]. In this proof-of-principle demonstration, the ultimate noise of the generated RF signal could not be assessed, as it was limited by the instrumental noise floor below ~500 Hz. However, the results were compared to the standard method of locking the OFC to the optical reference using the same OFC, demonstrating its benefits.

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