Frequency interleaving dual comb photonic ADC with 7 bits ENOB up to 40 GHz

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Abstract: We demonstrate a record high performance of frequency-interleaved analog-to-digital conversion using a phase-noise-engineered dual frequency comb photonic technique, enabling 7 effective number of bits (ENOB) for signals up to 40 GHz. © 2022 The Author(s)

1. Introduction

Analog to digital converters (ADC) that enable digital processing of optical signals has transformed lightwave communication systems in the last decade. Modern communications systems demand high resolution ADCs in order to detect higher order modulation formats and achieve a more effective compensation of nonlinear distortions [1]. The resolution of high speed (i.e. > 1 GHz) electronic ADCs is typically limited by clock jitter and, at especially high frequencies, the speed of the component transistors that results in comparator ambiguity [2]. This presents a trade-off between the frequency of the detected signal and accuracy, defined by the signal-to-noise-and-distortion-ratio (SINAD) or effective number of bits (ENOB). In a jitter limited ADC, the SINAD decreases quadratically with increasing frequency, giving a 6 dB SINAD penalty for every doubling of the input frequency.

Many have investigated photonic techniques for improving the performance of high speed ADCs [3]. An extensively-studied approach is to optically sample the incoming signal with an ultra low jitter mode-locked laser (MLL), where the sampling pulses are de-interleaved and the signal reconstructed digitally in a time interleaving architecture. While this approach has achieved a superior performance of 44 dB SINAD at a single frequency of 40 GHz [4], the impressive results are difficult to scale to detect broadband signals and translate to an integrated platform due to low power and jitter performance of high repetition integrated MLLs, which is fundamentally limited by the semiconductor material gain and the cavity length.

As an alternative to the time-interleaving approach, frequency-interleaved ADCs were proposed to divide a broadband signal into a number of sub-band signals that can be detected in parallel by a bank of low speed, high resolution ADCs. The frequency interleaving approach can relax jitter requirements and reduce channel mismatch errors compared to time interleaving, but has not seen widespread adoption in electronic ADCs due to the difficulty of designing the required analog electronic filter banks and synthesizing many low noise local oscillators [5]. In [6], we proposed a photonic frequency-interleaving ADC architecture based on dual optical frequency combs, potentially overcoming the aforementioned design challenges in the electronic frequency interleaving architecture. Nevertheless, the demonstrated performance so far was limited to 33 dB SINAD due to the un-optimized relative phase noise in the dual-comb system.

In this paper, we significantly improve the relative phase noise, optical power and receiver front end of our dual comb system and present a record high frequency-interleaved ADC performance that can detect signals up to 40 GHz at 7 bits ENOB with 12.5 GHz bandwidth.

2. Experimental setup and results

The dual frequency comb ADC concept has been described previously [6] and the implementation for this experiment is shown in Fig 1. Two frequency combs of spacing $f_{sig} = 26$ GHz ('signal comb') and $f_{LO} = 25$ GHz ('LO comb') are generated from a low linewidth (< 1 kHz) laser at 1555 nm through electo-optic modulation. The RF signals for the combs are generated from a common reference through ultra low phase noise frequency synthesizers. Furthermore, both electrical and optical paths on each comb are matched to ensure maximum coherence

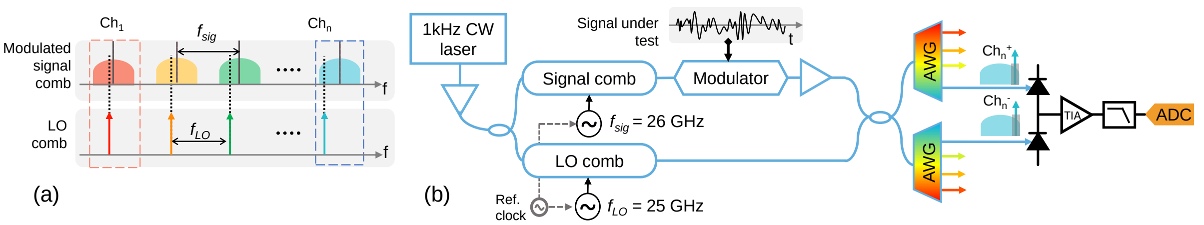

Fig. 1: (a) Dual comb channelization concept. (b) Experimental setup. AWG, arrayed waveguide grating; TIA, transimpedance amplifier; CW, continuous wave; ADC, analog to digital converter.

of both the laser and RF phase noise, which ensures the lowest relative phase noise for high SINAD digitization using the dual comb technique [7].

The signal comb is modulated with the input signal of interest by a 40 GHz bandwidth Mach-Zehnder modulator (MZM) biased at transmission null and is amplified by an erbium-doped fiber amplifier (EDFA). The modulated signal comb is then combined with the LO comb through a 50/50 coupler and split by two $f_{LO} = 25$ GHz spacing array waveguide gratings (AWGs) for parallel balanced detection. In this way, each channel contains a optical signal consisting of a single modulated comb line and a local oscillator comb line offset by $n\Delta f$, where $\Delta f = f_{sig} - f_{LO} = 1$ GHz. After detection by a balanced detector, the beating between the LO and signal comb in each channel simultaneously down-converts 1 GHz spectral slices of the original signal to baseband where they can be detected by 4-GSa/s high resolution ADCs with 10 bits ENOB. The full bandwidth signal can then be reconstructed digitally, resulting in signal digitization at much higher resolution than would be achievable by a single, high speed ADC.

In this experiment, we performed sequential detection of each channel in a 12.5 GHz bandwidth receiver in order to test the performance. The signal under test was a sine wave as per the the IEEE ADC testing standard [8], which we tested with various frequencies up to 40 GHz (4th Nyquist zone). The SINAD for the receiver across a range of frequencies is shown in Fig. 2(a). The SINAD is relatively flat with respective to frequency, indicating that the system is not fundamentally limited by clock jitter: in this case the system is limited by the amplified spontaneous emission noise of the EDFA following the modulator, which may be improved by using lower noise figure amplifiers or further increasing the power per comb line. For comparison, other high performing photonic ADCs are also plotted, along with the state-of-the-art electrical ADCs [9]. Our results outperform the reported high-speed electronic ADCs and show the SINAD performance across a range of frequencies up to the 4th Nyquist zone, which has not been shown in prior photonic ADC demonstrations [4, 10, 11].

An example fast Fourier transform of the detected 39.87 GHz signal is shown in Fig. 2(b). A low pass digital filter and Kaiser window is applied to signal after detection to prevent spectral leakage. This achieves 44 dB SINAD (equivalent to 7.0 bits ENOB) and a spurious free dynamic range of 63 dB. This result is equivalent to a timing jitter of 25 fs: i.e. an ADC with 25 fs jitter as its only source of noise would be able to detect the signal with the same fidelity. This equivalent jitter performance is highlighted as a dashed line in Fig. 2(a).

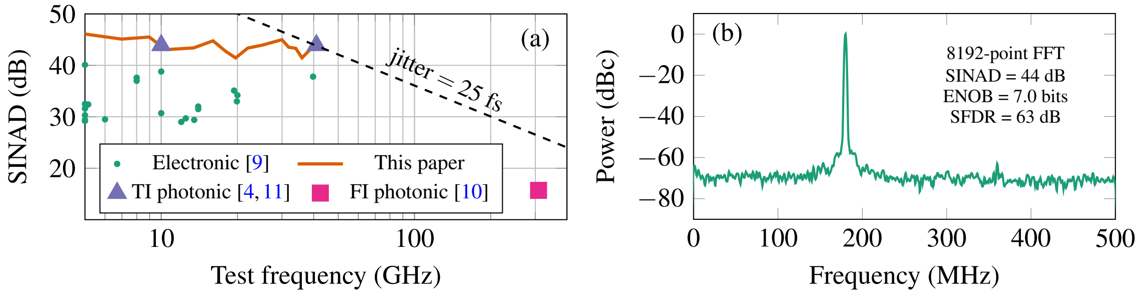

Fig. 2: (a) Measured SINAD up to 40 GHz, with the prior art of the best time interleaving (TI) photonic ADCs (purple triangles), frequency interleaving (FI) photonic ADCs (pink squares) and electronic ADCs (green dots). (b) An example fast fourier transform showing a 39.87 GHz signal detected in a single channel.

3. Conclusion

We demonstrate, to the best of our knowledge, the lowest effective jitter for a frequency interleaving photonic ADC, achieving 7 bits ENOB at 40 GHz. This outperforms all electronic ADC results and is equivalent to the best reported results of time interleaving photonic ADCs, with the potential for further improvements due to the relaxed jitter requirements of the frequency interleaving design.

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