Experimental Demonstration of a Photonic Analog-to-Digital Converter Architecture With Pseudorandom Sampling

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Abstract—A photonic analog-to-digital converter architecture is demonstrated that uses nonuniform, sub-Nyquist sampling combined with digital signal processing algorithms to unambiguously identify microwave signals of interest. X-band (8–12 GHz) operation is demonstrated with two-tone signals of separation extending to >2 GHz that were directly sampled and digitized at a mean rate of 995.3 MHz resulting in alias-free power spectra.

Index Terms—Analog-to-digital conversion, digital signal processing, microwave photonics, nonuniform sampling, photonic sampling.

I. INTRODUCTION

Advances in electronic analog-to-digital converters (ADCs) have impacted many technological areas. Since the survey of electronic ADC technology by Walden [1], advances in resolution and sample rate have resulted in impressive multigigasample ADCs for limited resolution applications, such as the <8-bit oscilloscope market [2]. Handling higher frequency microwave applications, such as those of communications and radio-frequency (RF) sensor systems, presently requires multiple stages of mixing and filtering to downconvert the signal(s) of interest to within the bandwidth of higher resolution digitizers. Unfortunately, downconversion generally introduces signal distortion, noise, and can violate size, weight, and power constraints of many application platforms. Direct digitization, requiring a uniform sampling rate twice the highest frequency of interest to unambiguously digitize a signal, can eliminate the need for downconversion. Achieving the required many gigasamples-per-second for direct, uniform sampling of microwave signals is typically accomplished through interleaving of lower sample rate electronic digitizers. This leads to deleterious interleaving spurs as well as extreme data management requirements. Additionally, precision timing and sample and hold requirements [1], [2] for high resolution, direct digitization of microwave signals presents a significant challenge for all-electronic architectures.

High-speed precision timing and large bandwidth capabilities have provided photonic ADC architectures [3], [4] with the ability to target dramatically increased bandwidth and resolution performance compared to electronic implementations. With high-speed photonic sampling, real-time digitization of continuous or quasi-continuous time-varying signals requires an equally high-speed quantizer or a demultiplexing system that enables parallel electronic digitization at slower individual digitizer speeds. Drawbacks of this approach include accurate setting of the gain and timing of many interleaved digitizers, and practical concerns regarding size, weight, power, and cost. Alternatively, for broadband input containing multiple narrow instantaneous bandwidth signals, a downsampling photonic ADC architecture [4] has been proposed which avoids interleaving issues, but results in the ambiguous aliasing of all signals to frequencies < 1/2 sample rate (the Nyquist frequency). Here hardware filtering at the RF input is required to uniquely identify the signals, limiting the versatility of this concept.

Aliasing of sub-Nyquist sampled signals can be removed with pseudorandom sampling—nonuniform sampling where the sampling instances are known—provided the analysis algorithm includes this information. Digital alias-free signal processing (DASP) algorithms have been shown to eliminate aliasing effects [5]. For example, wide-bandwidth, alias-free, high purity spectrograms have been measured using a conventional electronic digitizer [6], achieving electronic sampling hardware limited performance of 670-MHz alias-free analog bandwidth, and >55-dB signal-to-spur ratio. We recently proposed a photonic ADC architecture concept utilizing pseudorandom photonic downsampling, synchronous sub-Nyquist digitization, and DASP for alias-free wideband digitization of microwave signals [7]. In this letter, we describe the experimental realization of a pseudorandom, sub-Nyquist photonic ADC architecture capable of unambiguous digitization of multiple X-band signals covering multiple Nyquist zones without the need for band filtering hardware.

II. PSEUDORANDOM SAMPLING PHOTONIC ADC ARCHITECTURE

Our implementation of a pseudorandom sampled photonic ADC is presented in Fig. 1. For clarity, it is separated into three stages: the pseudorandom sampling pulse generation hardware, signal encoder, and optical-to-electronic digital electronics hardware.

The first stage consists of a mode-locked fiber ring laser with near 10-GHz pulse repetition rate, 4-ps pulsewidth, and 1550-nm center wavelength. To generate the sampling time sequence, pulses are selected from the output stream using a...
LiNbO$_3$ traveling wave Mach–Zehnder amplitude modulator (electrooptic modulator (EOM): 3-dB bandwidth $>$8 GHz, ON–OFF extinction ratio at dc $>$20 dB). The modulator is driven by a pulse pattern generator, programmed with a bit sequence to achieve the desired pseudorandom temporal sampling as follows: For every ten output pulses from the ultrafast optical clock, exactly one pulse, randomly selected from the middle four pulse time slots, are passed by the EOM, while all others are blocked. The bit sequence was derived by randomly choosing, with a uniform probability distribution, amongst four available time slots with a sufficient number of zeros inserted in between to give the desired mean repetition rate. This optical sampling pulse stream has a mean repetition rate of 995.3 MHz, with sample intervals resulting in pulse interval times ranging from 0.64 to 1.36 ns (or 735-MHz to 1.563-GHz instantaneous sample rates). An erbium-doped fiber amplifier, which operates from 0.64 to 1.36 ns (or 735-MHz to 1.563-GHz instantaneous sample rates), is used to amplify the signal. The sampling pulse stream is then applied to an electronic analog-to-digital converter (ADC). The ADC architecture is shown in Fig. 1. The versatility of this architecture is shown in Fig. 3. Three two-tone $X$-band RF test signals (single tone $V_{pp} \approx 0.2 V_n$) are input to the ADC along with the optical pulse train, as shown in Fig. 1. The electronic digitizer is clocked pseudorandomly sampled pulse train (PR CLK), and the captured pseudorandom pulse trace output of the photodiode/T/H circuit. Large edge drops and rises indicate the onset of pseudorandom T/H times (lower time units), followed by hold times long enough for the electronic digitizer to uniformly acquire the samples (upper time units). Filled black circles represent uniform time centers (spaced every 1005 ps for a 995.3-MHz acquisition rate) of the electronic digitizer illustrating sufficient hold and timing to avoid sampling a transition time. Note that it is not a requirement to have a T/H bandwidth or photodiode bandwidth of 10 GHz for our system to work. The shortest time between sampling pulses is 700 ps. The digitizer bandwidth of 3 GHz, effectively averaging over 300 ps of hold time, means the T/H tracking transient requirement was <400 ps (or $>$2.5 GHz bandwidth for a minimum pulse spacing of 700 ps). The T/H device was, therefore, more than sufficient and ultimately includes more noise bandwidth than required.

Signal processing of the pseudorandomly captured signal trace, yielding a Fourier decomposition, is accomplished with the use of DASP algorithms [5]. In particular, nonorthogonal transforms, based on the minimization of the mean square error between an approximated sample set and measured sample set [8], are utilized. For example, a matrix representing the approximated signal sample set is formed using the pseudorandom time vector and an analyzed frequency set. With a priori information about the signal (such as the input RF aperture bandwidth), the analyzed frequency set can be chosen ahead of time, limited by pseudorandom sampling parameters. After the measured signal set is pseudorandomly sampled and digitized, a least squares analysis is performed, giving a vector of calculated Fourier coefficients and providing a power spectrum of the signal. If the frequency range of interest is known, some of the processing matrices can be formed ahead of time thus significantly reducing the DASP computation time. This allows for near real-time analysis for the experimental testbed (performance monitoring with capture and processing code at $\sim$5-Hz refresh rate on a Pentium based laptop).

III. EXPERIMENTAL DEMONSTRATION AND DISCUSSION

The versatility of this architecture is shown in Fig. 3. Three two-tone $X$-band RF test signals (single tone $V_{pp} \approx 0.2 V_n$),
Within the same equivalent Nyquist zone (<497.7-MHz separation), separated by more than two equivalent Nyquist zones (>995.3 MHz) and separated by more than four equivalent Nyquist zones (>1.99 GHz), were sampled pseudorandomly, as described previously, at the mean rate of 995.3 Ms/s. Application of the DASP algorithms accurately reveals the frequencies of the test signals. Note that no clock related spurious signal generation is observed with our pseudorandom sampling-processing technique. For the near 100-ps minimum sampling interval, we have an effective instantaneous bandwidth of 5.0 GHz. Here the effective instantaneous bandwidth is defined as the continuous bandwidth, not necessarily starting at dc, over which signals can be identified without aliasing. For the parameters of our experiment, this bandwidth could extend over any 5.0-GHz range and would require other means to eliminate aliasing outside of the effective bandwidth. This powerful technique, coupled with the high-frequency photonic sample and hold circuit, allows the decoupling of the achievable resolution and frequency coverage without the need for downconversion or highly parallel hardware architectures.

The signal-to-noise ratio statistics were measured for pseudorandomly sampled two-tone test signal power spectra consisting of 9.0- and 10.8-GHz sinusoids (single tone $V_{pp} = 0.4V_{p}$) and determined to be 21.33 dB, resulting in 3.25 effective number of bits (ENOB). Noise measurements performed on the T/H circuit and electronic digitizer combination revealed the nonphotic backend ENOB to be 5.84. Amplitude noise measurements, performed on the sampling pulse generator and signal encoder combination using a digital communications analyzer resulted in a photonics limited ENOB estimated to be 3.7 bits for a full-scale (unity modulation depth) input. The measured 3.25 ENOB is consistent with the photonics system amplitude noise limitation for the applied modulation depth. Amplitude noise improvement will be the subject of future work. Further reduction in noise with this system can be made with the use of a lower noise laser source [9]. With further optimization in system architecture, combined with the techniques of pseudorandom sampling and DASP algorithms, we expect to significantly improve system performance of our photonic ADC architecture.

### IV. Conclusion

Using the novel techniques of DASP, we experimentally demonstrated for the first time a pseudorandom-sampled photonic ADC, which has been shown to unambiguously identify frequencies across multiple equivalent Nyquist zones. We developed a photonic-to-electronic interface that converts pseudorandom, optically sampled signals to the digital domain with the convenience of uniform baseband digitization and data management clocking. Furthermore, this architecture capitalizes on the strengths of photonics—high speed, wide bandwidth and precise timing capabilities—while eliminating the need to negotiate between performance and size, weight and power considerations of back-end processing hardware.

### References