Low-Phase Noise Microwave Generation using Self-Stabilized f_{ceo}-Free Comb

James P. Cahill, Tanvir Mahmood, Patrick Sykes, and Weimin Zhou
U.S. Army CCDC ARL
Adelphi, MD, USA
james.p.cahill15.civ@mail.mil

Rafal Wilk, Sebastian Mueller, Felix Rohde
TOPTICA Photonics, AG
Munich, Germany

Matthew J. Cich
TOPTICA Photonics, Inc.
Farmington, NY, USA

Curtis R. Menyuk
University of Maryland: Baltimore County
Baltimore, MD, USA

***Abstract*—Due to the inherently low crosstalk between carrier-envelope and repetition rate control mechanisms, difference-frequency generated (DFG) optical frequency combs are an attractive light source for low-phase-noise microwave generation based on feedback control. However, the DFG process adds phase noise to individual comb lines in accordance with the carrier-envelope noise. Here, we stabilized a DFG comb with a 7.5 m interferometer and generated a 10 GHz signal with a phase noise of −123 dBc/Hz at 1 kHz offset frequency.**

Keywords—Optical frequency combs, Low-phase noise microwave generation, Difference frequency generation

I. Introduction

Ultra-low phase noise microwaves at frequencies of 10 GHz and above are useful for high-frequency radar, radio astronomy, and probing quantum transitions. One way to produce microwaves is to multiply the low frequency output of a conventional oscillator, such as a quartz oscillator. However, because phase noise scales in proportion to the carrier frequency, this technique inherently yields microwave signals with relatively high phase noise. Instead, the lowest phase noise microwaves have been demonstrated by using optical frequency combs to coherently divide the frequency of ultra-narrow linewidth lasers to the microwave regime [1,2]. While this technique provides exceedingly low phase noise microwaves, the ultra-narrow linewidth lasers, which include carefully engineered and environmentally-isolated external cavities, are unsuitable for operation outside of laboratory settings—particularly in dynamic environments.

Direct stabilization of an optical frequency comb using a short path length interferometer has been shown to be a promising method for generating ultra-low phase noise microwaves in an architecture that could be implemented on a photonic integrated chip [3]. This architecture requires the carrier-envelope offset frequency (f_{ceo}) to be stabilized or canceled. In previous demonstrations of this technique, the f_{ceo} of an octave-spanning frequency comb was measured with an f-$2f$ interferometer, stabilized with an electronic feedback loop, and further suppressed by feedback into an external acousto-optic modulator.

By contrast, the f_{ceo} of a difference-frequency-generated (DFG) optical frequency comb is canceled in an optical nonlinear medium, via the difference-frequency nonlinear process [4]. Hence, no external electronic feedback loops are required to stabilize the f_{ceo}. Moreover, because the cancellation occurs externally to the cavity in which the frequency comb is generated, there is inherently minimal crosstalk between the stabilization of f_{ceo} and the repetition rate. Additionally, because the cancellation of f_{ceo} is mediated by an ultra-fast optical nonlinearity, the cancellation is broadband and inherently stable [5]. One drawback to DFG combs is that the DFG process broadens the optical linewidth of individual comb frequency components in accordance with the f_{ceo} noise of the underlying oscillator [6]. Nevertheless, to the extent that this additional noise in the optical domain is correlated across the comb spectrum or to the extent that it can be compensated, the DFG comb can be used to generate ultra-low-phase-noise microwaves. Hence, the DFG comb is an attractive light source for low-phase-noise microwave generation techniques that rely on feedback signals to stabilize the repetition rate, such as the coherent division of ultra-stable lasers or in direct comb stabilization using an interferometer.

In this work, we used an f_{ceo}-free DFG comb that was stabilized with a 7.5-m path-length interferometer to generate a 10 GHz signal that had a phase noise of −123 dBc/Hz at 1-kHz offset. Hence, at this phase noise level, it is clear that any optical linewidth broadening did not impact the phase noise of the generated microwave.

II. Methods/Results

We stabilized the DFG comb using the setup shown in Fig. 1. The DFG comb was generated by a commercially available fiber-based system (Toptica DFC) with a repetition rate of 80 MHz and output wavelengths near 1550 nm. Light

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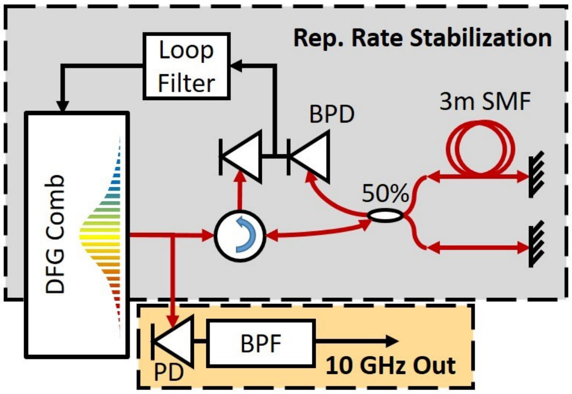

Fig. 1. Experimental setup to stabilize the repetition rate and generate the 10 GHz microwave.

from the DFG comb was split into two portions. One portion (yellow box) illuminated a PIN photodiode (PD) with 20 GHz bandwidth, generating an electrical pulse train with frequency components at the harmonics of the comb repetition rate. A bandpass filter (BPF) centered at 10 GHz selected the harmonic closest to our frequency of interest.

The other portion of light from the DFG comb entered a single-mode-fiber-based Michelson interferometer with a path difference of 37.5 ns. The return light from both arms of the interferometer illuminated a balanced photodiode pair (BPD). Each diode in the pair was a PIN diode with a bandwidth of 200 MHz. The photocurrent emerging from the BPD was proportional to the frequency noise of the DFG comb repetition rate. It passed through a proportional-integral loop filter and provided feedback on the DFG comb repetition rate to reduce its phase noise.

Figure 2 compares the phase noise of the 10 GHz microwave generated when the DFG comb was free-running (blue curve) versus when it was locked (green curve). The phase noise is decreased by a factor of approximately 20 dB at lower offset frequencies, reaching −123 dBc/Hz at 1-kHz offset frequency. The white phase noise level of −135 dBc/Hz is due to saturation in the 20-GHz PIN photodiode. The peaks in the 10s of kHz are from the delay-line phase noise measurement system. The phase noise at offset frequencies was limited by environmental fluctuations affecting the path length in the interferometer. These results indicate that the delay-line-stabilized DFG comb is a promising method towards compact and simple ultra-low-phase-noise microwave generation.

III. CONCLUSIONS

DFG combs use an external optical nonlinear interaction to provide an f_{ceo}-free comb with minimal cross-talk with the elements used to control the comb repetition rate. Consequently, DFG combs are an attractive light source for low-phase-noise microwave generation based on feedback control of the repetition rate of a frequency comb. However, the DFG process broadens the linewidth of individual comb teeth. Here, we generated a 10 GHz microwave with phase noise of −123 dBc/Hz at 1-kHz offset frequency using a difference-frequency-generated optical frequency comb that was self-stabilized with a 7.5-m Michelson interferometer. This level of performance indicates that ultra-low-phase noise microwaves can be generated despite any additional optical phase noise arising in the DFG process.

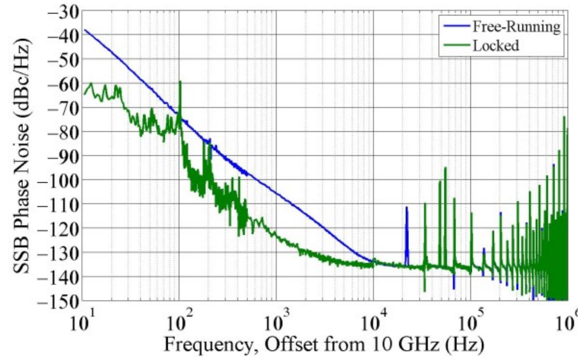

Fig. 2. Single sideband (SSB) phase noise of the 10 GHz microwave generated with the DFG comb.

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