Low-noise 300-GHz oscillator based on an optical SiN microresonator

T. Tetsumoto[1], F. Ayano[2], M. Yeo[1], J. Webber,[2] T. Nagatsuma[2], and A. Rolland[1]
[1]IMRA America, Inc., Boulder Research Labs, Longmont, CO, 80501 USA
[2]Graduate School of Engineering Science, Osaka University, Japan
E-mail address: arolland@imra.com

***Abstract*— We report on the generation of an ultralow phase noise 300-GHz signal using a soliton Kerr frequency microresonator comb (microcomb). By transferring the spectral purity of a 10 GHz dielectric resonant oscillator to the repetition rate of a silicon nitride microresonator, operating in soliton regime, we measure a phase noise of -88 dBc/Hz at 10 kHz offset frequency for a 300 GHz carrier.**

I. INTRODUCTION

MILLIMETER-WAVE and terahertz generation with state-of-the-art noise performance in chip-scale form factor will undeniably stimulate a plethora of civilian and defense applications such as radar, 5G and 6G deployment, wireless communication, and global navigation system [1]. While millimeter-wave oscillators based on CMOS technology have shown spectacular performance in terms of size and power consumption, phase noise performance is lacking as well as generating waves higher than 300 GHz. Photonics sources have shown to unlock electronic noise and bandwidth limitations but size and usability outside of the lab are still extremely arguable. However, soliton comb generation from a microresonator is a promising approach in order to use photonics advantages in a chip-scale form factor [2]. Here, we experimentally demonstrate a 300-GHz wave generation from a soliton microcomb with noise performance outstripping any other technologies with similar form factor.

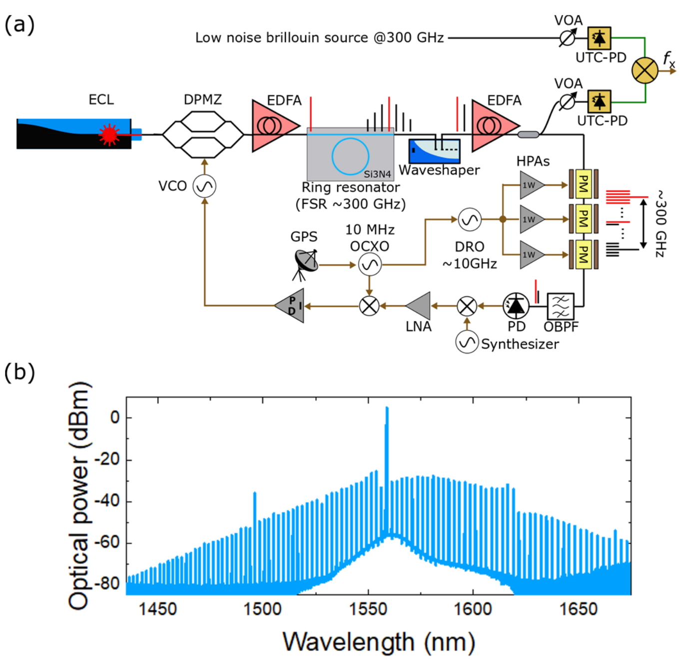

Fig. 1. (a) Microcomb-based 300-GHz experimental setup. See text for details. (b) Optical spectrum of a generated microcomb.

II. RESULTS

Figure 1(a) depicts the experimental setup of a potentially chip-scale millimeter-wave oscillator. A tunable external cavity laser (ECL) pumps a silicon nitride (Si3N4) microresonator through a dual parallel Mach-Zehnder modulator (DPMZ) and an erbium doped fiber amplifier (EDFA). Optical spectrum of an obtained microcomb is shown in Fig.1(b), where optical lines with a constant free spectral range (FSR) of 300 GHz are generated over a broad wavelength range. The output goes to a waveshaper acting as a double bandpass filter to select two optical lines of the microcomb with frequency separation of 1 FSR of 300 GHz. Then, the filtered light is split into two arms. One arm goes to a uni-traveling-carrier photodiode (UTC-PD) for detecting the difference frequency. On the other arm, both two lines are modulated by three cascaded phase modulators (PM) driven by a dielectric resonant oscillator (DRO) amplified with a high power amplifier (HPA).

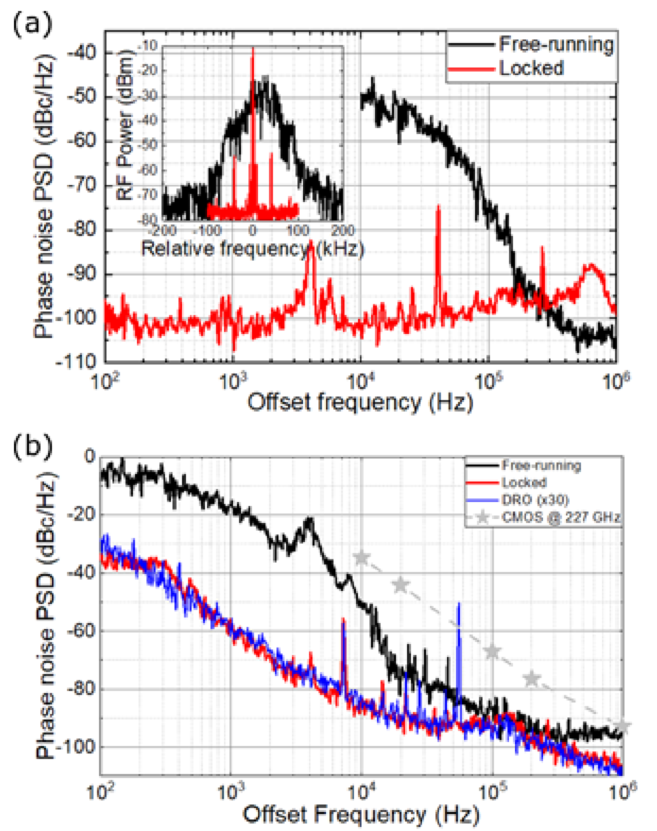

Fig. 2. (a) Phase noise of in-loop signals. The inset shows RF spectrum of the in-loop signals. (b) PSD of phase noise of the microcomb-based 300 GHz signal and the DRO signal. Noise level of a low noise CMOS oscillator at 227 GHz is shown as a reference.

The DRO is synchronized to a 10 MHz signal derived by a GPS signal. Two electro-optic (EO) frequency combs are then generated from the two optical lines of the microcomb. By detecting the spectral region where the two EO combs overlap, one can detect an RF frequency (< 5 GHz when the DRO frequency is 10 GHz). A signal from a low noise synthesizer is mixed with the intermediate frequency (IF) to down-convert it to several 10s of MHz. This RF frequency carries the phase noise of 300 GHz difference frequency as well as the phase noise of the DRO multiplied up by $f_{\mathrm{rep}}/f_{\mathrm{DRO}}$ as follows [3],

$$\delta f_{\mathrm{IF}} = \delta f_{300\mathrm{G}} - 2k\delta f_{\mathrm{DRO}}, \tag{1}$$

where δf_{IF}, $\delta f_{300\mathrm{G}}$, δf_{DRO} are phase noise of IF, 300 GHz difference frequency, and DRO and $2k$ is number of sidebands of the EO combs between two filtered optical lines (i.e. $2k = 30$). After RF amplification of the IF signal with a low noise amplifier (LNA), an error signal is generated with a phase detector where the RF frequency is mixed with the same 10 MHz signal that synchronizes the DRO. The error signal is applied to the DMZM through a PID filter driving a voltage controlled oscillator (VCO), which results in $\delta f_{\mathrm{IF}} \sim 0$. Therefore, the phase noise of the repetition rate is a copy of the phase noise of the DRO multiplied up by 30 following Eq. 1.

Phase noise power spectrum density (PSD) of in-loop signal is shown in Fig. 2(a). The free-running noise is dramatically suppressed below offset frequencies lower than the feedback bandwidth in the phase-locked condition, which is observed as a shrink of a signal peak in RF spectrum (inset of Fig. 2(a)). An out-of-loop measurement of the microcomb-based 300-GHz wave is realized by comparing it with a low noise Brillouin source at 300 GHz as a reference [4]. A millimeter-wave fundamental frequency mixer is used to detect a beatnote between the two millimeter-wave sources. Fig. 2(b) shows the measured phase noise. The phase noise of the 300 GHz signal follows the calibrated DRO noise faithfully, which shows that spectral purity of 10 GHz signal is perfectly transferred to 300 GHz signal. The noise level reaches - 88 dBc/Hz at 10 kHz offset and -106 dBc/Hz at 1 MHz offset (about 30 dB and 10 dB improvement from free-running operation). This is a record phase noise at 300 GHz generated by a microresonator. Moreover, it is worth noting that the obtained value is about 53 dB lower at 10 kHz and 12 dB lower at 1 MHz compared to a low noise CMOS oscillator at 227 GHz based on electrical multiplexing [5].

Finally, we measure frequency instability of the 300 GHz signal. The results are shown in Fig. 3. We obtain fractional instability at 1 second averaging time of 1 x 10^{-9} and 2 x 10^{-15} for a free-running out-of-loop signal and an in-loop signal in a locked condition, respectively. This indicates that the PID control suppresses the frequency instability significantly. On the other hand, a fractional frequency instability for an out-of-loop signal is 2 x 10^{-11}, which is limited by the instability of the reference 300 GHz Brillouin source, and we believe an actual value will be much lower.

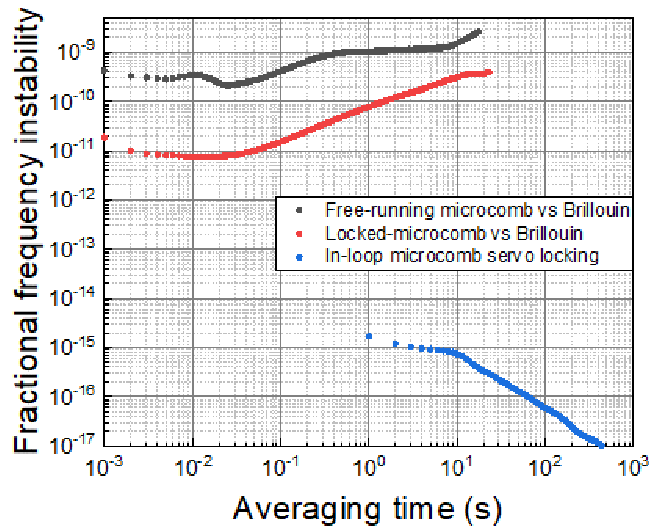

Fig. 3. Measured fractional frequency instability of in- and out-of-loop signals.

III. SUMMARY

We have experimentally demonstrated generation of a 300-GHz wave from a soliton microcomb stabilized to a low-noise 10 GHz microwave oscillator. The measured phase noise of - 88 dBc/Hz at 10 kHz offset is about 53 dB lower than that of a low noise oscillator based on electrical multiplexing, and a record low value for oscillators with a potential to be realized in chip-scale form factor. The obtained in-loop fractional frequency instability of 2 x 10^{-15} at 1 s suggests a high frequency stability of the generated 300 GHz signal. This work shows a great potential of a microcomb as a low noise and compact millimeter and terahertz wave oscillator, whose properties are attractive for applications such as wireless communication, radio-astronomy and rotational spectroscopy.

REFERENCES

[1]. T. Nagatsuma, *et al.*, "Advances in terahertz communications accelerated by photonics," Nature Photonics **10**, 371-379 (2016)

[2]. B. Stern, *et al.*, "Battery-operated integrated frequency comb generator," Nature **562**, 401-405 (2018)

[3]. A. Rolland, *et al.*, "Non-linear optoelectronic phase-locked loop for stabilization of opto-millimeter waves: towards a narrow linewidth tunable THz source," Optics Express **19** (19), 17944-17950 (2011)

[4]. Y.Li, *et al.,* "Low-noise millimeter-wave synthesis from a dual-wavelength fiber Brillouin cavity," Optics Letters **44**(2), 359-362 (2019)

[5] Amir Nikpaik *et al.*, "A 219-to-231 GHz Frequency-Multiplier-Based VCO With ~3% Peak DC-to-RF Efficiency in 65-nm CMOS," IEEE Journal of Solid-State Circuits **53**, 389-403 (2018)