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Undersampling a photonic analog-to-digital converter containing an optical hybrid combiner

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ABSTRACT

A self-coherent optically-sampled analog-to-digital converter using a 90° optical hybrid coupler is experimentally demonstrated. It leverages practical, commercially available components and is used for high-resolution undersampling at 50 Msps of up to 20 GHz carrier frequencies. The measured ADC resolution is 9 effective bits for a 10 GHz carrier frequency and shows little carrier frequency dependence from 6 to 20 GHz.

1. Introduction

Photonic analog-to-digital converters (ADCs) can in principle substantially out-perform their purely electrical counter-parts [1]. The performance improvement can come from a variety of mechanisms depending on the system design, for instance due to the use of ultra-low-jitter short-time-duration optical pulses [2,3] or dispersion in optical fibers to time-stretch the signal of interest [4]. Although photonic ADCs have been of great research interest, they have had some limitations that have prevented substantial practical applications. Depending on the method employed these limitations can include high degree of complexity, short capture times, large size-weight-and-power (SWAP), and the use of expensive components. Additionally, the experimentally realized resolution of many photonic ADCs do not achieve their potential due to a variety of practical difficulties such as optical noise and multiplexing errors.

The time-stretch ADCs can have exceptional performance for digitizing wide-band signals, but typically achieve such performance only over time durations that are impractically short for most applications (on the scale of nanoseconds). In principle, time-stretched ADCs can be scaled to continuous time, but the process of scaling increases the already substantial complexity and also tends to reduce performance [5]. For some complex instrumentation applications, such as extending the bandwidth of high performance oscilloscopes, the time-stretched ADC may be valuable. Other methods of photonic ADCs that scale gracefully to continuous time operation have, to our knowledge, never demonstrated performance that warrants the added cost and complexity of a photonic system. In fact, most implemented continuous-time compatible photonic ADCs perform worse or unsubstantially better than state-of-the-art electronic systems [1],[6,7].

Improved performance over electronic systems has been demonstrated in the undersampling (or subsampling) regime, where a high microwave frequency carrier is digitized over a relatively small fractional bandwidth. This kind of system is important in a wide variety of applications including radar and RF communications. An important innovation in this field was the use of phase encoded optical sampling [8], where both outputs of a Mach–Zehnder interferometer (MZI) (instead of just one) are digitized and the applied phase shift is found via signal processing. This design can greatly alleviate the natural distortion arising from the nonlinearity of the MZI modulator and reduces sensitivity to pulse amplitude fluctuations. A single-output MZI will cause distortions due to the modulator nonlinearity which limits the size of the maximum modulation signal. An improvement in tolerable modulation signal is important in high resolution applications since the signal-to-noise ratio varies as the square of the modulation index [1]. An effective number-of-bits (ENOB) of 7 was recorded for a 40 GHz carrier frequency over a 2 MHz bandwidth using an undersampled dual-port MZI [2]. The measured ENOB was limited to 7 due to jitter in the microwave signal itself, and an ENOB limit of 9 was predicted for an ideal signal source. That work has recently been extended to include two optical channels of different wavelength sampling at 1 Gsps that are interleaved in time to reach a cumulative 1 GHz bandwidth while maintaining 7 ENOB at 40 GHz carriers [3]. Further increases in the number of wavelength channels or their repetition rate could feasibly lead to Nyquist sample rates. The system of [3] makes use

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of high quality balanced detectors which help to increase SNR and reject common-mode noise. It also exploited a low-jitter custom-made mode-locked laser.

There are two incumbent methods of obtaining high ENOBs at high carrier frequencies. One is to use a sampler with a high enough analog input bandwidth to accept the input carrier frequency. Typically electronic samplers capable of digitizing 10’s of GHz carriers generally have relatively low ENOBs (limited for instance due to jitter) but when sampling at frequencies higher than twice the required signal bandwidth then signal-to-noise ratio (SNR) can be improved by post-processing (processing gain) thereby effectively trading off measurement bandwidth for SNR. Processing gain can lead to one bit of ENOB for every factor of four reduction in signal bandwidth (for an SNR limited system). As an example, a high performance oscilloscope with 5.5 bits of ENOB, 40 GHz bandwidth, and an 80 Gsps sampling rate can in principle achieve ~9 bits with a 312 MHz signal bandwidth (assuming noise and not distortions are limiting performance). However, such systems require substantial processing power (processing 8 bits at 80 Gsps leads to 640 Gb/s of data which would be very difficult to handle in real time) which increases the SWAP. Thus samplers of this type may not be well suited for many applications such as satellite communications. Additionally, we note that oversampling does not improve linearity which can be excellent in optically sampled systems [8].

Moreover, the optical sampling methods are capable of scaling to yet higher frequencies using current technology. The maximum operating frequency of pulsed optical under-sampling systems can be limited by the optical pulse-width, the optical pulse jitter, or the electro-optical modulator bandwidth. An optical pulse-width of <1 ps is commonly generated by many kinds of mode-locked lasers and has a 3-dB bandwidth limitation of >300 GHz [9]. Thus the optical pulse width is not in practice a limiting factor. Mode locked lasers have recently been demonstrated with 0.1 fs jitter with >77 MHz repetition rates [10]. Such low jitter values will in principle allow for sampling into the THz carrier frequencies with high resolution. Thus the current technological limit to operating frequency is the optical phase modulator. Phase modulators have been demonstrated to >100 GHz bandwidths [11], thus we expect that optical under-sampling methods can be scaled to 100 GHz carrier frequencies by choosing an appropriate phase modulator. Scaling electronic samplers is more difficult, and since their performance at such frequencies will be jitter limited the attainable ENOBs will continue to degrade as the operating frequency is increased.

Another method of digitizing signals of high carrier frequency and low fractional bandwidth is to use a down-conversion process. Here the input signal is mixed with a local oscillator (LO) in order to translate it to a lower frequency where high resolution ADCs are readily available. In such a case the ENOB resolution limit of the system is contrained by the jitter of the LO, but the overall performance is also impacted by the inherent nonlinearity of the mixer. Third-order nonlinearity can be observed by measuring the intermodulation power generated by mixing two input frequencies. The intermodulation power in a mixer tends to rise as the cube of the input signal power, thereby having a very significant impact for high input signal powers where SNR is inherently high. Other issues with mixers include conversion loss and LO isolation [12].

Optical methods can be used to realize high performance mixer-based down-conversion. For instance reference [13] used an optical interferometer with two phase modulators, one being used for signal modulation and the other for down-conversion. The process results in the desired signal band around the high-frequency carrier to be aliased down to a low frequency, thereby allowing for direct sampling with high-resolution electronic ADCs. The high quality mixing process in the highly linear lithium niobate phase modulators add very low distortions. We note that the interferometer made use of a 90° in-phase/quadrature-phase (I/Q) optical hybrid in place of the 180° combiner in MZI’s [2]. This allows for coherent detection over a full 2π modulation range which means that the system is linear for larger input signals and therefore can have a larger ENOB in principle. However, the mixing-based method of [13] still requires a very-low-jitter electrical signal source as well as an additional phase modulator. The method also requires some fore-knowledge of the input carrier frequency. In addition to these practical problems associated with using a mixer, the continuous wave optical signal was set to a high optical power (~19 dBm) in order to maintain a high optical SNR. To satisfy this need multiple optical amplifiers and exotic high-power-handling and highly-linear detectors were employed.

This paper describes a practical pulsed-I/Q-interferometer based photonic ADC. The system has an intrinsically high ENOB per sample, uses all commercially available off-the-shelf components, and has excellent linearity. A preliminary description of this device was presented in [14] and a modified version was used in [15] to nonuniformly undersample and determine the frequency of a wide range of microwave frequency inputs. A benefit of the design is its simple construction, as the mode-locked laser (MLL) is a compact commercially available unit, the optical detectors are standard single ended PIN detectors, and no optical amplifiers are employed. The only high frequency ($>$ GHz) component required in the entire system is an optical phase modulator. A 50 MHz rate passively-mode-locked laser is used to sample the input signal, leading to a 25 MHz digitization bandwidth (digitization bandwidth is ½ the sampling frequency). After optical-to-electrical detection two ADCs sample the interferometer outputs at 50 Msps. Simple post-processing reproduces the sampled output signal. The commercially available laser consumes <2 W of electrical power and has a footprint of just 240 cm^3 (not including the power supply). Carrier frequencies in the range 5.8–20 GHz are digitized, with excellent performance including 9 ENOBs at 10 GHz carrier frequencies. All carrier frequencies in the above range exhibit similar ENOB versus modulation-signal-size performance. The third-order mixing products are kept low even for large modulations of π radians (spur-free dynamic range of >60 dBc). The I/Q interferometer does not need phase bias feedback control since it functions over a full 2π range. The method is also compatible in principle with antenna remoting, where many of the active system components (such as the laser, detectors, ADCs, and signal processing circuit) are remotely located from the input signal and the system is interconnected via long fiber optical cable. Such a configuration gives more flexibility in where to locate these components which can be a practical advantage when digitizing the signal from an antenna that may be in an inconvenient location. We note that for remoting applications, the fiber cable linking the MLL to the interferometer should have an acceptably low dispersion level since a short pulse is required at the phase modulator in order to maintain a high sampling bandwidth. The fiber cable connecting the interferometer outputs to the detectors are more robust to dispersion. The compact size, off-the-shelf components, and high performance make this photonic-assisted ADC highly practical for field applications.

2. Operating principle

The I/Q interferometer based ADC operates similarly as the push–pull Mach–Zehnder interferometer of [3] with the interferometer output coupler changed from a 180° combiner to an I/Q optical hybrid. A pulsed optical source of repetition frequency F_L (in Hz) is split into two arms, where one arm serves as a reference signal and the other arm is phase modulated by the input RF