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A low phase noise microwave frequency synthesis for a high-performance cesium vapor cell atomic clock

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We report the development, absolute phase noise, and residual phase noise characterization of a 9.192 GHz microwave frequency synthesis chain devoted to be used as a local oscillator in a high-performance cesium vapor cell atomic clock based on coherent population trapping (CPT). It is based on frequency multiplication of an ultra-low phase noise 100 MHz oven-controlled quartz crystal oscillator using a nonlinear transmission line-based chain. Absolute phase noise performances of the 9.192 GHz output signal are measured to be -42 , -100 , -117 dB rad²/Hz and -129 dB rad²/Hz at 1 Hz, 100 Hz, 1 kHz, and 10 kHz offset frequencies, respectively. Compared to current results obtained in a state-of-the-art CPT-based frequency standard developed at LNE-SYRTE, this represents an improvement of 8 dB and 10 dB at $f = 166$ Hz and $f = 10$ kHz, respectively. With such performances, the expected Dick effect contribution to the atomic clock short term frequency stability is reported at a level of 6.2×10^{-14} at 1 s integration time, that is a factor 3 higher than the atomic clock shot noise limit. Main limitations are pointed out. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4896043>]

I. INTRODUCTION

Atomic frequency references provide the most stable signals over long integration times because their frequency is determined by an atomic transition. A wide range of industrial and technical fields, such as telecommunication, navigation, defense, and space applications, require stable and reliable timing signals that can be provided only by atomic frequency standards. Vapor cell atomic clocks constitute a valid solution because they combine compactness, reliability, low power consumption, and excellent relative frequency stability. Over the last years, thanks to the progress of semiconductor lasers and the use of dedicated techniques, state-of-the-art laboratory-prototype vapor cell atomic clocks, based on optical-microwave double resonance technique¹ or coherent population trapping (CPT),² have demonstrated short-term frequency stability in the $1\text{--}3 \times 10^{-13}$ range,^{3–7} making them competitive for short and mid-term integration times with bulky hydrogen masers. INRIM has developed a pulsed optically pumped Rb frequency standard with optical detection with a fractional frequency stability of $1.7 \times 10^{-13} \tau^{-1/2}$ up to 10 000 s integration time.³ LNE-SYRTE has proposed a pulsed Cs vapor cell CPT clock with short term frequency stability of 3.2×10^{-13} up to averaging times of 1000 s.⁴ LTF-UNINE has demonstrated a CW regime Rb clock with a frequency stability of $1.36\text{--}2.4 \times 10^{-13}$ up to averaging times of 1000 s.^{5–7}

Up to date, a major contribution to limitation of the short term frequency stability of these high-performance compact vapor cell atomic clocks is the local oscillator (LO) phase noise through the so-called intermodulation effect in continuous (CW) regime clocks⁸ or Dick effect^{9,10} in pulsed clocks. Indeed, the short-term frequency stability of an atomic clock can be degraded by down conversion of the LO frequency

noise at even multiples of the cycle rate into the frequency band of the selective resonator response. In a CW atomic clock with resonance frequency ν_0 , operating at a LO modulation frequency f_m , the frequency stability limitation $\sigma_{y_{LO}}(\tau)$ due to this aliasing effect is given such as

$$\sigma_{y_{LO}}^2(\tau) \sim \frac{1}{\tau} \left(\frac{f_m}{\nu_0} \right)^2 S_\varphi(2f_m) = \frac{1}{\tau} S_y(2f_m), \quad (1)$$

where $S_\varphi(2f_m)$ is the power spectral density (PSD) of the local oscillator phase fluctuations in the free-running regime at Fourier frequency $f = 2f_m$. $S_y(f) = \frac{f^2}{\nu_0^2} S_\varphi(f)$ is the PSD of the microwave oscillator fractional frequency fluctuations at offset frequency f . According to this relation, the development of a Cs atomic clock with a relative frequency stability of 10^{-13} at 1 s, operating at a LO modulation frequency $f_m = 83$ Hz, requires a local oscillator with a phase noise at $2f_m = 166$ Hz lower than -99 dB rad²/Hz. In a pulsed clock, the effect of the LO frequency noise has been characterized by the sensitivity function $g(t)$ ¹⁰ which is the response of the atomic signal to a phase step of the interrogation oscillator at time t . The shape of $g(t)$ depends on the atomic system and on the kind of interrogation used. The frequency stability limitation of an atomic clock due to the Dick effect is given from¹⁰

$$\sigma_{y_{LO}}^2(\tau) = \frac{1}{\tau} \sum_{i=1}^{\infty} \frac{g_i^2}{g_0^2} S_y(i/T_c) = \frac{1}{\tau} \sum_{i=1}^{\infty} \frac{g_i^2}{g_0^2} S_y(2if_m). \quad (2)$$

The parameters g_i and g_0 are defined from the sensitivity function g .¹⁰ T_c is the clock cycle time and $f_c = 1/T_c$ is the clock cycle frequency. i/T_c are the harmonics of the interrogation frequency. For the pulsed Cs CPT clock developed in LNE-SYRTE, the clock cycle time is $T_c = 6$ ms, i.e.,

$f_c = 166$ Hz. Additionally, compared to classical clocks based on a two-level atomic system, it has been recently demonstrated that the pulsed CPT clock Allan deviation exhibits a higher sensitivity to high frequency components of the LO noise.⁴

Reducing the Dick effect contribution requires the development of ultra-stable and low phase noise local oscillators. The purest microwave signals are nowadays obtained through optical-microwave frequency division with optical frequency combs^{11,12} or the use of cryogenic sapphire oscillators¹³ and associated frequency synthesis.¹⁴ Nevertheless, these systems remain voluminous, complex, and are not compatible with compactness requirements of vapor cell atomic clocks. In this domain, the generation of microwave signals referenced to an ultra-low noise quartz crystal oscillator remains a well-adapted solution.^{15–17}

In the frame of the EURAMET MClocks project,¹⁸ this paper describes the development of a microwave 9.192 GHz frequency synthesis chain for a high-performance CPT clock. It is inspired from Ref. 16 but different component references are used for some key steps. Absolute phase noise and predicted Dick effect contributions are reported whereas only residual phase noise was given in Ref. 16. Compared to Ref. 16, the synthesis residual noise is slightly degraded in the 100–1 kHz range. This is attributed to the use of new-generation nonlinear transmission line (NLTL) comb generators that exhibit excess flicker noise. At the opposite, the present synthesis residual noise floor is about 10 dB better mainly thanks to a new-design phase lock loop (PLL) electronics (see Sec. II). Additionally, a 4.596 GHz output signal is generated from the 9.192 GHz signal to be used in a simple-architecture pulsed Cs CPT clock in which a pigtailed electro-optic modulator is used to detect Ramsey-CPT fringes.¹⁹ Most significantly, thanks to the use of an ultra-low phase oven-controlled quartz crystal oscillator (OCXO) pilot, a relevant 4–13 dB improvement of absolute phase noise performances in the 100 Hz–1 kHz offset frequency range is obtained compared to the current system used in LNE-SYRTE. The Dick effect contribution limitation to the clock frequency instability is reduced at a level of 6.2×10^{-14} .

II. ARCHITECTURE OF THE FREQUENCY SYNTHESIS CHAIN

Figure 1 shows a detailed scheme of the microwave frequency synthesizer architecture. The pilot and key element of the synthesis chain is a 100 MHz oven-controlled quartz crystal oscillator (Pascall OCXOF-E-100).²⁰ This source exhibits ultra-low phase noise in the 1 Hz–1 MHz Fourier frequency range and is of relevant interest for compact vapor cell atomic clocks applications. The output power of the OCXO is +19 dBm. Its tuning voltage-frequency sensitivity was measured to be 500 Hz/V. Its tuning voltage-output power dependence was measured to be cancelled at the first order around a tuning voltage of 5 V. The output 100 MHz signal is split into two arms. In the first arm, reference signals at 100 MHz and 10 MHz using a digital frequency divider (Zarlink SP8401) are generated. In the second and main arm, the output 100 MHz signal is frequency-doubled to 200 MHz

FIG. 1. Architecture of the frequency synthesis chain. 6 main blocks are indicated on the diagram for better understanding. 1: the 100 MHz OCXO pilot, 2: 100 MHz and 10 MHz outputs, 3: 100–200 MHz frequency doubling stage, 4: NLTL-based 200–9200 MHz chain, 5: 9.192 GHz DRO phase lock loop, 6: 9.192–4.596 GHz frequency division chain.

using a passive frequency-doubler (Mini-Circuits FD2). The output 200 MHz signal is bandpass filtered and amplified to a power of 23 dBm with a low noise amplifier (Minicircuits ZFL-1000VH2+). The 200 MHz signal is used to drive a NLTL comb generator device (Picosecond Model 7110) that generates harmonics up to about 20 GHz. The 9.2 GHz harmonic output is bandpass-filtered with a 50 MHz-bandwidth bandpass filter and amplified to a power of about 0 dBm with a low noise microwave amplifier (AML612L2201). Microwave isolators and attenuators are added at the output of the NLTL to help for impedance matching, optimization of the phase noise performances, and to prevent undesired feedback. The NLTL component was found to be a critical element. Setting the optimal configuration that optimizes phase noise performances of this synthesis chain section can require patience and numerous experimental tests. Microwave isolators were selected for their high isolation properties. Optimization of impedance matching of NLTL input and output was found to be important. Once the best configuration is found, we observed excellent repeatability and stability of performances along time. The output 9.2 GHz is mixed with the 9.192 GHz signal coming from a dielectric resonator oscillator (DRO MITEQ-DRO-G-09192-MT±140), to produce a frequency beatnote at 7.368 MHz. The latter is low-pass

FIG. 2. Schematic of the DRO phase lock servo loop.

filtered, amplified with a high-isolation radiofrequency amplifier (Avantek UTC-573), and compared to the 7.368 MHz signal from a direct digital synthesis (DDS Agilent 33220A). The DDS is referenced by a 10 MHz signal generated from the initial 100 MHz OCXO. The DRO is phase-locked to the frequency-multiplied 100 MHz signal with a bandwidth of about 1 MHz using the circuit described in Figure 2. Both input signals are mixed with a double balanced mixer (Mini-Circuits TFM-3MH) with a sensitivity of 0.225 V/rad. The resulting error signal is filtered, processed in a proportional-integral (PI) controller, summed with an offset voltage to fix the OCXO bias point, and eventually used to phase-lock the DRO. High speed operational amplifiers (THS4011) are used to ensure proper and high-bandwidth lock of the DRO. An additional OP27 amplifier is used to monitor the error signal. A low phase noise 9.192 GHz signal with a microwave power of about 13 dBm is then obtained at the output of the DRO. This signal is split into two different arms. In the first arm, the 9.192 GHz arm is ready to use. In the other arm, the 9.192 GHz signal is frequency-divided by 2 with a low noise microwave frequency divider (Hittite HMC36158G). The 4.596 GHz output microwave signal is bandpass filtered and amplified with a 4-12 GHz bandwidth high-power amplifier (Nextec NBL-00426) to produce a microwave power of about 20-22 dBm. A 5-GHz bandwidth switch (Minicircuits ZASW-50-DR2+) is implemented in this arm to make possible fast and high-extinction switching of the 4.596 GHz microwave signal.¹⁹

III. ABSOLUTE PHASE NOISE MEASUREMENTS

Measurements are performed with a signal source analyzer (Agilent E5052B) using cross-correlation techniques for enhanced sensitivity.^{21–23} The phase noise uncertainty at effective offset frequencies from 1 Hz to 100 MHz is given to be about ± 5 dB.^{23,24} This uncertainty has to be considered for phase noise plots of Figures 3, 4, and 8. Figure 3 plots

FIG. 3. Absolute phase noise performances of key signals of the synthesis chain. (a) 100 MHz OCXO, (b) 200 MHz signal at the output of the ZFL-1000VH2+ amplifier (not connected to NLTL-chain), (c) 9200 MHz signal at the output of the NLTL-based chain, (d) free-running DRO at 9.192 GHz, (e) locked DRO at 9.192 GHz, (f) synthesis output at 9.392 GHz in LNE-SYRTE.

FIG. 4. Absolute phase noise of the 200 MHz signal in three configurations. (a) NLTL connected to the 200 MHz stage output without IMC. (b) NLTL-chain disconnected from the 200 MHz chain. (c) NLTL connected to the 200 MHz stage output with IMC.

absolute phase noise performances of key signals of the synthesis chain at 100, 200, 9200, and 9192 MHz (free-running or locked DRO). The phase noise of the 9.192 GHz signal used in LNE-SYRTE CPT clock is shown for comparison. The phase noise spectrum of the free-running 100 MHz Pascall OCXO is given in $\text{dB rad}^2/\text{Hz}$ by the power law $S_\phi(f) = \sum_{i=0}^{-4} b_i f^i$ with $b_0 = -182$, $b_{-1} = -130$, and $b_{-3} = -82$. These performances are excellent and are found to be in the $f = 1 \text{ Hz}$ -10 kHz frequency range significantly better than other OCXOs we tested. For $f < 10 \text{ kHz}$, the phase noise of the 200 MHz output signal is measured to be as expected 6 dB higher than the 100 MHz signal phase noise. For $f > 10 \text{ kHz}$, the phase noise of the output 200 MHz signal is degraded compared to the ideally multiplied 100 MHz signal. The white phase noise floor of the 200 MHz signal is measured to be $-168 \text{ dB rad}^2/\text{Hz}$ and is limited by the input power of the ZFL-1000VH2+ amplifier.²⁵ The 9200 MHz signal phase noise is -42 , -100 , -130 , and $-135 \text{ dB rad}^2/\text{Hz}$ at 1 Hz, 100 Hz, 10 kHz, and 1 MHz offset, respectively. Except for the 200 Hz-1 kHz region where an excess noise degradation of about 3 dB attributed to the NLTL residual phase noise is observed, the signal frequency multiplication from 200 MHz to 9200 MHz causes a 33-dB increase of the noise as expected.

Interestingly, we observed that impedance mismatching between the 200 MHz stage output and the 200-9200 MHz NLTL-based chain can perturbate significantly the absolute phase noise of the 200 MHz signal. To highlight this point, Figure 4 shows the absolute phase noise of the 200 MHz signal in different situations. For curve (a), the 200 MHz stage output is connected to the NLTL-based chain while the 200 MHz signal is measured through the coupler C1 (see Figure 1). For curve (b), the signal is directly measured at the 50Ω impedance-matched output of the 200 MHz band-pass filter while the NLTL-chain section is removed. In the latter case, we observe a relevant improvement (up to 4 dB) of the absolute phase noise at 200 MHz in the 200 Hz-20 kHz offset range. Simultaneously, the white noise floor is slightly degraded by about 3 dB in the last case.

For further investigation, we measured the input impedance at 200 MHz of the NLTL component using a network analyzer. The complex impedance of the NLTL with associated connectors was measured to be $z_{\text{NLTL}} = 7 + 22j$, that is far to be compatible with required 50Ω impedance matching. In this case, the magnitude of the reflection coefficient S_{11} is only -2 dB , meaning that 79% of the RF power of the 200 MHz output stage is reflected back by the NLTL. For improvement, a basic impedance matching L-network circuit (IMC) with lumped elements, shown as an inset in Figure 4, was designed²⁶ in order to match the NLTL input impedance to the 200 MHz stage output. With this circuit, the magnitude of the reflection coefficient S_{11} was improved to be -15 dB . As shown on Figure 4 curve (c), in presence of the NLTL chain, the absolute phase noise of the 200 MHz signal was then improved in the 200 Hz-20 kHz range while achieving optimal phase noise floor value.

In the free-running regime, the DRO exhibits a phase noise of $-112 \text{ dB rad}^2/\text{Hz}$ at $f = 100 \text{ kHz}$. Its phase noise floor for $f > 10 \text{ MHz}$ is $-172 \text{ dB rad}^2/\text{Hz}$ (not shown here). In the locked regime, the 9.192 GHz output signal exhibits phase noise performances of -42 , -100 , -129 , and $-130 \text{ dB rad}^2/\text{Hz}$ at $f = 1 \text{ Hz}$, 100 Hz, 10 kHz, and 1 MHz, respectively. The peak at 7.3 MHz is the signal frequency generated by the DDS included in the DRO PLL. A phase noise reduction of 4-13 dB is measured in the 100 Hz-1 kHz range compared to the current synthesis used in LNE-SYRTE, Paris⁴ (see Fig. 3, curve (f)). Moreover, the number of spurious is greatly reduced in the present synthesis. While not reported for clarity of the figure, phase noise performances of the 4.596 GHz signal were measured to be in good agreement with performances obtained at 9.192 GHz (6 dB reduction of the noise). The phase noise floor of the 4.596 GHz signal is limited for $f > 1 \text{ MHz}$ by the frequency divider residual noise at a level of $-146 \text{ dB rad}^2/\text{Hz}$.

IV. RESIDUAL PHASE NOISE MEASUREMENTS AND LIMITATIONS

Residual phase noise measurements of key components of the frequency synthesis chain were realized. For this purpose, a standard Schottky-diode saturated double-balanced mixer working as a phase detector is used in association with a FFT analyzer (HP 3562A) in single-channel configuration. The uncertainty associated with the measurement of phase noise is estimated to be $\pm 2 \text{ dB}$. Figure 5 shows the residual phase noise of main components in the frequency synthesis chain. All measurements are reported to a carrier frequency of 9.2 GHz and compared to the ideally frequency-multiplied OCXO signal. We observe that the residual noise of the microwave mixer and the microwave amplifier are well below the phase noise of the 100 MHz OCXO. The residual phase noise of the frequency doubler (FD2) is low enough not to degrade the initial OCXO 100 MHz signal for $f < 10 \text{ kHz}$. On this figure, the residual noise floor of the doubler reported at 9.2 GHz is $-130 \text{ dB rad}^2/\text{Hz}$, that becomes $-163.2 \text{ dB rad}^2/\text{Hz}$ when scaled down at 200 MHz. The doubler noise floor was found to be in fact limited by the noise measurement setup at 200 MHz. Observing that the absolute

FIG. 5. Residual phase noise reported at 9200 MHz of key components of the synthesis chain. These measurements are compared to the ideal absolute phase noise of the 100 MHz OCXO reported at 9200 MHz to highlight main limitations of the chain. (a) OCXO 100 MHz, (b) NLTL chain (input power $P_i = 23$ dBm), (c) Frequency doubler FD2+ (output referred), (d) Microwave amplifier, (e) Microwave mixer.

phase noise floor at 200 MHz is -168 dB rad²/Hz (see Fig. 3), we can assume that the actual residual noise floor of the frequency doubler is at least 5 dB better than the value reported on Fig. 5. To conclude on the limitations of the synthesis, we find that the 9.192 GHz output signal white noise floor is degraded for $f > 10$ kHz by about 6 dB by the frequency doubling stage residual noise floor. In the 100 Hz–1 kHz offset frequency range, it is measured that the NLTL chain residual phase noise remains a limitation to the ideal frequency multiplication of the OCXO 100 MHz signal.

Further words and independent analysis on the NLTL component are now reported. Figure 6 reports the residual phase noise of the NLTL-based 200–9200 MHz frequency multiplication chain for different input power of the NLTL component. In this experiment, the NLTL-based chain residual phase noise is decreased with decreased input power. The best measurement is obtained for an input power of 23 dBm. In this case, the phase noise spectrum exhibits different slopes, f^{-1} for $1 \text{ Hz} < f < 100 \text{ Hz}$, f^{-2} for 100 Hz

FIG. 6. Residual phase noise at 9200 MHz of the NLTL-based frequency multiplication chain versus the NLTL input power.

$< f < 10 \text{ kHz}$, and f^{-1} again far from the carrier. This behavior is not clearly explained and was observed on 4 different tested NLTLs. With increased NLTL input power, we observe up to 15 dB of degradation of the chain residual phase noise in the 100 Hz–1 kHz offset range. The NLTL input power for best phase noise performances needs to be found experimentally.

For information, compared to old-generation NLTLs,¹⁶ we note that the new-generation NLTL presents several relevant drawbacks. It is more expensive, needs to be driven with higher RF power (23–27 dBm instead of 19–23 dBm) and exhibits a residual phase noise about 10 dB higher. Note that in Ref. 27, the residual phase noise of Step Recovery Diodes (SRD) was measured to be -120 dB rad²/Hz at $f = 100$ Hz for a carrier of 10 GHz, that is about 10 dB better than the residual phase noise of our NLTL comb generator. These components could be good candidates for improved performances of the synthesis chain, mainly in the 100–1 kHz offset frequency range. Another solution could be to reduce largely the excess flicker noise of the NLTL using the phase noise suppression technique proposed in Ref. 27.

V. DICK EFFECT CONTRIBUTION

In atomic clocks based on CPT physics, the microwave interrogation signal of the LO is optically carried. Consequently, it has to be checked that there is no phase noise degradation between the microwave synthesis output and the optical beatnote that actually interrogates the atoms. Different techniques can be proposed to generate optical sidebands required for CPT interaction. In LNE-SYRTE, both optical lines frequency-split by 9.192 GHz are generated using two phase-locked lasers.¹⁶ In FEMTO-ST, as resumed by Figure 7, CPT optical sidebands are generated by driving a pigtailed 895 nm Mach-Zehnder intensity EOM at 4.596 GHz.¹⁹ In this setup, an original microwave synchronous detector (not shown here) is implemented to stabilize the optical carrier suppression at the output of the EOM.²⁸

Figure 8 reports absolute phase noise performances at 9.192 GHz (a) and corresponding Dick effect contribution on the atomic clock short term frequency stability (b) for

FIG. 7. Generation of the 9.192 GHz optically carried microwave signal by modulating at 4.596 GHz a DFB laser with a pigtailed Mach-Zehnder electro-optic modulator (MZ EOM). The dc bias voltage of the EOM (not shown here) is actively adjusted to stabilize the optical carrier suppression at the output of the EOM.²⁸ FPD: fast photodiode, LNA: low noise amplifier.

FIG. 8. Absolute phase noise at 9.192 GHz (a) and expected Dick effect contribution to the CPT atomic clock short term frequency stability (b). Curves are: (a) Optical beatnote signal using 2 phase locked lasers (LNE-SYRTE setup), (b) optical beatnote using an EOM (noise floor limitation due to the measurement setup), (c) output from the present synthesis chain, (d) OCXO ideally frequency-multiplied.

different cases noted (a)-(d). The latter contribution is calculated using Eq. (2). Operating parameters and conditions of the pulsed sequence are reported in Ref. 4. The Dick effect contribution is plotted as a function of the noise integration bandwidth. Once this integrated noise stops to contribute to the Dick effect, σ_y reaches a floor that is the total Dick effect contribution.

Case (a) is the phase noise of the 9.192 GHz optical beatnote generated from the optical phase lock loop (OPLL) used in LNE-SYRTE. In this system, the 2 MHz-bandwidth OPLL degrades greatly the interrogation signal phase noise floor seen by the atoms. The Dick effect contribution is reaching 2.7×10^{-13} in a 2 MHz bandwidth.⁴ Case (b) is the phase noise of the 9.192 GHz optical beatnote at the output of the EOM using the setup described in Fig. 7 while case (c) is the phase noise of the 9.192 GHz signal at the direct synthesis output. In this system, no phase noise degradation is observed between the 9.192 GHz optical beatnote and the direct synthesis output for $f < 1$ kHz. For $f > 1$ kHz, the phase noise floor of the 9.192 GHz optical beatnote is limited at a level of

-118 dB rad²/Hz. We checked that this limit is intrinsically due to the phase noise measurement setup (PNMS), more precisely by the low input power (~ -54 dBm) of the microwave amplifier²⁵ placed at the output of the fast photodiode used to detect the optical beatnote. In the EOM-based CPT clock, there is no noise to be integrated for frequencies higher than 20 kHz. In case (b), the Dick effect contribution is reported at 8.4×10^{-14} . Neglecting the limitation due to the PNMS (case (c)), the latter is further reduced at the level of 6.2×10^{-14} . This value is a factor 3 higher than the atomic clock shot noise limit. It has been calculated that the 3 dB-degradation due to the DRO PLL has no impact on the Dick effect limitation.

In order to evaluate ultimate achievable performances of this chain, case (d) reports the phase noise spectrum of the OCXO 100 MHz signal ideally multiplied to 9.192 GHz. In this ideal case, the clock frequency stability limitation would be slightly further reduced at 5.3×10^{-14} . Note that removing totally spurious lines from the OCXO phase noise spectrum, the ultimate Dick effect contribution of the OCXO would be minimized to a level of 3.3×10^{-14} , a value close to the atomic clock shot noise limit.

VI. CONCLUSIONS

We reported the development of a high-performance microwave frequency synthesis chain driven by an ultra-low phase noise 100 MHz OCXO. Key steps are a 100-200 MHz frequency multiplication stage, a 200-9200 MHz NLTL-based chain, and the phase lock of a DRO onto the frequency-multiplied 100 MHz signal. Absolute phase noise performances at 9.192 GHz are found to be -100 dB rad²/Hz and -119 dB rad²/Hz at $f = 100$ Hz and $f = 1$ kHz, respectively. Performances of the synthesis chain are mainly limited by the NLTL-based chain residual noise in the 100 Hz-1 kHz offset frequency range (3 dB degradation). The white noise floor is limited by the 100-200 MHz frequency doubling stage residual noise (6 dB degradation) and the DRO phase lock loop (3 dB degradation). Impedance matching issues between the 200 MHz output stage and the 200-9200 MHz NLTL-chain section were pointed out, impacting on the synthesis phase noise performances. No absolute phase noise degradation was found between the direct synthesis output and the optical beatnote at the output of a MZ EOM for $f < 1$ kHz. In present configuration, the Dick effect contribution is reported at the level of 6.2×10^{-14} . This could be further lowered at 5.3×10^{-14} if the OCXO spectral purity is perfectly transferred to 9.192 GHz and even further reduced at 3.3×10^{-14} if the final phase noise spectrum presents no spurious lines. Performances demonstrated are fully compatible with the development of a high-performance Cs vapor cell atomic clock with expected relative frequency stability better than 10^{-13} at 1 s integration time.

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