Photonic Synthesis of Continuously Tunable (5-170 GHz) Microwave Signals with Frequency Independent Phase Noise

Abstract— **We propose and demonstrate continuously tunable frequency synthesis over 5-170 GHz using phase locked narrow linewidth lasers. The phase locking over wide a wide frequency range is achieved by detecting the high order harmonic components that generated through modulating the continuous wave (CW) lasers. This harmonic based phase lock loop significantly reduces the phase noise within the locking bandwidth. Due to the low fundamental linewidth of the lasers, the high frequency (>1kHz) components of synthesized RF signals exhibit a constant phase noise irrespective of the RF frequency. Such behaviour leads to a decreased jitter as the frequency increases, achieving a jitter of 27 fs at 170 GHz, outperforming high-end commercially available electronic frequency synthesizers. We demonstrate low phase noise RF signal generation from 5 GHz to 170 GHz with 1-MHz-step tunability using low-speed control electronics for cost-effective implementation.**

Keywords— **RF synthesizer, phase noise, optical phase locked loop, narrow linewidth lasers**

I. INTRODUCTION

The emerging 6G envisages wireless communications and sensing using multi-band radio frequencies (RF) from sub-6 GHz to up to 170 GHz (D-band) [1]. High-capacity wireless transmission and high resolution sensing require low phase noise and tunable RF signals as carrier and local oscillators at different bands [2,3]. The phase noise of conventional electronic frequency synthesizers increases quadratically with the signal frequency and is becoming a major limit of spectral efficiency and resolution in high carrier frequency (e.g. >30GHz) wireless communications and sensing.

To overcome this limit, optoelectronic oscillator (OEO) and microwave photonics approaches are actively explored to synthesis low phase noise RF and mm-wave signals. OEO has demonstrated superior phase noise. However, its output frequency depends on the loop cavity resonance, thus, it is not continuously tunable [4,5]. Microwave photonic approaches that beat two lasers using a photodetector (PD) can synthesize arbitrary frequency RF signals within the PD's bandwidth. Stable and low phase noise signal synthesis requires locking the frequency and phase of the two independent lasers, which can be achieved by locking the lasers to each other using an optical phase lock loop (OPLL) [6-9] or an injection locked phase lock loop [10], or by locking the laser to a reference a frequency comb [11,12] or a stable cavity reference [13].

However, conventional heterodyne based OPLL typically requires a local oscillator (LO) of similar frequency to down convert the generated RF signals to an intermediate frequency (IF) for feedback control, which becomes costly and power hungry due to need for broadband RF components such as broadband mixers, RF amplifiers, high speed PDs and high frequency LOs. Locking lasers to frequency combs or optical cavities requires additional cavities or comb sources, and the frequency tunability (range and resolution) is limited due to the fixed comb spacing and free spectral range. A low phase noise, large tuning range, and continuously tunable frequency synthesizer is lacking. In this paper, we propose and demonstrate a robust and cost-effective approach for achieving tunable and low phase noise frequency synthesis using harmonic based frequency and phase locking method. The proposed method relates the frequency and phase of two widely-spaced continuous wave (CW) lasers by modulating them with the same RF source and generating high order harmonic components that are closely spaced in the optical domain. The frequency and phase difference between the harmonic components can then be detected using low bandwidth PD and phase and frequency detector (PFD) for feedback control. The harmonics generation process brings the widely spaced optical frequencies close to less than 100 -MHz-bandwidth PD and this allows for generating error signal from the overlapped high order harmonic components generated by modulating two independent combs continuous wave lasers, requiring only low speed (100 MHz) PD and sub-50MHz-bandwidth a phase and frequency detector (PFD) to generate error signals for feedback control.

Compared to conventional heterodyne based OPLL, our method significantly reduces the frequency and bandwidth requirements of the RF components, and it permits continuously frequency tuning within the bandwidth of the PD. Using a 100-MHz-bandwidth PD and PFD, we demonstrate widely tunable RF frequency synthesis over 5-110 GHz and 110-170 GHz, and continuous fine tuning capability down to 1MHz. Compared with electronic synthesizers whose phase noise increases quadratically with the signal frequency, our approach exhibits frequency independent phase noise, resulting in a reduced jitter with increased frequency, yielding 27 fs jitter at 170 GHz, outperforming tested high-end electronic frequency synthesizers.

II. EXPERIMENTAL SETUP

Fig.1a shows the schematic diagram of the proposed method. We used two narrow linewidth continuous wave (CW) lasers with sub-kHz linewidth outputting 40 mW as sources. Laser 1 is a 600-Hz fibre laser with a frequency modulation bandwidth of 1 kHz and laser 2 is a 100-Hz external cavity laser with a frequency modulation bandwidth of about 100 kHz.

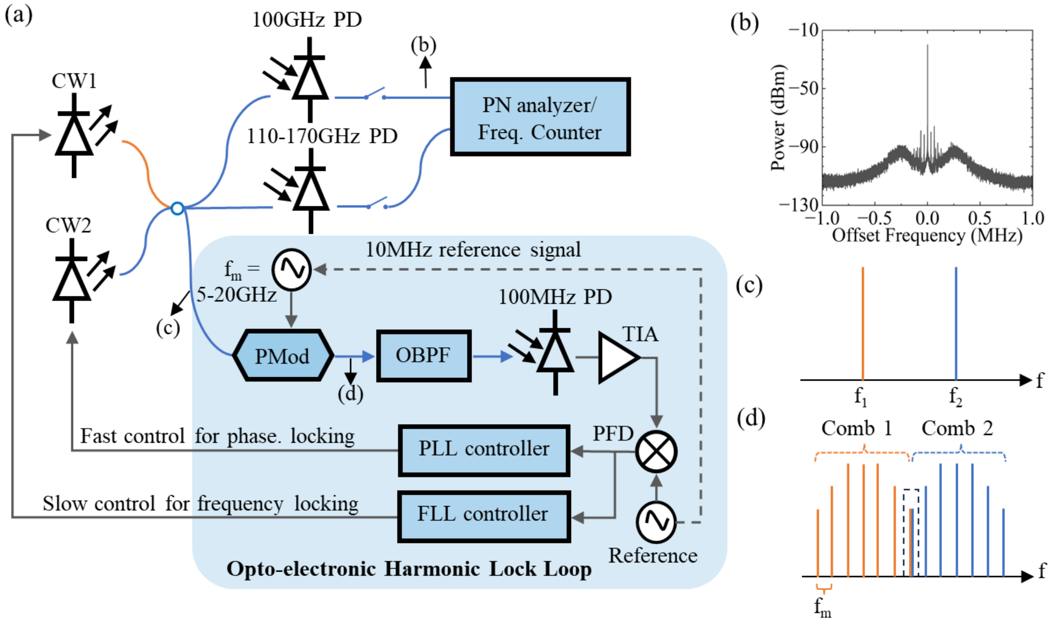

Fig.1: (a) Experimental set-up. OBPF: optical bandpass filter, PD: photodetector, PMod: phase modulator, TIA: transimpedance amplifier, PFD: phase frequency detector (b) Measured RF spectrum at 170 GHz of the optical harmonic lock frequency synthesizer (c) Two CW lasers combined (d) Output of the phase modulators, in which both CW lasers are expanded to generate harmonic components with frequency spacing of f_m.

The outputs of the lasers are combined using a 50/50 polarization maintaining (PM) coupler. One of the combined outputs is directed to the control loops, while the other is fed either into a broadband photodetector (PD) with a 3-dB bandwidth of 100 GHz, for generating RF signals up to 100 GHz, or into a uni-travelling-carrier (UTC) PD, which has a bandwidth from 110 GHz to 170 GHz, to generate RF signals up to 170 GHz.

Our proposed opto-electronic harmonic lock loop (OHLL) subsystem consists of a phase modulator (PMod) driven with an RF synthesizer operating from 5-30 GHz (f_m). By driving the PMod with high RF power, we generate high order harmonic tones following the Jacobi-Anger expansion [14], which exhibits two comb-like signals in the frequency domain, as shown in Fig.1d. The upper sideband (USB) tones of the laser 1 expansion and the lower sideband (LSB) tones of laser 2 expansion overlap in the center of the spectrum and are subsequently filtered out using an optical bandpass filter (OBPF) of about 10 GHz bandwidth, leaving only the +nth USB tone from comb 1 and the nth LSB tone from comb 2.

By tuning both f_m and the lasers' operation frequencies, the filtered 3rd order harmonic tones from the modulated signals (comb 1 and comb 2) are kept less than 100 MHz spacing. The filtered tones carry the frequency and phase information of the seed lasers and are directly converted to a sub-100-MHz IF signal using a 100-MHz bandwidth PD followed by a transimpedance amplifier (TIA). The detected IF signal is fed to a phase frequency detector (PFD) and compared with a 25 MHz reference to generate phase error signal. Both f_m and the 25 MHz reference in the PFD are clocked to the same 10 MHz external reference.

The generated error signal is split to feed two laser control units to enable frequency and phase locking. The frequency lock loop (FLL) is a slow proportional integral (PI) controller with about 300 Hz loop bandwidth, which drives the piezo frequency tuning of laser 1 to track frequency variations and as such lock the frequency-difference between the two lasers to less than 1 MHz. Once frequency locking is achieved, we use a fast loop to stabilize the relative phase between the two lasers. The fast loop has a loop delay of about 120 ns and drives the piezo driver of laser b with about 100 kHz control bandwidth.

To demonstrate both the coarse tunability and the phase noise advantage of the proposed system, we measure the phase noise at different beat frequencies from 5 GHz to 170 GHz, where the upper limit is set by the bandwidth of the PD and the measurement instrument (phase noise analyzer). The measurements are done by tuning the wavelength of laser 2 to control the frequency spacing between the two lasers and as such the generated high-frequency beat note. The spacing between the harmonic tones are kept within 100 MHz by adjusting the RF frequency f_m, which can be flexibly tuned at 1MHz resolution to achieve continuous tuning of laser spacing. The phase noise is measured using a cross-correlation based phase noise analyzer (Rohde & Schwartz FSWP50) with W (90-110 GHz) and D band (110-170 GHz) extension.

III. EXPERIMENTAL RESULTS

Fig.2 compares the phase noise of the generated 170 GHz RF signal with free-running and phase locked lasers using the proposed photonic-assisted synthesizer. Using our OHLL The low frequency (10-1kHz) was significantly improved by approximately 70dB. Both curves converge at around 200 kHz, a limitation imposed by the frequency modulation bandwidth of laser 1. As a result, the high-frequency noise exhibits a similar phase noise performance, as it is predominantly governed by the inherent phase noise characteristics of the laser.

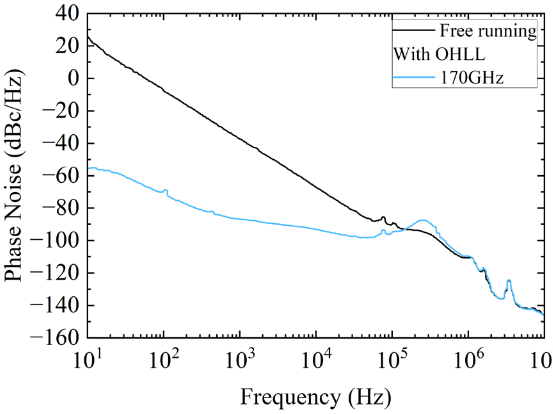

Fig.2: Phase noise measurements of the photonic-assisted frequency synthesizer at 170 GHz vs. free-running lasers

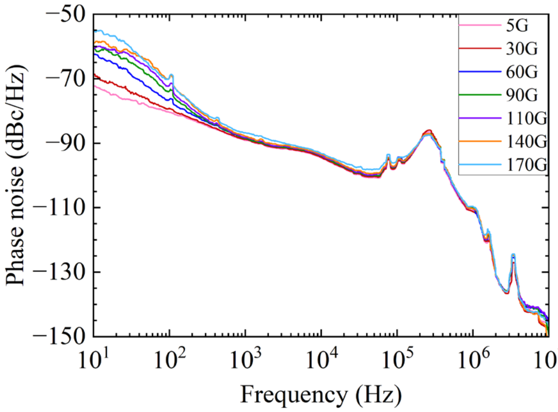

Fig.3: Phase noise measurements of the photonic-assisted frequency synthesizer at different frequencies

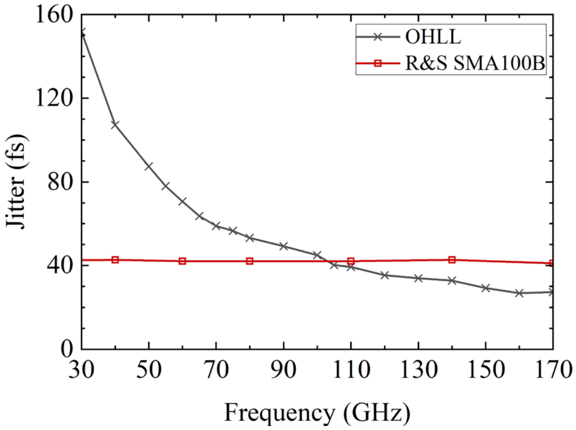

Fig.4: Measured jitter of the photonic-assisted frequency synthesizer at different frequencies vs. commercial electronic synthesizer

Fig.3 shows the measured phase noise of the generated RF signal at different frequencies from 5 GHz up to 170 GHz. The high-frequency (1kHz-10MHz) phase noise exhibits similar performance irrespective of the generated frequency. However, the low frequency (10Hz-1kHz) phase noise increases quadratically with the carrier frequency. Such noise enhancement at the low-frequency region is attributed to the RF noise of the electronic synthesizer that drives the phase modulator, which got coupled into the OHLL with a locking bandwidth of approximately 300 Hz.

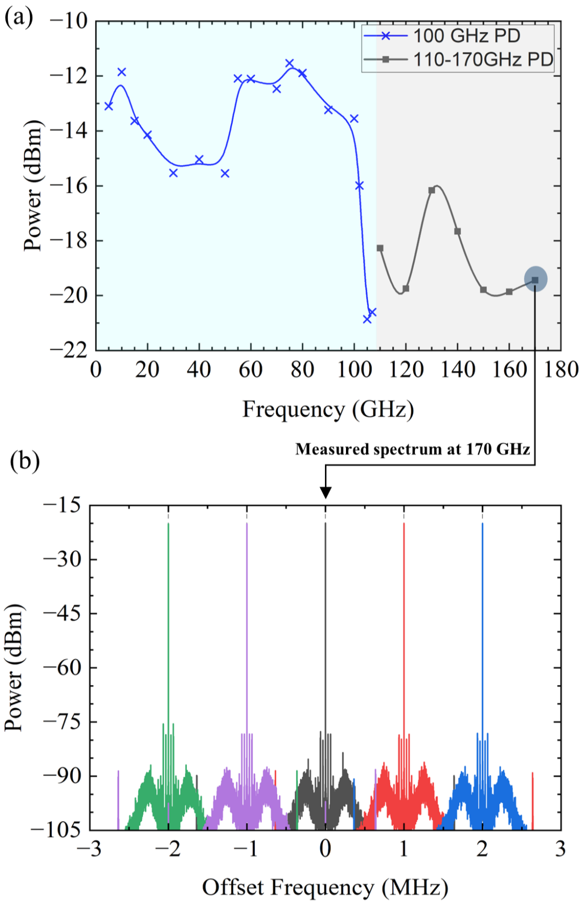

Fig.5: (a) Measured RF signal power across frequency for the two different PDs used. (b) Measured spectrum showing 1 MHz fine tuning capability of the photonic-assisted synthesizer at 170 GHz centre frequency

The constant phase noise observed in the 1k-10MHz region indicates that the high-frequency phase noise of our photonic synthesized microwave signal is dominated by the lasers' phase noise. Importantly, this phase noise does not scale with frequency spacing of the lasers. As a result, the integrated jitter (10 Hz to 10 MHz) decreases with the increase of the carrier frequency. Conventionally electronic synthesizer, however, exhibits a constant jitter due to the quadratically increased phase noise. To assess our signal performance, we conducted a comparison with a commercially available electronic synthesizers: R&S SMA 100b, which has a maximum frequency of 20 GHz and an integrated jitter of 42 fs.

Fig.4 compares the jitter measurements of the photonic-assisted synthesizer vs the R&S synthesizer. For the commercial synthesizers, jitter measurements were carried out using an x8 frequency multiplier (R&S SMZ170). In contrast, the proposed photonic-assisted frequency synthesizer outperforms the tested electronic synthesizer in >110GHz frequency region, reaching 27 fs at 170 GHz. Such advantage is attributed to the OHLL and the small fundamental linewidth of the lasers.

Fig.5a shows the RF signal power measured across the whole frequency region using two different PDs. The signal power variations are less than 4 dB in the 5-100 GHz region, which is mainly due to the combined frequency responsivity of the PD and the RF cable. The sharp roll of beyond 100 GHz is due to the bandwidth of the 100-GHz-PD [15]. Similarly, the generated signals in the 110-170 GHz region also vary by about 4 dB, with the highest power at around 140 GHz due to the responsivity of the used UTC-PD. In practice, the power could be further boosted using corresponding broadband amplifiers.

To demonstrate the fine tuning, we show the measured spectra of the signals with 1 MHz step in different colors in Fig.5b. The measured signals are centered at 170 GHz. The signals show about 55 dB spurious free dynamic range (SFDR) due to the side-mode suppression ratio of the laser. Higher SFDR could be achieved using high SMSR lasers. Such fine frequency tuning is enabled by changing the reference frequency input to the PFD, which allows for up to 40 MHz fine frequency tuning limited by the bandwidth of the PFD.

IV. CONCLUSION

We propose a tuneable and low noise RF frequency synthesizer using optical harmonic locking method. We demonstrate tuneable frequencies from 5 GHz to up to 170 GHz. The phase noise of the proposed OHLL based photonic frequency synthesizer is independent from the carrier frequency, leading to a decrease of the integrated jitter from 42 to 27 fs, with the carrier frequency increases from 100 GHz to 170 GHz. The wide frequency tunability and constant phase noise features is beneficial in generating high RF frequencies (e.g.>50 GHz), which is a major challenge for the electronic frequency synthesizers. Our method benefits high frequency RF and mm wave generation and will be of interest to wireless transmission and microwave applications.

REFERENCES

[1] P. Yang, Y. Xiao, M. Xiao and S. Li, "6G Wireless Communications: Vision and Potential Techniques," in *IEEE Network*, vol. 33, no. 4, pp. 70-75, July/August 2019.

[2] M. Matinmikko-Blue, S. Yrjölä and P. Ahokangas, "Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020.

[3] Z. Zhou, D. Nopchinda, M. -C. Lo, I. Darwazeh and Z. Liu, "Simultaneous Clock and RF Carrier Distribution for Beyond 5G Networks Using Optical Frequency Comb," *2022 European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022, pp. 1-4.

[4] X. Steve Yao and Lute Maleki, "Optoelectronic microwave oscillator," J. Opt. Soc. Am. B 13, 1725-1735 (1996)

[5] Jian Tang, Tengfei Hao, Wei Li, David Domenech, Rocio Baños, Pascual Muñoz, Ninghua Zhu, José Capmany, and Ming Li, "Integrated optoelectronic oscillator," Opt. Express 26, 12257-12265 (2018)

[6] F. Friederich, G. Schuricht, A. Deninger, F. Lison, G. Spickermann, P. Bolívar, and H. Roskos, "Phase-locking of the beat signal of two distributed-feedback diode lasers to oscillators working in the MHz to THz range," Opt. Express 18, 8621-8629, 2010.

[7] Lipka, M., Parniak, M. & Wasilewski, W. Optical frequency locked loop for long-term stabilization of broad-line DFB laser frequency difference. *Appl. Phys. B* 123, 238 (2017).

[8] J. Appel, A. MacRae, and A. I. Lvovsky, "A versatile digital GHz phase lock for external cavity diode lasers", Measurement Science and Technology, vol. 20, no. 5, p. 055 302, 2009.

[9] X. Chen, Q. Liu, Y. Wang, F. Meng and B. Luo, "A High-Precision Offset Frequency Locking Technique With Delay Line Reference and AOM-Based Compensation," in *IEEE Photonics Journal*, vol. 13, no. 4, pp. 1-6, Aug. 2021.

[10] Z. Liu and R. Slavík, "Optical Injection Locking: From Principle to Applications," in *Journal of Lightwave Technology*, vol. 38, no. 1, pp. 43-59, 1 Jan.1, 2020.

[11] Pedro Largo-Izquierdo and Pedro Martín-Mateos, "Frequency-tunable photonic frequency synthesis from an optical frequency comb reference," Opt. Lett. 42, 3777-3780 (2017).

[12] Yusuke Hisai, Kohei Ikeda, Haruki Sakagami, Tomoyuki Horikiri, Takumi Kobayashi, Kazumichi Yoshii, and Feng-Lei Hong, "Evaluation of laser frequency offset locking using an electrical delay line," Appl. Opt. 57, 5628-5634 (2018).

[13] Fortier, T., Kirchner, M., Quinlan, F. *et al.* Generation of ultrastable microwaves via optical frequency division. *Nature Photon* **5**, 425–429 (2011).

[14] C. Deakin and Z. Liu, "Noise and distortion analysis of dual frequency comb photonic RF channelizers", Opt.Express, vol. 28, no. 26, pp. 39 750–39 769, Dec. 2020

[15] Fraunhofer Institute, P. Runge, "100 GHz photodetector module," https://www.hhi.fraunhofer.de/fileadmin/PDF/PC/DET/20191121_10 GHz-Photodetector-Module.pdf, 2019.