Photonic Bandwidth Compression Front End for Digital Oscilloscopes

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***Abstract*—Time-stretch photonic analog-to-digital converter (ADC) technology is used to make an optical front end that compresses radio-frequency (RF) bandwidth before input to a digital oscilloscope. To operate a time-stretch ADC in a continuous-time mode for bandwidth compression, the optical signal on which the RF is modulated must be segmented and demultiplexed. We demonstrate both spectral and temporal methods for overlapping the channels. Using the temporal method, we obtain a compression ratio of 3 with four channels. Mating this optical front end with a state-of-the-art four-channel digital oscilloscope with an input bandwidth of 16 GHz and a sampling rate of 50 GS/s gives a digitizer with 150 GS/s and an input bandwidth of 48 GHz. We digitize RF signals up to 45 GHz and obtain effective number of bits (ENOB) $\sim$2.8 with single channels and $\sim$2.5 with multiple channels, both measured over the 48-GHz instantaneous bandwidth of our system.**

***Index Terms*—Analog-to-digial conversion (ADC), microwave photonics, optical analog link, optical modulation, optical signal processing, photonic assisted ADC, photonic time stretch.**

I. Introduction

APPLICATIONS ranging from basic science to advanced communications could benefit from digital oscilloscopes with faster sampling rates and wider input bandwidths than are commercially available. Today, such oscilloscopes are limited to sampling rates less than 60 GS/s and input bandwidths less than 20 GHz [1], [5]. The building blocks for such oscilloscopes, single-chip analog-to-digial conversions (ADCs), continue to improve but at a relatively slow rate [2]. These ADCs are limited by clock jitter and comparator ambiguity [2], and these properties are directly tied to fundamental semiconductor device properties.

To extend the performance of single-chip ADCs, two electronic approaches have been developed to interleave multiple lower rate ADCs. The first is temporal interleaving in which an array of ADCs is operated with subsampling period offsets. This enables the skewed sample-and-hold circuits to collect data at a much higher aggregate rate and allows more time for the individual quantizers [3]. In this system, each individual time sample must be interleaved in the time domain with data from a different ADC, and this puts tremendous strain on the back-end processing, calibration, and equalization. Sample interleaving has also been used in a photonic ADC [4] with many of the same issues as electronic sample interleaving. The second electronic approach, frequency-domain interleaving [5], uses bandpass filters to demultiplex a wideband signal followed by downcoversion and digitization. The advantage of frequency-domain interleaving is that it reduces the constraints on both the ADC and the RF amplifier, as front-end amplification is implemented after the demultiplexing. This technique also requires extensive post-processing for reconstructing the time-domain waveform and this processing is especially difficult for broadband signals that overlap two frequency bins.

In contrast to electronic approaches, a photonic technique has been developed that stretches radio-frequency (RF) signals in time and hence achieves bandwidth compression [6]. In this technique, the RF signal to be digitized is modulated onto the intensity of a chirped optical carrier. This signal propagates through a dispersive medium, which stretches both the optical pulse and the RF waveform, and finally, the optical signal is rectified at a photodiode whose output is fed to an electronic ADC or digital oscilloscope. Three promising applications of the time-stretch technology have been developed over the past few years. First, it can be used as a transient digitizer to achieve extremely high sampling rates over short time windows of an RF waveform. The record for this approach is 10 TS/s with input signal frequencies up to 90 GHz [7]. A second application is increasing the resolution for continuous-time digitizers at input bandwidths where electronic digitizers already exist. The best results here are seven effective bits of resolution (ENOB) over 10-GHz input bandwidth [8], [9] for systems that have the potential to be scaled to continuous time. Finally, a third application is extending the performance of existing real-time oscilloscopes to input bandwidths greater than can be achieved with electronics alone [10], [11]. Here we review these previous results, add information about the dispersion penalty, which is the major impediment to implementing this application, demonstrate stitching of 70 pulses together into a continuous time

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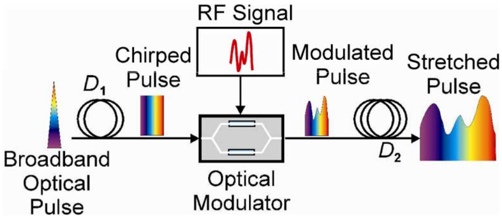

Fig. 1. Single-channel time-stretch system.

waveform, calculate the effective number of bits for a single wavelength channel, for four stitched wavelength channels in a single pulse and for 280 channels in 70 pulses, and propose a system that avoids the dispersion penalty.

The time-stretch technology offers three advantages compared to electronic interleaving. One is that all back-end electronics operate at a bandwidth reduced by the compression ratio. Second, the demultiplexing required to make the photonic bandwidth compression possible in continuous time is performed passively in the optical domain using wavelength-division multiplexers (WDMs), which are commercially available. Finally, the digitized time segments at the ADCs consist of multiple time samples, rather than single samples, and this decreases the number of digital signal processing (DSP) stitching steps per time compared to sample interleaving and also allows for better calibration if the segments are overlapping.

The single-channel time stretch system is shown in Fig. 1. Here a broadband optical pulse is dispersed and chirped by the first dispersive medium D_1, the chirped pulse is modulated by the RF signal, and the modulated pulse is stretched again by the second dispersive medium D_2. Extending this system to continuous time requires that the signal input to the optical modulator be continuous in time and that the optical signal after the final stretching medium be demultiplexed to a bank of photodiodes and input to multiple channels of a digital oscilloscope. Alternatively, it is possible to demultiplex before the final stretching medium and stretch each wavelength channel individually. As shown in Fig. 2, stretching the input pulse to the inter-pulse period (the inverse of the pulse repetition rate of the laser) allows the continuous RF signal to be modulated onto a constant intensity repetitively chirped optical signal. Four adjacent channels are shown, limiting the maximum stretch ratio (or, equivalently, bandwidth compression ratio) M to four without signal ambiguity due to overlap within each channel. Typically, the stretch ratio is smaller than the number of channels to account for guard bands and channel overlap.

II. Temporal Versus Spectral Overlap

An important step in increasing the stretch ratio is finding a spectrally efficient overlap technique. Redundancy in signal content at the edges of each segment is useful to correct for static and slowly varying mismatches between channels. In previous work [10], custom trapezoidal filters were constructed with filter profiles similar to those shown in Fig. 3(a). Unlike conventional WDM filters, this introduces intentional crosstalk among adjacent channels. In the construction of a photonic bandwidth compression system with spectral overlap, such trapezoidal filters are the most spectrally efficient method of overlap. This is due

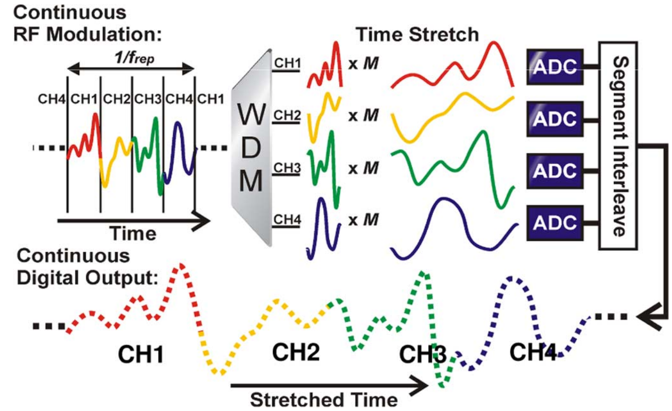

Fig. 2. Implementation of continuous-time four-channel photonic bandwidth compressor.

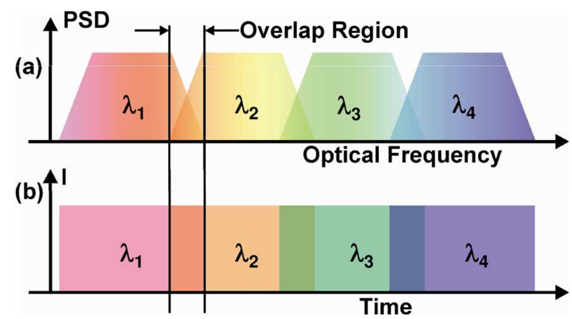

Fig. 3. (a) Illustration of the spectral overlap technique in the frequency domain. (b) Temporal overlap technique plotted in the time domain with spectrally diverse segments.

to limits of energy conservation and the fundamental behavior of the optical amplifiers. There is a finite amount of power spectral density (PSD) which must be shared in the overlap region. Unfortunately, this limits the stretch ratio of systems employing spectral overlap. High M calls for a fast roll-off. This means that the wavelengths at which one channel has a high PSD, the adjacent channel is limited to low PSD. This large power imbalance reduces the effective overlap region. Further amplifying this problem are the ADC quantization and noise sources that make the regions of low PSD unusable and forces a gradual filter roll-off. We solve these problems by developing the temporal overlap scheme, shown in Fig. 3(b) that provides several advantages over the spectral scheme. Instead of relying on WDM filters with custom cross-talk profiles, conventional WDMs with guard bands can be used. Conservation of energy no longer limits the spectral roll-off in the overlap region, allowing for steep, brick-wall thin film filters making full use of the overlap. The signal-to-noise ratio (SNR) and quantization levels are also kept constant across the entire channel, making best use of the power in the channel. All of these features combine to allow a much higher stretch ratio.

We can summarize the advantages of the temporal overlap scheme as follows. First, the temporal overlap system enables the use of COTS wavelength-division multiplexer (WDM) filters as opposed to the customized CFBGs needed for the spectral overlap method. Second, the temporal overlap system allows easy control of channel overlap and equalization. Third, with the temporal overlap system, one can remove the direct current (dc) component of the optical waveform using the offset feature of

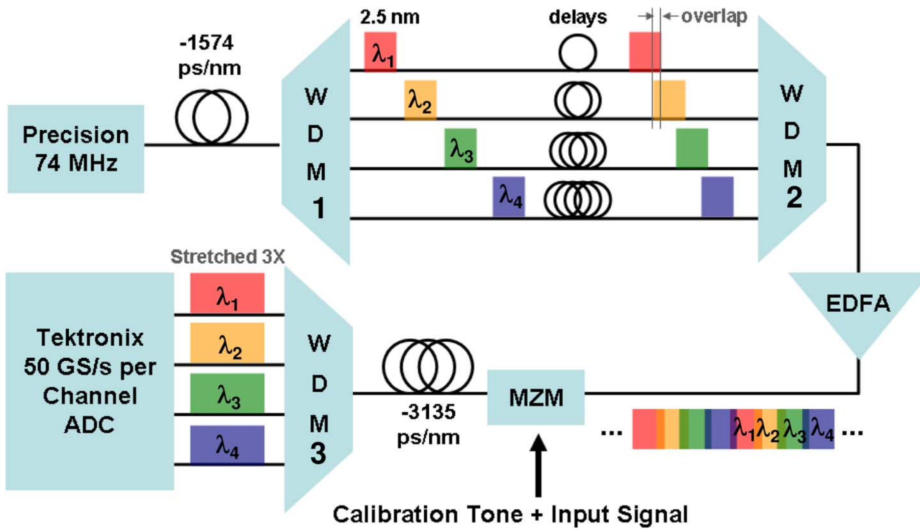

Fig. 4. Experimental setup of photonic bandwidth compression system for 150 GS/s. After WDM1, the spectral bandwidth of each channel is 2.5 nm and the channel pulse width is 4 ns. After WDM3, the spectral bandwidth remains 2.5 nm while the channel pulse width is 12 ns.

the digital oscilloscope thus allowing the analog-to-digital conversion (ADC) dynamic range to digitize only the RF modulation. On the other hand, with the spectral overlap system, the ADC dynamic range must capture both the trapezoidal profile and the RF modulation, which reduces the maximum possible resolution of the whole system.

III. Four-Channel Bandwidth Compression Experiment

A functional schematic of the 150 GS/s oscilloscope with a photonic bandwidth-compression front end is shown in Fig. 4. The optical source of the system is a 1.5-ps mode-locked fiber laser (Precision Photonics) that emits a pulse centered at 1550 nm with 24 nm of spectral width. A repetition rate multiplier is used to increase the pulse repetition frequency to 74 MHz. This reduces the dispersion necessary in the first stage to achieve a continuous time stream of chirped pulses with a fixed optical bandwidth. These pulses are then dispersed in commercial dispersion compensating fiber (DCF) with dispersion parameter D_1 equal to -1574 ps/nm.

After the initial dispersion stage, the chirped pulses proceed to the temporal overlap filters. This configuration of brick-wall thin-film filters (Bookham) and precision delay lines takes four nonoverlapping 2.5-nm spectral channels and overlays them in time. The fiber delay lines have been fixed to achieve 15% overlap. These WDM filters also serve as implicit bandpass filters, removing extraneous frequencies to increase the system efficiency of the fiber amplifier that follows the WDM. A zero-chirp Mach–Zehnder (MZ) modulator then applies the RF tone to the chirped optical pulses through direct amplitude modulation. In addition to the 47-GHz tone to be digitized, a second 6-GHz pilot tone is added to the optical modulation. This second, out-of-band tone is used for calibration and segment interleaving [11].

The modulated signal is then dispersed a second time through DCF with dispersion parameter $D_2 = -3135$ ps/nm. This combination of D_1 and D_2 yields a stretch ratio of $M = 1 + D_2/D_1 = 2.99$. A final WDM filter distributes the stretched signal to four parallel digitization channels. This ADC is accomplished by a Tektronix DSA72004 50-GS/s oscilloscope with four input channels each of which digitizes the full 16-GHz input bandwidth at 50 GS/s. The optical front end increases the sampling rate to 150 GS/s and the analog bandwidth to 48 GHz.

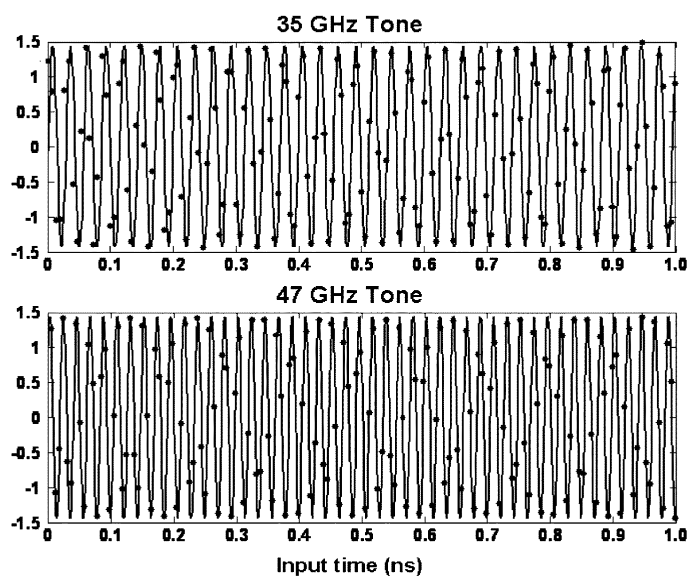

Fig. 5. The 35 and 47 GHz signals a function of time. The points are the measured data and the curves are sine fits to the data.

Fig. 5 shows single-shot real-time data for 35- and 47-GHz tones digitized at 150 GS/s. Fig. 6(a) illustrates the implementation of a pilot-tone calibration technique to stitch four adjacent channels into a continuous time waveform [11]. Adjacent channels are concatenated by adjusting the gain, offset, and clock skew of each channel with the aid of the 6- GHz pilot tone. Fig. 6(b) shows the fast Fourier transform (FFT) of the 6-GHz pilot tone and the 35-GHz signal tone for a single channel and for four channels stitched together. The pilot tone provides real-time calibration data that is used to mitigate errors between adjacent segments. The effective number of bits (ENOB) for the 35-GHz signal over a 48-GHz noise bandwidth

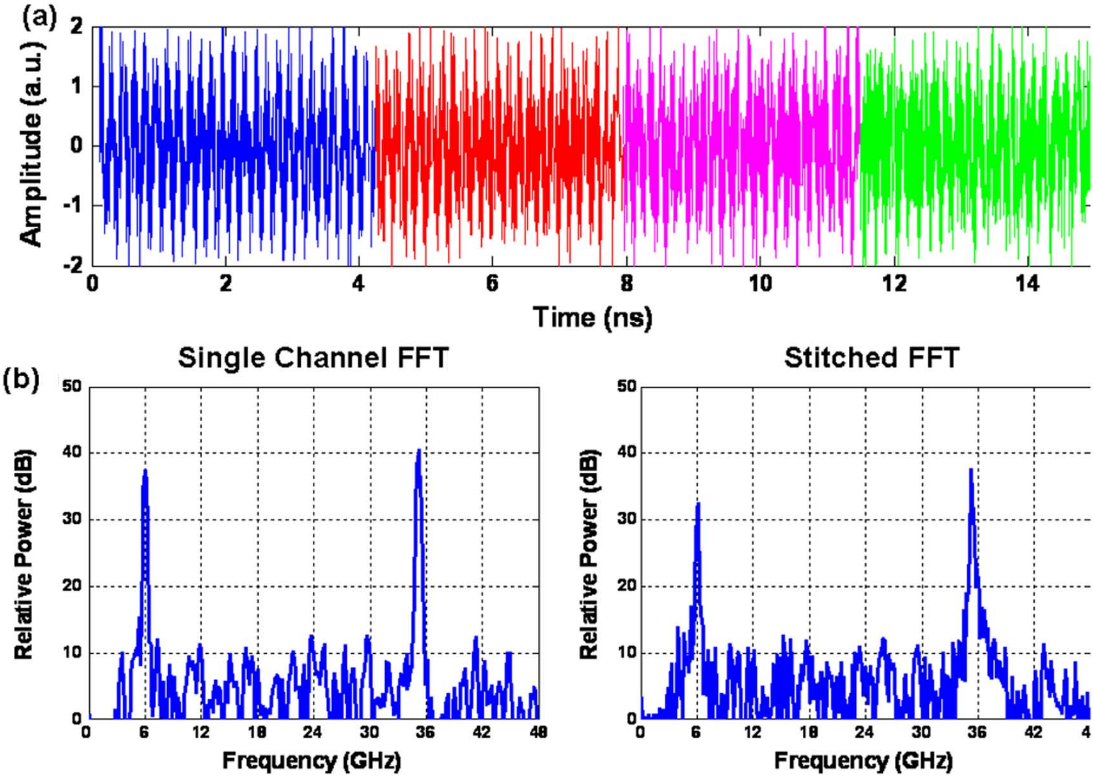

Fig. 6. (a) Plot of real time 150-GSa/s digitized data of a 35-GHz tone from four adjacent channels. (b) FFT of both single channel and stitched digitized data.

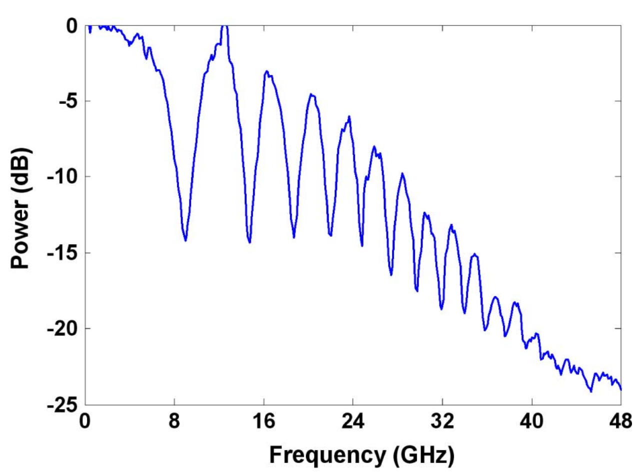

Fig. 7. Power penalty as a function of frequency in time-stretch ADC.

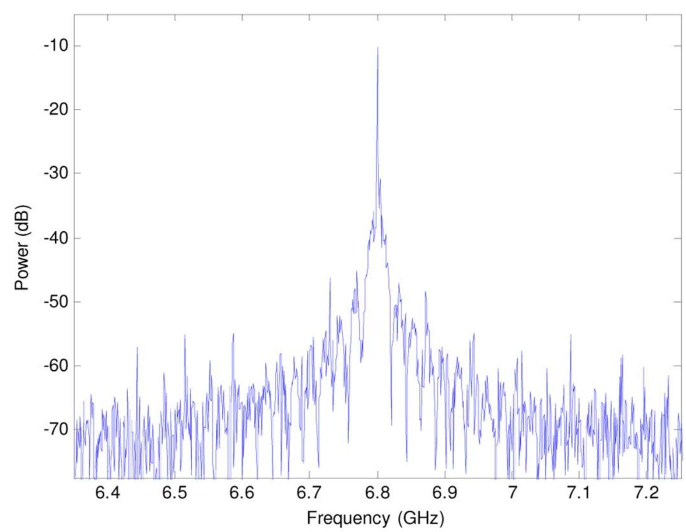

Fig. 8. FFT of a 6.8-GHz tone and input time aperture of 1 μs (stitching of $\sim$280 single-shot channel pulses over 70 laser pulses).

for the single channel data shown in Fig. 6(b) is 2.8. For the four stitched channels, the ENOB drops to 2.5.

Input time apertures as long as 1 μs have been demonstrated without additional degradation in ENOB. This represents the stitching of about 280 single-shot channel pulses over 70 laser periods. These demonstrations were done at RF frequencies of 6.8 and 13 GHz for purposes of avoiding the roll-off in system response seen in Fig. 7. The FFT for the 6.8-GHz tone is shown in Fig. 8. A time-stretch linearization technique using measured DCF and WDM filter dispersions [9] is employed to suppress stitching spurs. While these are relatively low ENOBs, it should be noted that these ENOBs are completely adequate for observing signals as shown in Fig. 6(b) and that there does not exist any other way to directly digitize such signals at present. This ENOB is primarily limited by the level of the input signals to the back end digitizer. Without additional amplification, the input signals to the oscilloscope were at 1/4 of full scale in our experiments, and since we measured the oscilloscope full-scale ENOB $\sim$5 over 16 GHz, the maximum ENOB over 1/4 full scale is less than about 3.

The major limitation of the photonic bandwidth compressor presented in this paper is the presence of dispersion penalty nulls in frequency response as shown in Fig. 7. These nulls are caused by the difference in group velocity of the upper and lower RF sidebands during propagation through the second dispersive fiber in Fig. 4. When these sidebands beat with the optical carrier at the photodiode before the Tektronix oscilloscope, they destructively interfere with each other causing the nulls shown in Fig. 7. The best method to remove these nulls is to employ single sideband modulation at the optical modulator, but the electronics needed to do this are limited to RF frequencies less than about 20 GHz [12]. The other alternative is to remove one of the sidebands after modulation, but conventional optical filters are not useful because of the large chirp on the optical signal in the time-stretch systems. We have developed a unique time-gated filter for use in this application [12] and combining this technique with the system shown in Fig. 4 is expected to provide enhanced performance over the entire 48-GHz band.

IV. Conclusion

In summary, we have demonstrated a 150-GS/s continuous-time oscilloscope implementing the photonic bandwidth compression technique. Such results have not been possible using electronic interleaving techniques to date. We have experimentally demonstrated a four-channel system that multiplies the sampling rate (50 GS/s) and input bandwidth (16 GHz) of a state-of-the-art digital oscilloscope by a factor of 3. A novel temporal overlapping technique has been developed to increase the stretch ratios and maximize the system spectral efficiency.

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