Response Function of Homodyne Wavelength Difference Stabilization

James P. Cahill, Tanvir Mahmood, Patrick G. Sykes and Weimin Zhou
CCDC Army Research Laboratory
Adelphi, MD, USA
james.p.cahill15.civ@army.mil

Curtis R. Menyuk
CSEE Department
UMBC
Baltimore, MD, USA

***Summary*—We measured the response function at wavelengths of 1540 nm and 1560 nm of an 8-m homodyne interferometer to modulations of the repetition rate and carrier-envelope offset frequency (f_{ceo}) of an optical frequency comb (OFC). It is known that subtracting the response at one wavelength from the other generates an error signal free of f_{ceo} noise, forming a wavelength difference stabilization (WDS) interferometer that may stabilize non-octave-spanning OFCs. We calculate the WDS response function from our data, and find that while the sensitivity is expected to match a heterodyne system, changes in the response function of a homodyne WDS interferometer due to large-scale drifts of f_{ceo} pose a challenge to robustly stabilize an OFC.**

Keywords—Optical frequency combs, low-phase-noise microwave generation, optical frequency division

I. Introduction

Self-stabilization of optical frequency combs (OFCs) may allow for fully on-chip ultra-low phase noise microwave sources. While fiber-optic demonstrations have previously yielded promising results, on-chip implementation imposes significant restrictions on the architecture [1]. For example, obtaining on-chip OFCs (e.g. Kerr combs) that are octave-spanning and have an FSR in the microwave regime remains challenging. A second challenge is that frequency-shifting components, such as acousto-optic modulators, are not commonly available in commercial fabrication services for photonic integrated circuits (PICs), and interferometric modulators, such as single-sideband modulators which may provide a similar function, present additional difficulties when acting on pulsed light, such as the output of an OFC. Even simple modulators, such as a phase modulator, may add significant costs to an otherwise completely passive PIC, particularly in material platforms such as silicon nitride, where the fabrication of fast modulators requires additional materials and processing steps. As a result, it is challenging to implement heterodyne-detection-based OFC stabilization on a PIC.

Previously, we have demonstrated a homodyne self-stabilization scheme to address the lack of frequency-shifting components [1,2]. Meanwhile, a method has also been demonstrated to cancel the f_{ceo}-noise by filtering the interferometer output to generate signals corresponding to two distinct wavelengths and subtracting their phases in the electrical domain [3]; we will refer to this method as

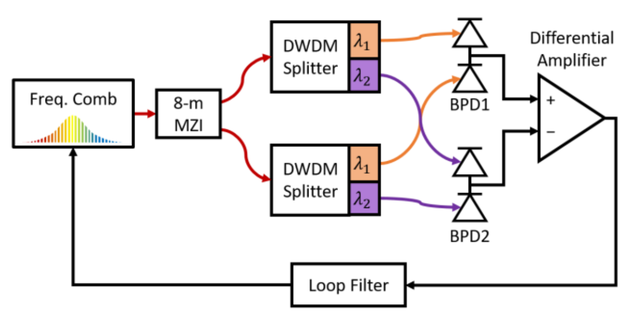

Fig. 1. Circuit diagram for homodyne wavelength-difference stabilization (WDS). MZI: Mach-Zehnder interferometer, DWDM: dense wavelength division multiplexing, BPD: balanced photodiode.

wavelength difference stabilization (WDS). To simultaneously address the aforementioned challenges of OFC stabilization on a PIC, we may combine these schemes to form a homodyne wavelength difference stabilization scheme, shown in Fig. 1.

In this work, we analyze the response function of a homodyne-WDS interferometer (hom-WDSI). We present a simple model to describe the response function, and we verify that it agrees with experimental results. While the sensitivity of the hom-WDSI is expected to be the same as a comparable heterodyne WDS interferometer (het-WDSI), the hom-WDSI response function changes in the case of large-scale drifts of the f_{ceo}, which poses a challenge for closing a robust feedback lock.

II. Methods/Results

The repetition rate stabilization circuit outlined in Fig. 1 is a phase-locked loop, in which the proposed hom-WDSI serves as a frequency discriminator. The response functions, $H_{\lambda 1}$ and $H_{\lambda 2}$, of the interferometer at wavelengths λ_1 and λ_2 are

$$H_{\lambda 1}(t) = \sin[2\pi\tau(N_1 f_{rep} + f_{ceo})], \text{ and} \quad (1)$$
$$H_{\lambda 2}(t) = \sin[2\pi\tau(N_2 f_{rep} + f_{ceo})], \quad (2)$$

The response function of the hom-WDSI, H_{WDS}, will simply be the difference of the response functions $H_{\lambda 1}$ and $H_{\lambda 2}$.

$$H_{WDS} = \sin[2\pi\tau(N_1 f_{rep} + f_{ceo})] - \sin[2\pi\tau(N_2 f_{rep} + f_{ceo})] \quad (3)$$

where τ is the group delay in the interferometer, and $N_{1,2} = (c/\lambda_{1,2} - f_{ceo})/f_{rep}$.

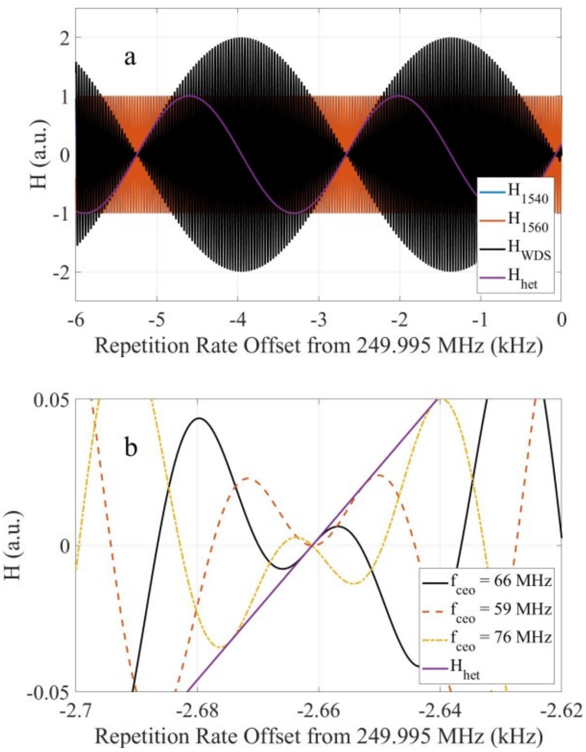

Fig. 2. (a) Interferometer response functions, (b) close-up of homodyne WDS response function for different values of carrier-envelope offset frequency (f_{ceo}), with heterodyne response function (H_{het}) overlaid.

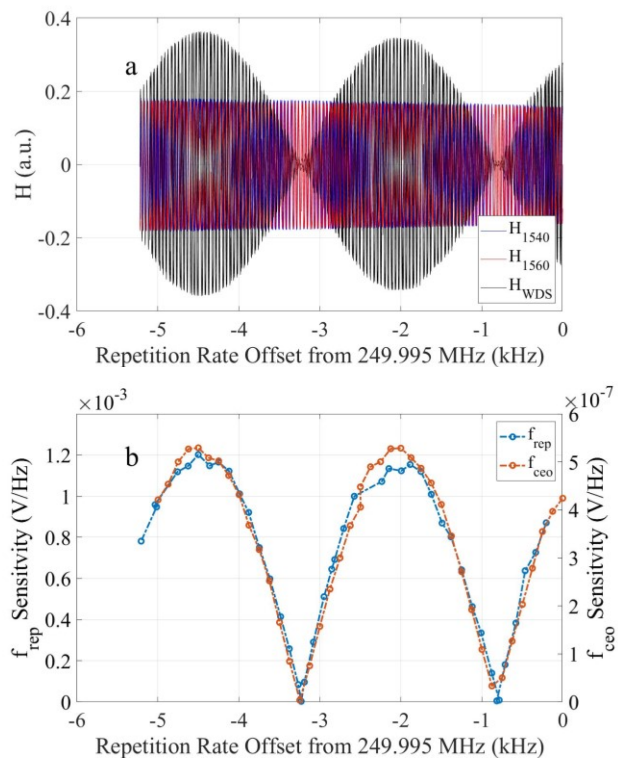

Fig. 3. Experimentally-measured (a) response functions, and (b) sensitivity of homodyne WDS interferometer to changes in the repetition rate (f_{rep}) and carrier-envelope offset frequency (f_{ceo}).

Fig. 2a shows the expected response functions of the interferometer at wavelengths of 1540 and 1560 nm (blue and red) and the hom-WDSI (black). Plotted alongside is the response function of the het-WDSI, H_{het} (purple). Fig. 2b shows a close-up of the zero-crossing regime of the WDS response function for several values of f_{ceo}. For some values of f_{ceo}, such as 66 MHz, the sensitivity of the hom-WDSI (i.e., the slope at the zero-crossing) is comparable to that of the het-WDSI. However, Fig. 2b also shows that changes in f_{ceo} dramatically affect the zero crossing, indicating that stabilization with the hom-WDSI may not be robust if f_{ceo} is left free-running.

To validate this picture, we experimentally measured the response function of the hom-WDSI. We modulated f_{rep} with a sine wave with a frequency of 20 Hz and simultaneously recorded the outputs of BPD1 and BPD2. Due to the limited orthogonality of f_{rep} and f_{ceo} actuators [4], modulation of f_{rep} results in a noticeable modulation of f_{ceo}. To mitigate the influence of this effect on our characterization of the response function, we stabilized f_{ceo} with an f-2f interferometer. In a properly-biased hom-WDSI, measurement and stabilization of f_{ceo} will not be necessary, since the error signal will not be sensitive to the f_{ceo}.

Fig. 3a shows the experimentally-measured response functions. The results agree well with the expected response functions shown in Fig. 2. Fig. 3b shows the experimentally-measured sensitivity of the hom-WDSI to modulations in f_{rep} and f_{ceo}, black and red, respectively. Notably, the sensitivity of the hom-WDSI to f_{ceo} is minimized only for certain values of f_{rep}, such as pictured in the center of Fig. 2b. This result indicates a second challenge with the hom-WDSI: only zero-crossings with a small locking range can be used when mitigating f_{ceo} noise.

III. Conclusions

We have proposed and analyzed a homodyne WDS interferometer to stabilize a non-octave-spanning OFC. We found that the sensitivity to the repetition rate is comparable to a heterodyne WDS interferometer. However, we also found that for the hom-WDSI, the shape of the response function and its residual coarse sensitivity to f_{ceo} will pose challenges to ensuring a robust stabilization. These challenges may be addressed in future work by strategies such as implementing IQ detection or performing a two-point lock on the OFC with the two wavelength outputs. Hence, further investigation and innovation of the WDS interferometer may enable robust on-chip stabilization of non-octave-spanning OFCs.

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