A Flexible All-Digital Transfer Beat Implementation for Precision Frequency Metrology

Andreas Noack, Mattias Misera, Julia-Aileen Coenders, Uwe Sterr, Erik Benkler
Physikalisch-Technische Bundesanstalt
38116 Braunschweig, Germany

***Summary* — Using a frequency comb as a transfer oscillator, 'virtual' or 'transfer' beats between widely separated optical frequencies can be created. These real-time beats between a frequency and a rational fraction of a second optical frequency can be employed for comparing or phase-locking lasers, independent of fluctuations of the frequency comb. We demonstrate an all-digital FPGA-based implementation for the creation of a transfer beat which is simple to scale and can be reconfigured with high flexibility. The noise performance of this all-digital transfer beat implementation is at least on par with its analogue counterpart.**

Keywords—optical frequency comb, clock comparison, transfer beat, field-programmable-gate-array, FPGA

I. Introduction

Comparing or transferring the stability of two optical frequencies, hundreds of terahertz apart is a common task in frequency metrology, such as in the stability transfer from an ultra-stable laser in the telecommunication band to interrogation lasers for optical clocks in the visible range [1]. Here, optical frequency combs are employed to phase-coherently bridge the gap between the two frequencies. However, as the comb's repetition rate and carrier-envelope offset (CEO) fluctuate, techniques to eliminate such fluctuations up to Fourier frequencies of at least a few 100 kHz are required. With the transfer oscillator method [2] contributions of repetition rate and CEO frequency are eliminated by detecting and processing beat notes and the CEO frequency in the radiofrequency (RF) regime (Fig. 1a). The processing can be implemented using RF electronics to provide a real-time beat.

While the concept has been proven many times, there are several experimental challenges involved in setting up such a transfer beat. First, a lot of RF electronic components are required resulting in a large volume and complex setup, which is not efficiently scalable. In particular, the spread over large volume results in delay mismatches, which can limit the noise suppression of the method. Second, the RF implementation requires several bandpass filters, which often are not available from the shelf and such render prototyping a tedious task. Third, amplifiers are required due to mixing losses that add noise to the analog signals.

To solve these issues, we propose a flexible all-digital system to implement a transfer beat algorithm. This system consists of three all-digital-phase-locked loops (ADPLL) and a simple algorithm to calculate the transfer beat phase from the retrieved phase values. This digital algorithm is advantageous over existing analogue implementations as, first, it does not require any additional hardware which reduces complexity and volume of the setup and delay matching is improved. Second, it is perfectly linear after the signals have been digitalized and, third, it is very flexible and scales well, which supports rapid prototyping and optimization.

A. Transfer oscillator concept and transfer beats

The spectrum of a frequency comb is comprised of equally spaced modes at optical frequencies:

$$\nu_{\mathrm{m}} = \nu_{\mathrm{CEO}} + m\, f_{\mathrm{rep}},$$

where ν_{CEO} is the carrier envelope frequency, m the mode number and f_{rep} the comb's repetition rate. Both, ν_{CEO} and f_{rep}, can fluctuate. To compare the two optical frequencies ν_{cw1} and ν_{cw2}, photodiodes detect the optical RF beat signals with the respective comb's modes m_1 and m_2 at f_{x1} and f_{x2} (Fig. 1 top).

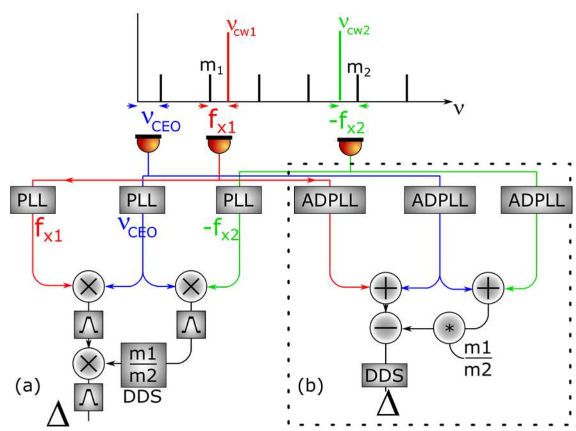

Figure 1: Detected beats at frequency comb (top). Schematic of traditional transfer beat implementation (a) and newly developed fully-digital transfer beat implementation (b).

Phase locked loops (PLLs) filter the raw signals for further processing. The bottom left part of Fig. 1 shows the traditional partially analogue RF processing scheme for real-time transfer beat generation. It comprises of three steps: ν_{CEO} is eliminated from the RF beat signals at f_{x1} and f_{x2} by mixing and afterwards filtering unwanted mixing products. A rational frequency divider, comprising of a direct digital synthesizer (DDS), scales one of the frequencies by the ratio of the comb's mode numbers. Last, the two signals are mixed to eliminate the repetition rate. The transfer beat frequency Δ now only depends on the mode numbers and on the two optical frequencies:

$$\Delta = \nu_{cw1} - \frac{m1}{m2}\nu_{cw2}.$$

We propose an all-digital implementation of a transfer beat where the detected beat signals are converted to digital signals using ADCs. The phases of the digital signals are retrieved using all-digital-phase-locked-loops (ADPLL) [5] (Fig. 1b). In general, an ADPLL compares the input signal phase to the phase of a direct digital synthesizer (DDS) signal. The phase difference is fed back to the phase increment (frequency tuning word) of the DDS through a loop-filter. The DDS phase follows the input signal phase and the DDS tuning word represents the input signal frequency within a bandwidth determined by the loop-filter. We use this tuning word for further processing. Instead of RF signal processing techniques we can now use mathematical operations for the transfer beat calculation as shown in Fig. 1b, which turns out to be much easier. Applying the calculated output tuning word to an additional DDS a transfer beat signal can be generated. If a reference frequency is subtracted, the unwrapped phase can be generated to provide an error signal for phase-locking without phase ambiguity. Furthermore, as the tuning words represent the frequencies of the involved RF signals, we can implement frequency counting of these frequencies directly on the same FPGA chip.

II. Experimental Setup

To experimentally demonstrate its working principle, we tested the all-digital implementation in parallel to a traditional transfer beat setup used to transfer the stability of an ultra-stable laser at 1542 nm [4] to the strontium clock interrogation laser at 698 nm. In this setup, the beat frequency between the ultra-stable laser and the comb mode number m_1 = 767240 was $f_{x1} \approx$ - 31 MHz and for the strontium clock laser m_2 = 1694030, $f_{x2} \approx$ 66 MHz. The repetition rate was phase locked to the optical reference and the CEO frequency was phase-locked to 20 MHz.

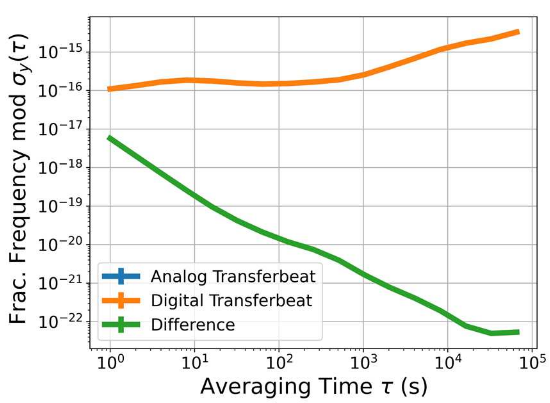

Figure 2: Plot of the modified Allan deviation of the analogue and digital transfer beat (blue and orange) and the difference of the two measurements (green).

Our digital platform consists of a *Trenz* FPGA Board (TE0712) hosting an Artix-7 FPGA (XC7A200T FBG484-2). We employ an FPGA for its parallel processing capability. This board sits on top of a custom-made electronics board hosting an eight-channel 14bit analog-to-digital converter (ADC) LTM9011-14 sampling at 100 MHz and a digital-to-analog converter (DAC) AD9783 [6]. The ADC converts the three beat signals detected by the photo diodes and the ADPLLs lock to these input signals with a bandwidth of around 1.5 MHz. We used Xilinx DDS Compiler IP v6.0 to convert the calculated transfer beat tuning word to a transfer beat. The DAC converts the digital transfer beat signal to an analogue output signal at 59 MHz and, after filtering and amplification, the signal was fed to a K&K FXE counter configured for lambda averaging at 1 s report time.

III. Results

Fig. 2 shows the modified Allan deviation of the analogue (blue) and digital (orange) transfer beat, normalized to an optical frequency of 194.4 THz. Both graphs exactly overlap. In addition, the modified Allan deviation of the difference between the two frequencies is shown. The difference measurement is not limited by the K&K counter resolution, which is about a factor 5 lower. This noise might be caused by the processing delay in the FPGA algorithm relative to the analogue implementation. The digitally determined transfer beat matches the analogue one to modified Allan deviation of 5×10^{-18} @1s and 10^{-22} @10000 s. Currently, this is well below any reported optical clock instability.

IV. Conclusions

We have demonstrated a novel all-digital transfer beat implementation proving to be much simpler and more flexible in comparison to a traditional setup using analogue electronics. The added noise was on par with the analogue implementation.

Drawbacks of this approach are the limited input range of frequencies below 50 MHz. However, the undersampling capability of the ADC can be employed to sample signals above 50 MHz. Furthermore, some laser locking applications demand large bandwidth above 1.5 MHz where the processing delay might limit the achievable bandwidth.

Acknowledgment

We thank the time and frequency department 4.4. at PTB, especially Michael Kazda and Christof Hellmann for the development and testing of the described electronics board. We acknowledge support by the Project 18SIB05 ROCIT, which has received funding from the EMPIR program co-financed by the Participating States and from the European Union's Horizon 2020 Research and Innovation Program.

References

[1] E. Benkler et al., "End-to-end topology for fiber comb based optical frequency transfer at the 10^{-21} level," Opt. Expr. 27, 36886–36902, 2019.

[2] H.R. Telle et al., "Kerr-lens, mode-locked lasers as transfer oscillators for optical frequency measurements," Appl. Phys. B 74, 1–6, 2002.

[3] N. Scharnhorst et al., "High-bandwidth transfer of phase stability through a fiber frequency comb," Opt. Expr. 23, 19771–19776, 2015.

[4] D.G. Matei et al, "1.5 um lasers with sub 10 mHz linewidth," Phys. Rev. Lett., 118, 263202, 2017.

[5] F. Brandonisio and M. P. Kennedy, "Noise-Shaping All-Digital Phase-Locked Loops," Analog Circuits and Signal Processing, 2014.

[6] Christof Hellmann, "Erzeugung ultra-stabiler Signalquellen von Mikrohertz bis Petahertz mit Hilfe von SDR-Techniken," Master's Thesis, TU Braunschweig, 2018.