Low-Phase-Noise Microwave Generated by an Optical Frequency Comb Locked to an On-Chip Interferometer

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***Summary*—We generated a low-phase-noise microwave by stabilizing an optical frequency comb with a 56.5-cm long photonic-integrated Mach-Zehnder interferometer that was fabricated in a commercial foundry. The phase noise of the 9.987-GHz tone was −105 dBc/Hz at a 1-kHz offset frequency, corresponding to a reduction of the free-running phase noise by 15 dB. Our results point towards a fully integrated low-phase-noise microwave source.**

***Keywords*—Low Phase Noise Microwave Generation, Optical Frequency Combs, Integrated Photonics**

I. Introduction

Compact and low-cost low-phase-noise microwave sources are of interest for a variety of emerging applications such as next-generation wireless networks and automotive radars. The lowest phase noise microwaves are generated by coherently dividing stable optical frequency references using optical frequency combs (OFCs) [1], but such systems typically use bulky equipment in a laboratory environment. One approach to developing compact and low-cost low-phase-noise microwave sources is to stabilize an OFC using an on-chip optical frequency reference. In particular, our group has previously presented an architecture that uses a short-path interferometer to stabilize an OFC with no additional optical sources [2,3]. In these initial demonstrations, we used an 8-m long fiber-optic interferometer to prove the concept with an interferometer that was shorter than integrated photonic delay lines fabricated by other groups [4].

In the present work, we generated a low phase noise 10-GHz signal by stabilizing the repetition rate of an OFC using a 56.5-cm long Mach-Zehnder interferometer (MZI) that was fabricated on a photonic integrated chip (PIC) in a commercially-available multi-project wafer (MPW) service (Ligentec AN-800). When the OFC was stabilized, we measured the phase noise of the 10-GHz tone to be −105 dBc/Hz at a 1 kHz offset, corresponding to a reduction of the free-running phase noise of approximately 15 dB. Our analysis indicates that the phase noise reduction was limited by the available optical power, including a substantial fiber-to-chip coupling loss of 10 dB. Hence, we expect that future implementations where the OFC and photodiodes are included directly on-chip or are connected with lower-loss couplers (e.g., photonic wire bonds) may achieve even lower phase noise. Furthermore, the MPW service that we used is also attractive as a commercial source for fabricating on-chip optical frequency combs [5], so that the OFC and MZI could be fabricated together in future work.

II. Methods/Results

To generate the microwave under test, we illuminated a PIN photodiode (PD, Optilab PD-20) with the output of a fiber-optic OFC (Menlo Systems FC-1500, 250 MHz repetition rate) and used an RF bandpass filter to isolate the 40th harmonic of the comb's repetition rate (f_{rep}). As shown in Fig. 1, we stabilized f_{rep} with an on-chip Mach-Zehnder interferometer (PIC MZI), which had a path length difference of approximately 56.5 cm, such that the relative group delay between the two arms of the MZI was equal to the time between OFC pulses (i.e., $1/f_{rep}$ = 4 ns). The output of the MZI illuminated a set of balanced photodiodes (BPD), which generated a photocurrent proportional to the frequency noise of f_{rep}. We fed this signal back to modulate f_{rep} through a loop filter in order to reduce the phase noise of the microwave generated by the OFC. The bandwidth of the light entering the PIC MZI was limited using

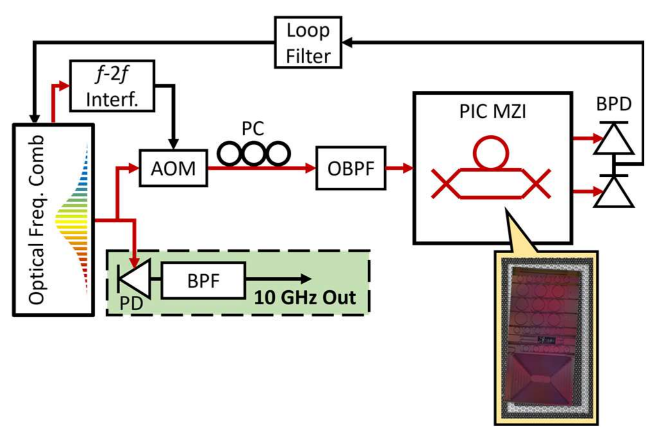

Fig. 1. Experimental setup showing the optical frequency comb (OFC), *f*-2*f* interferometer (*f*-2*f* Interf.) used to measure f_{ceo}, acousto-optic modulator (AOM), polarization controller (PC), optical bandpass filter (OBPF), Mach-Zehnder interferometer fabricated on a photonic integrated chip (PIC MZI), balanced photodiodes (BPD), and loop filter. A photo of the 5mm x 10 mm chip that includes the PIC MZI is inset to illustrate the relative size.

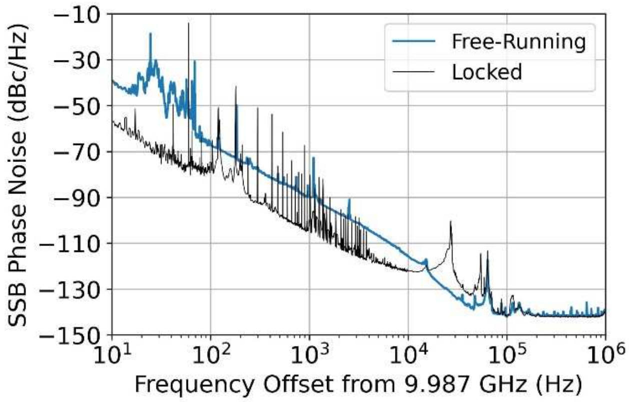

Fig. 2. Experimentally measured phase noise of 9.987-GHz tone generated by the OFC when the repetition rate was free-running (blue) vs. when it was locked to the 56.5-cm PIC MZI (black).

a 3.2-nm wide optical bandpass filter (OBPF, Dicon Optics). This step mitigated the impact of waveguide dispersion, which allows only a finite wavelength range of the light at the output of the PIC MZI to interfere at once [3].The OFC's carrier-envelope offset frequency (f_{ceo}) was stabilized to 60 MHz by a low-gain electronic feedback loop and was further suppressed from the signal entering the PIC MZI by a feed-forward cancellation loop using an acousto-optic modulator (AOM) in a frequency shifting configuration. The polarization of the light launched into the PIC MZI was controlled using a fiber-optic polarization controller (PC).

Fig. 2 shows the phase noise of the 9.987 GHz signal when f_{rep} is free-running (blue) and when f_{rep} is locked to the PIC MZI (black). Stabilizing f_{rep} with the PIC MZI reduced the free-running phase noise by approximately 15-20 dB for offset frequencies from 10 Hz to approximately 10 kHz. The phase noise at 1-kHz offset was −105 dBc/Hz. The spurs appearing in the phase noise when f_{rep} was locked occurred at harmonics of 60 Hz and hence represent coupling of power-line fluctuations into the measurement. They can be suppressed in future work by making refinements to the experimental setup such as suppressing ground loops.

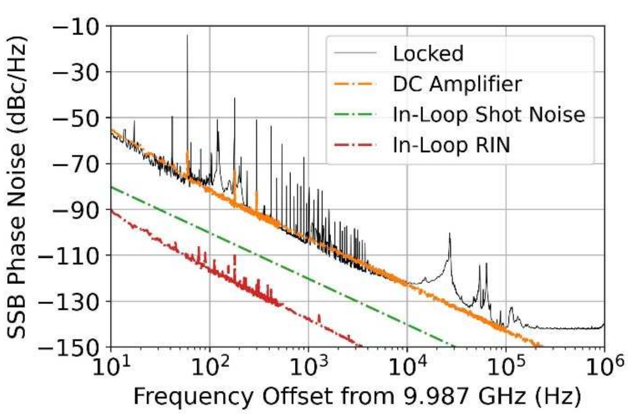

Fig. 3. Experimentally-measured phase noise of the 9.987 GHz tone generated by the locked OFC (black) with the expected phase noise contributions from the in-loop DC Amplifier (orange), in-loop shot noise at the balanced photodiodes (green) , and in-loop OFC relative intensity noise (RIN, red).

Fig. 3 compares the locked phase noise (black) with the expected contributions from the in-loop DC amplifier (orange), shot noise (green), and the relative intensity noise (RIN) of the OFC (red). The expected contribution of the DC amplifier matches well with the measured phase noise, while the expected shot noise contribution is approximately 18 dB below and the OFC RIN contribution is even lower. So, we conclude that the present performance is limited by the DC amplifier contribution. This limitation can be mitigated by increasing the sensitivity of the interferometer—e.g., either by increasing the optical power incident on the in-loop balanced photodiode or by increasing the interferometer path length. The optical power that was available in our experiments was limited by the OFC power of approximately 14 mW, the waveguide chromatic dispersion which allowed only approximately 10% of the light to interfere, and the fiber-to-waveguide coupling loss which totaled approximately 10 dB. Notably, the fiber-to-waveguide coupling loss is expected to be insignificant in a future, fully-integrated system, which would not need to couple light on or off the PIC. The phase noise scales with the square of the optical power, so recovering the 10 dB of coupling loss could lead to a phase noise of −125 dBc/Hz at an offset of 1 kHz. Even lower phase noise could be achieved by increasing the comb power and reducing the dispersion in the waveguide via dispersion engineering.

III. Conclusions

In this work, we have generated a low-phase-noise microwave generated by an OFC that was stabilized using a 56.5 cm-long delay-line on-chip interferometer. The phase noise of the 9.987 GHz signal was −105 dBc/Hz at a 1-kHz offset frequency, corresponding to a 15-dB reduction of the free-running phase noise. Furthermore, we have shown that the performance reported here was limited by the 10-dB fiber-to-waveguide coupling loss as well as the available optical power. These limitations can be overcome in future work by incorporating the OFC and photodiodes directly on-chip. The interferometer was fabricated in Ligentec's commercially-available process, which has also been used to generate OFCs on-chip. These results point towards a high-performance, fully-chip-integrated ultra-low-phase-noise microwave source.

References

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