X-BAND METROLOGICAL MICROWAVE SOLUTION

Sebastian Müller, Dr. Mikhail Volkov, Dr. Thomas Puppe
TOPTICA Photonics SE

This white paper presents the design and performance of the TOPTICA X-band metrological microwave solution (X-MMS). The X-MMS is an ultra-high-purity 9.6 GHz local oscillator, realizing the optical frequency division principle and based on all-TOPTICA commercial components. The phase noise is characterized in a cross-correlation measurement against two semi-identical X-MMS systems, revealing a single-sideband phase noise of –102 dBc/Hz at 1 Hz offset frequency, reaching down to below –166 dBc/Hz above 10 kHz offsets. Ultrabroadband and all-passive f_{CEO} stabilization via the difference frequency process (TOPTICA's CERO technology) ensures extremely low intensity- and phase noise. The fractional frequency instability of the microwave signal is 2.0 × 10^{-15} at 1 s averaging time. Our patented PURACY technology allows us to additionally discipline X-MMS to a 10 MHz reference for long-term stability, such as those derived from clocks, GPS, or frequency-distribution networks, enabling fast, accurate, and SI-traceable radiofrequency measurements.

1. INTRODUCTION

Ultra-low-noise microwave local oscillators in the X-band (8-12 GHz) are a crucial component in a variety of radiofrequency (RF) metrology, test & measurement applications, such as atomic fountain clocks, deep-space sensing, very-long-baseline interferometry (VLBI), hyperfine RF qubits, and characterization of new oscillators.

Conventional ultra-low-noise RF sources, such as cryogenic sapphire-loaded cavities (CSLC) and whispering gallery mode resonators, source their purity from high-quality (high-Q) RF resonators. However, optical resonators exhibit significantly higher Q-factors even at room temperatures, translating into better fractional frequency stability. Their performance can be transferred from the optical to the RF domain via optical frequency division (OFD) [1] with the help of an optical frequency comb, yielding some of the highest-purity microwave signals reported to date. A frequency comb with an ideal transfer property between the optical and RF domains maintains the fractional frequency stability:

$$\frac{df_{RF}}{f_{RF}} = \frac{df_{opt}}{f_{opt}} \sim \frac{1}{Q}$$

where the optical and radio frequencies are connected via a comb equation:

$$f_{RF} = \frac{f_{opt}}{N}$$

Here, f_{RF} is the comb repetition rate, and $N \sim 10^6$ is the division factor, corresponding to the mode number.

Since its first demonstrations [1], OFD-generated microwave systems have been evolving towards lower noise and increased reliability. Pioneering works used conventional frequency combs with f–2f stabilization. However, to date, some of the best phase noise results [2-4] relied on the transfer-oscillator principle (TO-OFD), in which the carrier–envelope offset frequency f_{CEO} is electronically mixed rather than actively locked. While TO-OFD schemes perform well in laboratory environments, they may be sensitive to environmental drifts outside controlled conditions.

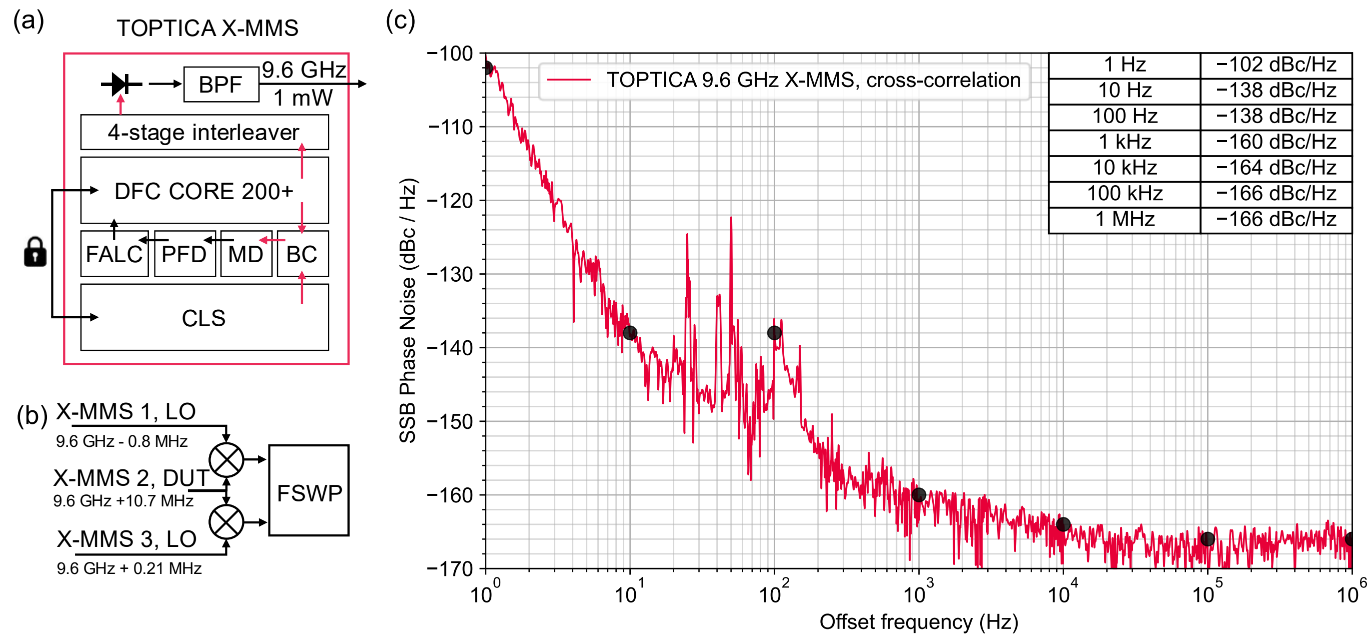

Fig. 1. Cross-correlation measurement of 3 independent TOPTICA's X-MMS systems.

TOPTICA's Difference Frequency Comb (DFC) combines the advantages of both approaches, without compromising either noise performance or system stability. The DFC is intrinsically offset-free, $f_{CEO} = 0$, down to the few-microhertz level, supporting 10^{-21} stability [5, 6]. For the DFC, all optical modes are harmonics of the repetition rate, and their noise is simply the repetition-rate noise scaled by the mode index [7]. Since f_{CEO} is completely decoupled from the repetition rate and the frequency comb's fixed point is at zero, the leverage effect of frequency division is maximized, while control is simplified through direct oscillator current actuation.

2. TOPTICA'S PHOTONIC MICROWAVE: CROSS-CORRELATION MEASUREMENT

While the frequency comb lies at the heart of OFD, high spectral purity of the microwave signal at all offsets can only be achieved through impeccable performance of every system component. Fueled by rapid progress in quantum technologies, the past decade has seen the commercial deployment of robust, rack-integrated laser reference systems. This momentum directly enables commercial ultra-high-purity microwave systems, which rely on the same core components.

TOPTICA's X-MMS comprises our off-the-shelf products (Fig. 1a): Clock Laser System (CLS), Difference Frequency Comb (DFC), Beam Combiner (DFC BC) and Monochromatic Detector (DFC MD) units as well as control electronics – Phase Frequency Detector (PFD) and Fast Analog Linewidth Controler (FALC). To boost the RF power at 9.6 GHz we use a 4-stage fiber interleaver to concentrate the RF power into the harmonics of $2^4 \times 200$ MHz = 3.2 GHz. The output power of the filtered microwave at 3 × 3.2 GHz = 9.6 GHz is 1 mW or 0 dBm. The detailed schematic and the long-term stability in a two-system comparison have been reported earlier in our peer-reviewed publication [8].

Here, we present the three-system cross-correlation (3CC) analysis of the phase noise, the "gold standard" of phase noise characterization. We construct three systems with identical architecture and characterize them with a phase noise analyzer (Rohde & Schwarz FSWP26). Two systems are used as independent local oscillators (LO 1/2), and the third one is the device under test (DUT). The frequency of the local oscillators is detuned from the 9.6 GHz DUT by ~10 MHz. The DUT is externally mixed with both LOs, providing two 10 MHz signal inputs to the FSWP (Fig. 1b). The X-MMS performance is discussed in the next section.

3. PERFORMANCE

The single-sideband (SSB) power spectral density of the phase noise is shown in Fig. 1c. Values at selected frequencies and reference values with higher performance, when available, are reported in Table 1. Note that two-system comparisons are limited by the instrument's noise floor; X-MMS and ref. [3] are measured with 3-system cross-correlation.

Offset frequency	SSB phase noise, dBc/Hz			
	TOPTICA 9.6 GHz	Higher reported performance in X-band		
10 mHz	–47	–60[9]		
100 mHz	–69	–80[9]		
1 Hz	–102	–104[11]	–106[3,4]	
10 Hz	–138			
100 Hz	–138			
1 kHz	–160			
10 kHz	–164	–173[3]	–170[4]	–167[12]
100 kHz	–166	–170[3,18]	–178[13]	–171[17]
1 MHz	–166	–170[16]	–173[18]	–175[17]

[3] OFD, SYRTE
[9] CSLC, University of Western Australia
[11, 4] OFD, NIST
[12, 13] OFD, JILA / University of Colorado Boulder
[16, 17] room-temp. sapphire loaded cavity, Saetta Labs, PSI
[18] cavity-stabilized dielectric resonant oscillator, NIST

In the close-to-carrier range (10mHz-1Hz) the performance is limited by the mid-term stability of the Fabry-Pérot cavity of the CLS and environmental influences. In this range, phase noise is rarely reported. The closest benchmark that we could identify between **10 mHz and 1 Hz**, is the two-CSLC comparison that yielded 5-10 dB better phase noise [9]. At 1 Hz, OFD and CSLC systems [3, 4, 9- 11] report similar performance to TOPTICA's X-MMS in two-system comparisons.

Between **1 Hz and 1 kHz** the short-term stability of the Fabry-Pérot cavity dominates. Excellent acoustic and electromagnetic shielding of our CLS helps us achieve performance that is unmatched, to the best of our knowledge.

Between **1 kHz and 100 kHz**, phase noise is limited by photo-electronic conversion. Low relative intensity noise (RIN) of our frequency comb results in a –166 dBc/Hz floor. This noise floor is still 11 dB above the electronics thermal limit (–177 dBc/Hz), thus cross-correlation collapse [14] is unlikely. Optimized photodetection with RIN suppression can yield even lower values down to –173 dBc/Hz, as demonstrated in national metrology labs [3,12,13].

Between **100 kHz and 1 MHz**, X-MMS stays at the photodetection limit, due to absence of f_{CEO} and f_{rep} control servo bumps or their crosstalk in the DFC.

The measured overlapping Allan Deviation (OADEV) is 2.0×10^{-15} at 1 s and, 1.85×10^{-15} at 10 s. The long-term performance can be seamlessly locked to atomic frequency standards or to primary laboratory 10 MHz oscillators (for common-reference RF measurements), via the patented TOPTICA DFC PURACY add-on.

4. SUMMARY

With off-the-shelf TOPTICA components, we readily achieve a performance level unmatched by currently available commercial X-band microwave systems, surpassed only at selected offset frequencies by the best published research-grade systems. For offsets between 10 Hz and 1 kHz the phase noise of TOPTICA X-MMS is currently unrivalled, as benchmarked in our survey table. Combined with industry-grade reliability and optional SI referencing, X-MMS is uniquely positioned for the most demanding microwave metrology applications.

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