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Performance of a Time- and Wavelength-Interleaved Photonic Sampler for Analog–Digital Conversion

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***Abstract*— We experimentally demonstrate the sampling of microwave signals using a novel time- and wavelength-interleaved pulse train derived from a mode-locked fiber laser. Experimental results are presented indicating a modulator limited bandwidth of 18 GHz and a laser relative intensity noise limited effective number of bits of ∼7 when tested for use in a hybrid photonic analog–digital converter architecture.**

***Index Terms*—Analog–digital conversion, microwave receivers, optical data processing, photonic sampling, wavelength-division multiplexing.**

I. Introduction

The advantages of digital signal processing have led to intense recent interest in the direct digitization of the microwave analog signals of communications and radar. The high-sampling rate requirement has been unobtainable for current electronic analog–digital converter (ADC) technology [1], with up to a few gigasamples per second resulting in high power dissipation and limited resolution [2]. Superconducting technology has been able to achieve the high sampling rates, but the cryogenic requirements make them impractical for many system applications [3]. The standard technique of microwave signal downconversion for electronic ADC digitization requires numerous stages of mixing and filtering, which leads to increased size and weight of phased-array radar receiver modules and introduces additional noise sources which degrade the signal-to-noise ratio (SNR) of such systems.

Current photonic technology offers many attractive features including high bandwidth capability (DC−80 GHz), reduced size and weight of components, nearly lossless signal remoting, and reduced front-end components and power requirements on receiver systems. As a result of these favorable features, numerous photonic ADC architectures have recently been proposed [4]–[6] In this letter, we experimentally investigate the performance of a high bandwidth photonic sampler and highly parallel ADC architecture based on *discrete* time domain to wavelength domain mapping utilizing commercially available technology.

II. Photonic ADC Architecture

A hybrid optoelectronic ADC architecture with a photonic sampler based on the time interleaving of spectrally distinct pulses [7] is shown in Fig. 1. Spectrally broad pulses from a mode-locked laser are sliced by a wavelength division multiplexer (WDM) into N wavelength discrete channels. Connected to each channel is a fiber stretcher (FS), variable attenuator (AT), fiber delay loop (DL) and Faraday mirror (FM). Dispersion shifted fiber is used to reduce the pulse broadening and relative dispersion between the channels. The Faraday mirror provides polarization compensation for the nonpolarization maintaining components of each channel system as well as a second pass through the WDM. The length of each channel's propagation loop is chosen to discretely fill the interpulse period of the original pulse train and the fiber stretcher provides temporal fine tuning. The variable attenuators allow the compensation of the input pulse spectrum to provide equal optical power in each channel. After amplification to the desired optical power per channel, a $LiNbO_3$ integrated electro-optic modulator (IEOM) amplitude modulates the pulse train with the signal to be digitized. The back-end digitization portion of the system utilizes a second WDM to demultiplex the time- and wavelength-interleaved pulse train for parallel digitization by the use of photodetectors (PD) and electronic ADC's. The digitization of each channel occurs at a rate which is N times slower than the photonic ADC sampling rate, thus significantly reducing the requirements on the bandwidth of the back-end electronic components.

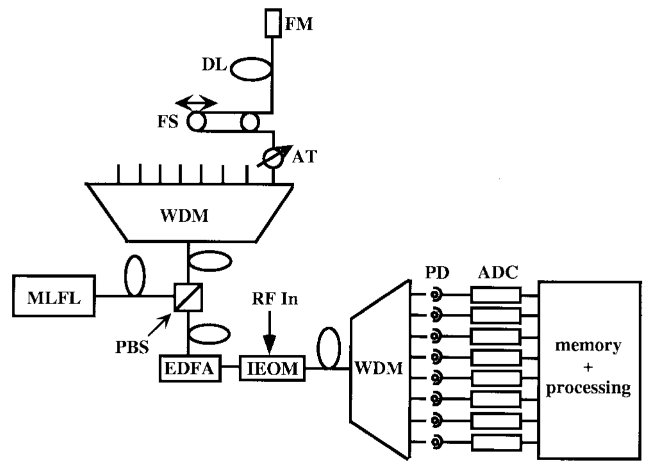

Fig. 1. Photonic ADC system.

The fundamental limitation on the bandwidth, Δf_{ADC}, of the described ADC system is due to RF modulation induced spectral broadening causing crosstalk between adjacent channels [5] and/or loss of modulation information after the demultiplexing channel passband. The system sampling rate

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for a WDM with N channels and a laser with repetition rate R_{laser} is given by $f_s = R_{\text{laser}}N$. Assuming Nyquist sampling, $f_s = 2 \cdot \Delta f_{\text{ADC}}$, the constraint on the number of WDM channels and the demultiplexing passband, $\delta\lambda_{\text{ch}}$, can be shown to be

$$\left(\frac{\delta\lambda_{\text{ch}}}{N}\right)_{\text{WDM}} > \frac{\lambda_0^2 R_{\text{laser}}}{C} \tag{1}$$

where c is the speed of light in vacuum and λ_0 is the laser wavelength. An additional constraint on the number of WDM channels results from the laser bandwidth where $\Delta\lambda_{\text{laser}} > N\delta\lambda_{\text{ch}}$. Current commercially available dense WDM technology (200-GHz channel spacing, and up to 32 channels with 1-nm passband) would allow a 1.5-μm laser with 50-nm bandwidth and 4 GHz repetition rate to operate with a sampling rate of over 120 GSPS. These numbers indicate the great potential for the method and show that the current WDM and laser technology are not the limiting factors for the bandwidth of such an ADC system. In practice, the bandwidth of the photonic ADC is limited by the electrooptic modulator technology to ~40 GHz.

There are several advantages to photonic sampling with this method. By forming a distinct pulse for each channel's spectral region, there is no degeneracy in the wavelength–time mapping. This is in contrast to what occurs in the overlapping leading/trailing edges of two temporally adjacent continuously chirped optical pulses [5], [6] The interpulse period of the mode-locked laser is also easily filled in a compact manner and is adaptable to any laser repetition rate by adjustment of the fiber delay loop lengths providing real-time optical sampling. In addition, amplification of the wavelength-interleaved pulse train and using a matching WDM channel spacing for demultiplexing allows signal sampling with the maximum optical power per channel by not wasting power on spectral regions which will not be used in the digitization.

III. Experiment and Discussion

We constructed an eight channel optical pulse train sampler and performed preliminary testing of its use in a photonic ADC system. The time- and wavelength-interleaved pulse train was formed by slicing the mode-locked pulses of a stretched pulse fiber laser ($\tau_p \sim 1$ ps, $\Delta\lambda \sim 50$ nm and 40-MHz repetition rate) with an eight channel WDM which had a ~1-nm passband and ~3-nm channel separation. Fig. 2(a) shows the spectrum of the sampler output after amplification by a two pass erbium-doped fiber amplifier (EDFA) with the sampler input spectrum overlayed. Note that the variable attenuators of each channel have compensated for the input pulse and amplifier spectral variations. An 18-GHz $LiNbO_3$ electrooptic modulator was used to modulate the sampling pulse train with the RF signals to be digitized. The measured optical power per channel transmitted through the modulator was ~1 mW. Both a slow real-time sampler (320 MSPS with infinite aperture time) and a high frequency sampler (10 GSPS with 700-ps aperture time) were constructed and tested. Shown in Fig. 2(b) and (c) are the real-time and high frequency sampler pulse trains constructed by adjusting the fiber delay loops to meet the 3-ns and 100-ps respective pulse separation requirements.

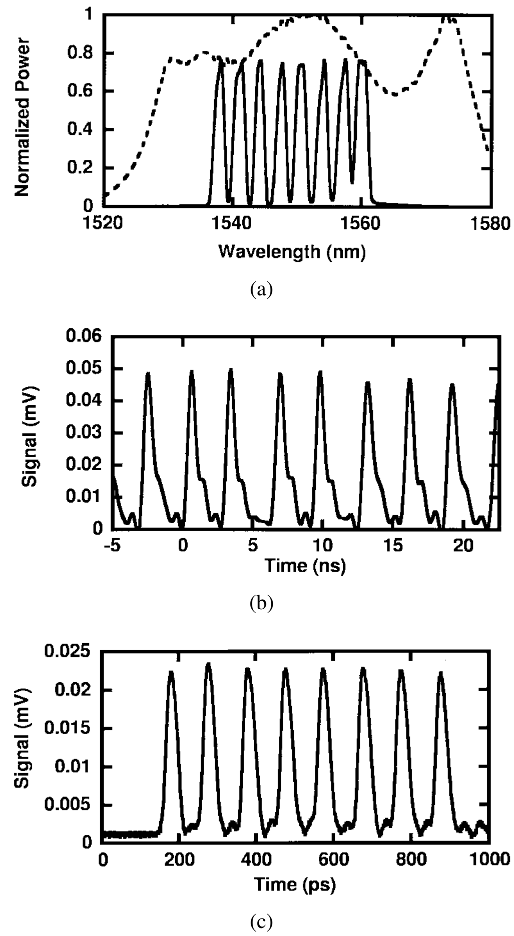

Fig. 2. (a) Spectrum of photonic sampler input (dashed line) and eight-channel sampler output. Pulse train of sampler with (b) 320 MSPS and (c) 10 GSPS sampling rates.

In order to demonstrate the use of the sampler in an ADC system, equivalent-time digitization of synchronous signals was performed using an optical spectrum analyzer, with its internal scanning grating, photodetector and electronic ADC simulating the back-end digitization. Note that the digitization resulting from this test is the result of integrating many waveforms due to the slow scan rate of the optical spectrum analyzer. A portion of the laser output was split off before entering the sampler system and sent to a 20-GHz photodetector. Bandpass filtering of the electrical photodiode signal then provided synchronous sinusoidal signals for digitization testing. Fig. 3 shows the agreement of the eight channel 10 GSPS digitization with the averaged 20 dBm, 1.2-GHz input signal measured on a sampling scope. The agreement accuracy for this measurement is estimated to be ~5 bits using deviation from the reference waveform and is limited by a combination of the OSA resolution, sampler resolution and input waveform noise. For this experiment, a bandpass filter with center frequency of 1.2 GHz selected the 30th harmonic of the laser frequency from the photodiode signal and the effective pulse train chirp rate of approximately 0.03 nm/ps was used to reconstruct the sampled signal.

Single-channel testing of the system was performed to quantitatively evaluate the effective number of bits of the

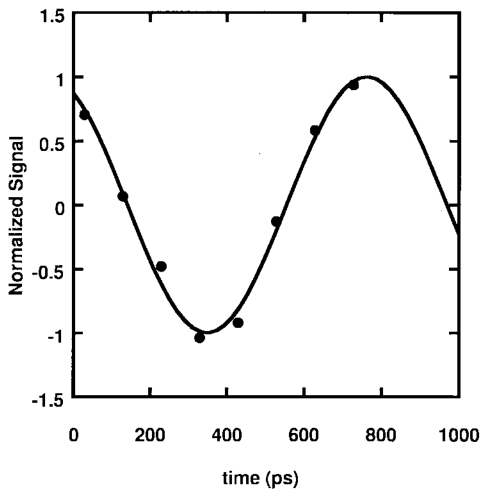

Fig. 3. Comparison of input 1.2-GHz sinusoidal signal (solid curve) and eight-channel digitization (filled circles).

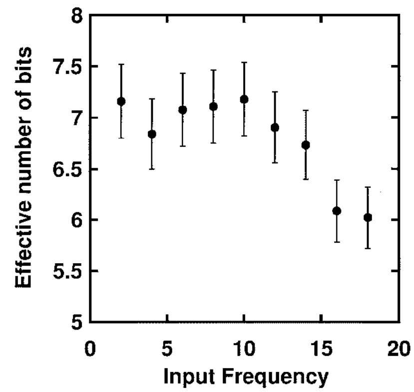

Fig. 4. Effective number of bits as a function of modulator input frequency.

photonic sampler at high frequency. Single tone asynchronous microwave signals of varying frequency (2–18 GHz) were amplified by a high-frequency amplifier ($P_{\max} = 27$ dBm) and applied to the $LiNbO_3$ modulator. The timing jitter of the laser was not included in this test due to the asynchronous nature of the driving signal. A 20-GHz photodetector and a low-noise sampling head were used to measure the maximum signal level at each frequency when the IEOM was biased at quadrature. The rms noise floor of the detector-sampling head system was measured to be <350 μV, which with the $\sim$300-mV full-scale pulse amplitude set the maximum possible SNR measurement at $\sim$58 dB. The minimum measurement time for this experiment was set by the sampling scope persistence time of 1 s. The potential effective number of bits of the sampler was deduced from the measured SNR for each frequency using the expression $N_{\text{eff}} = \log_2(A_{md}/A_n)$, where A_{md} is the modulation voltage range and A_n is the root-mean-square (rms) noise voltage. Fig. 4 shows the measured effective number of bits of the system with increasing frequency for $\sim$25 dBm RF input power. The drop in effective number of bits above 12 GHz is due to the increase in the applied V_π of the modulator with frequency resulting in a reduced modulation signal level and the response of the sampling head which had a bandwidth of 12.5 GHz. The measured system noise level of $\sim$0.8 mV for an unmodulated pulse amplitude of $\sim$150 mV is consistent with the independently measured [8] RIN ($<1\%$) of the mode-locked fiber laser output in its current configuration. This indicates that the RIN is not significantly degraded by the photonic sampling architecture demonstrated here and the effective number of bits can be significantly improved with the use of a lower RIN laser. In addition, the bandwidth can be improved with the use of a lower V_π and higher bandwidth modulator.

IV. Conclusion

We have experimentally investigated a photonic sampler for the digitization of microwave signals in a hybrid photonic ADC architecture based on discrete wavelength–time mapping. Our system has the advantages over previously demonstrated continuous wavelength–time mapping architectures of eliminating the wavelength–time degeneracy, maximizing the optical power per channel, and exhibiting adaptability to any laser repetition rate. Experimental results show the large bandwidth potential of the method currently limited (to $\sim$18 GHz) by the electro-optic modulator and an effective number of bits (of $\sim$7 bits) currently limited by laser RIN.

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