Spectral Efficiency Improvement in Photonic Time-Stretch Analog-to-Digital Converter via Polarization Multiplexing

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***Abstract*—Dual-polarization photonic time-stretch technique, which exploits polarization multiplexing to improve the spectral efficiency of the conventional photonic time-stretch technique, is proposed. This technique reduces the demand on optical bandwidth for large record length of the photonic time-stretch analog-to-digital converter. It is shown that this technique can capture high-bandwidth radio-frequency signals ($>$10-GHz instantaneous bandwidth). Experimentally, 12.5-Gb/s data eye-diagram measurement using this preprocessor operating in equivalent-time mode is demonstrated.**

***Index Terms*—Analog-to-digital converter (ADC), eye diagram, oscilloscope, photonic time-stretch, polarization multiplexing.**

I. INTRODUCTION

THE rapid growth of internet traffic requires optical communication networks with high capacity [1], [2]. Data demodulation at the receiver of such systems relies on high-bandwidth real-time digitizers, which are becoming the major bottleneck. High-bandwidth analog-to-digital converters (ADC) with real-time capabilities facilitate rapid measurement and evaluation of signal quality in optical performance monitoring [3] of self-managed and reconfigurable optical switch networks. In defense applications, such digitizers are the central tools in radar systems, military receivers, and battlefield airborne communications nodes (BACN) [4]. In biomedical imaging, high-performance digitizers are needed to record images continuously over a large time period [5]. Moreover, availability of high-resolution, high-bandwidth digitizers enables development of advanced laboratory instruments such as real-time oscilloscopes and radio frequency (RF) vector network analyzers.

The photonic time-stretch (PTS) preprocessor [6]–[9] is a novel technique to slow down and capture the dynamics of fast repetitive or nonrepetitive signals, and rare events using a low-bandwidth ADC. It stretches the RF signal in time by exploiting a dispersive analog optical link and a broadband chirped optical source. It can provide continuous digitization of ultrahigh bandwidth electronic signals [9]–[11] with high-resolution that cannot be achieved by purely electronic ADCs [12]. The real-time burst sampling technique performed by time-stretch enhanced recording (TiSER) oscilloscope, which is the single-wavelength channel version of the PTS system, enables capture of bursts of samples, spanning several real-time sample points [13]. When operated in equivalent-time mode, it can generate eye-diagrams of repetitive data streams.

A crucial feature of the PTS system is the spectral efficiency, i.e., the optical bandwidth required to capture a certain time aperture of an RF signal over sufficient RF bandwidth. It is naturally desirable to maximize the time aperture so that more of the signal is captured. The time aperture of the PTS system is equal to the width of the optical pulse after the first dispersive fiber, given by $T_A = \Delta\lambda D_1$, where $\Delta\lambda$ is the optical bandwidth and D_1 is the initial dispersion. When double sideband modulation (DSB) is employed to modulate the RF signal onto the prechirped pulse, a frequency-fading phenomenon due to dispersion [9], i.e., dispersion penalty, is inevitable. The overall effect is to limit the effective 3-dB RF bandwidth of the PTS to an expression proportional to the inverse square root of the initial dispersion: $\Delta f_{\rm RF} = [1/(8\pi|\beta_2|L_1)]^{1/2}$, where β_2 is the group-velocity dispersion (GVD) parameter. Hence, for a certain desired RF bandwidth, a limit is placed on the maximum predispersion that can be tolerated, at which point, to increase the time aperture, one must use time-stretching pulses with larger optical bandwidth. Alternatively stated, the product of the time aperture and RF bandwidth, a figure of merit termed the time-bandwidth product (TBP), depends linearly on optical bandwidth [11]. In order to meet the increasing RF bandwidth demands of modern applications, the PTS system must therefore employ broadband optical pulses with larger optical bandwidth, straining the capabilities of the supercontinuum (SC) source, and eventually leading to undesired distortions, such as wavelength-dependent loss and optical nonlinearity. Improving the spectral efficiency of the PTS system equates to increasing the TBP independent of optical bandwidth, so that large RF bandwidth demands can be met feasibly and efficiently.

In this letter, we demonstrate the dual-polarization photonic time-stretch preprocessor (DP-PTS), which exploits polarization multiplexing in the PTS system to double the spectral efficiency. The DP-PTS maps two consecutive segments of the RF signal onto two orthogonal polarization states and multiplexes them on a single-wavelength channel, thereby doubling the effective time aperture while keeping the optical bandwidth constant. This technique can also be used in the TiSER oscilloscope to significantly increase the record length and hence, the sampling throughput.

Manuscript received February 15, 2011; revised April 03, 2011; accepted April 09, 2011. Date of publication April 15, 2011; date of current version June 22, 2011. This work was supported by the National Science Foundation through CIAN ERC and by the DARPA-MTO RADER program.

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Digital Object Identifier 10.1109/LPT.2011.2142414

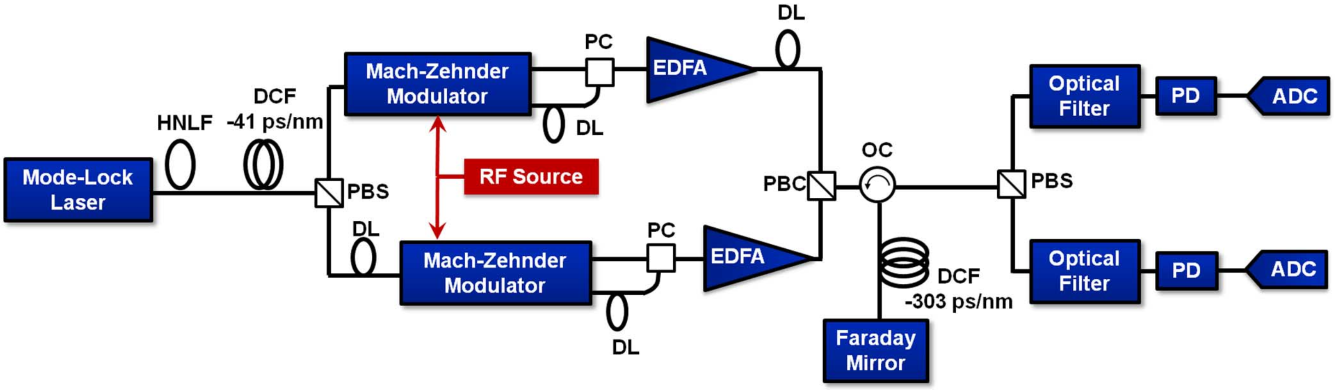

Fig. 1. Schematic of dual-polarization photonic time-stretch (DP-PTS) preprocessor. HNLF: Highly nonlinear fiber. DCF: Dispersion-compensating fiber. PBS: Polarization beam splitter. DL: Delay line. EDFA: Erbium-doped fiber amplifier. PC: Power combiner. PBC: Polarization beam combiner. OC: Optical circulator. PD: Photodetector. ADC: Analog-to-digital converter. In order to mitigate the crosstalk between the polarization channels in the DP-PTS, a double-pass configuration consisting of a spool of DCF and a Faraday mirror was used to stretch the RF signal. For simplicity, the polarization controllers before the polarization beam splitters/combiners and Mach–Zehnder modulators are not shown.

II. DUAL-POLARIZATION TIME-STRETCH PREPROCESSOR

The DP-PTS uses a mode-locked laser (MLL) followed by a highly nonlinear fiber (HNLF) to generate the broadband optical pulses as illustrated in Fig. 1. The pulses are chirped using a spool of dispersion compensating fiber (DCF) with total dispersion value of -41 ps/nm. The prechirped optical pulses are polarized and split into two orthogonally polarized pulse trains via a polarization beam splitter. A polarization controller before the polarization beam splitter is adjusted to ensure equal amplitudes in the two channels upon detection.

The two orthogonally polarized pulse trains are skewed relative to each other in time, leaving a small region of overlap. They are then modulated by the same RF signal in two dual-output push-pull Mach–Zehnder modulators. Due to the time skew, the two corresponding pulses capture two consecutive segments of an RF signal, doubling the time aperture. The two complementary outputs of the modulators are used to perform differential operation for 2nd order distortion cancellation. To avoid mismatch between the signal paths of the complementary outputs, the complementary pulse trains are multiplexed in time onto the same polarization state. Polarization controllers at each output are used to align the polarizations. The pulses from the complementary outputs are delayed relative to each other by approximately half the pulse period to avoid overlap after stretching. The orthogonally polarized pulse trains from the two modulators are overlapped in time by a second delay line in one of the arms and then separately amplified using two C-band erbium doped fiber amplifiers (EDFA). The two signals are then polarization-multiplexed using a polarization beam combiner. The polarization multiplexed optical pulse trains are stretched using total dispersion of -606 ps/nm to achieve stretch factor of ~ 16.

In order to mitigate the crosstalk between the polarization channels due to polarization mode dispersion (PMD), a double-pass configuration consisting of a spool of DCF with total dispersion value of -303 ps/nm, circulator, and Faraday mirror was used. After dispersion, the polarization multiplexed signals are demultiplexed via a polarization beam splitter. The useful portion of the optical bandwidth ($\sim$20 nm) around 1551 nm is filtered, and the stretched optical pulses are detected using two photodetectors. The obtained RF signals are digitized by a 16 GHz real-time oscilloscope with 50 GS/s sampling rate (Tektronix-DPO71604).

Since the bandwidth of the time-stretched RF signal is lower than 1.1 GHz, a digital low-pass filter was applied in the digital signal processing stage to reduce the bandwidth from 16 GHz to 1.1 GHz and thereby, emulating a monolithic commercial off-the-shelf ADC. Digital signal processing is performed offline for correcting nonlinear distortions such as 2nd order distortion due to dispersion, time-warps [12], and 3rd order distortion due to Mach–Zehnder modulator [14]. The DP-PTS preprocessor demonstrated here achieves an effective time aperture of $2 * 41\ \mathrm{ps/nm} * 20\ \mathrm{nm} = 1.64$ nsec. In the current configuration, the 3-dB RF bandwidth due to dispersion penalty is 28 GHz, whereas a single channel PTS, requiring double the dispersion, would have a reduced 3-dB RF bandwidth of 20 GHz.

III. EXPERIMENTAL RESULTS

To demonstrate the functionality of the DP-PTS preprocessor, we performed a single-tone test at 6 GHz and a two-tone test at 8.2 GHz and 10.25 GHz as shown in Fig. 2(a) and (b). After distortion corrections, the captured segments of each polarization channel are stitched in the digital domain to verify the increase in the effective time aperture. The power spectrum of the RF signal is calculated after stitching more than 300 consecutive segments. For 10 GHz instantaneous bandwidth, the single-tone (Fig. 2(a)) and two-tone (Fig. 2(b)) tests show 6.1–6.3 (obtained by sine-curve fitting method) and 5–5.1 (obtained by spectral domain method) effective number of bits (ENOBs) respectively. These results showcase the recording of high-bandwidth RF signals using this system.

Polarization mode dispersion (PMD), caused by the birefringence of optical fiber and the random variation of its orientation along the fiber length [15], is the major source of noise in the DP-PTS system. The PMD results in the crosstalk between the two polarization channels, while propagating through the second spool of DCF. The double-pass configuration for time-stretching in the second spool of DCF reduces the channel crosstalk to a great extent. However, this configuration may not

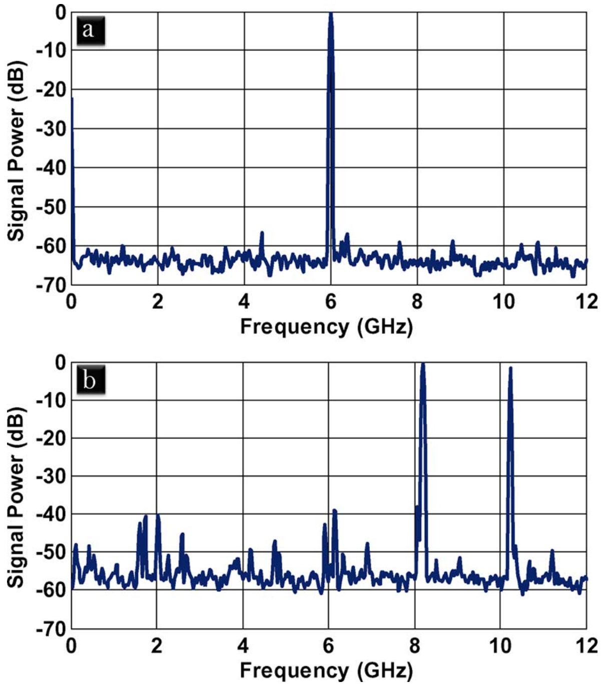

Fig. 2. (a) Single-tone test with 6-GHz RF signals; (b) two-tone test with 8.2- and 10.25-GHz RF signals. More than 600 segments (300 segments per polarization channel) are stitched coherently to generate these plots.

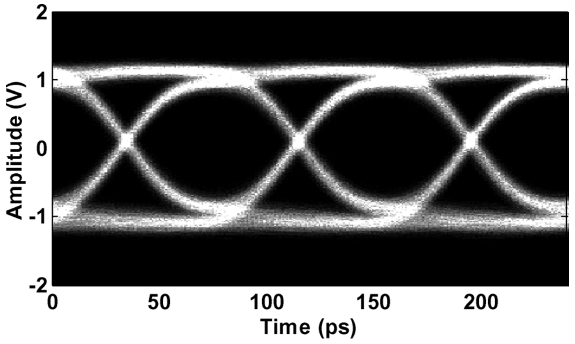

Fig. 3. Eye diagram of 12.5-Gb/s 2^31 − 1 PRBS captured by the DP-PTS combined with the TiSER oscilloscope. The number of sample points is twice more than the conventional TiSER oscilloscope, doubling the sampling throughput of the TiSER oscilloscope.

be useful for application in which the RF signal is to be detected at a remote site. An additional source of noise is the Rayleigh back scattering of the signal in forward propagation that is directed to the photodetector.

In order to demonstrate the use of DP-PTS in the TiSER oscilloscope, an eye-diagram of 12.5 Gb/s $2^{31} - 1$ PRBS data was captured as shown in Fig. 3. Due to the significant increase in the time-aperture, a particular number of sample points is recorded in a shorter time period than with the conventional TiSER oscilloscope. Thereby, the sampling throughput of the TiSER oscilloscope is improved by a factor of two, providing 200 times higher sampling throughput than the state-of-the-art sampling (equivalent-time) oscilloscopes [16].

IV. CONCLUSION

We have demonstrated the dual-polarization photonic time-stretch (DP-PTS) preprocessor to improve the spectral efficiency of the photonic time-stretch (PTS) preprocessor. By using polarization multiplexing, this technique reduces the demand on optical bandwidth for larger time aperture per channel. It is shown that this system is able to record high-bandwidth RF signals. Furthermore, the DP-PTS preprocessor can be used to achieve a significant improvement in the record length and sampling throughput of the time-stretch enhanced recording (TiSER) oscilloscope.

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