High-speed optical sampling system combined with cavity-less pulse source

Bo Shao, Yue Zhou* and Kun Xu

State Key Laboratory of Information Photonics and Optical Communications (IPOC), Beijing University of Posts and Telecommunications, 10 Xitucheng Road Beijing, China

*Corresponding author. Email: yuezhou@bupt.edu.cn

Abstract. High-speed optical sampling can overcome the limitation faced by electronic systems, such as bandwidth and precision. In this work, a 4-fold optical sampling time-parallelization is combined with a cavity-less 10GHz pulse source. The 4-fold sampling time-parallelization is based on a 1x4 optical switching matrix. Three dual-outputs Mach-Zehnder modulators (D-MZM) in cascaded configuration are included. Instead of a 10GHz repetition mode-locked laser (MLL), a cavity-less 10GHz pulse source is designed and used to provide the 10GHz modulated pulse as used in the switching matrix, which consists of a Mach-Zehnder amplitude modulator (MZM), a phase modulator (PM) and a highly dispersive optical fiber. We demonstrate a 4-fold sample time-parallelization with a high repetition rate up to 10GHz and 2.5GHz per channel, also with a signal-to-noise ratio (SNR) of 30dB, and combined with a 10GHz cavity-less pulse source with a pulselength of 9ps, which can be used into the advancements in radar and telecommunication systems.

1. Introduction

The evolution of telecommunication systems requires the advancements in analog-to-digital convert techniques. The bandwidth and accuracy that traditional electrical oscilloscopes and photodetectors can reach is extremely limited, and can no longer meet the bandwidth requirements [1-4]. In the absence of multiplexing, optical sampling reduces the time aperture and can significantly increase the effective number of bits (ENOB) of the analog-to-digital converter (ADC), but it is still necessary to maintain a higher sampling rate when processing high-frequency and broadband signals, which requires a higher demand for the photoelectric detection and electrical ADC [4-8]. By using time division multiplexing (TDM) technology, the sampled high-speed optical pulse sequence is decomposed into multiple sets of low-speed optical pulse sequences, and then passes through the photodetection arrays for the next step of processing. TDM technology can greatly reduce the performance requirements of electronic devices.

The combination of TDM technology and optical sampling electrical ADC was first proposed by Bell Labs in a study in 1989, and Francesco Laghezza et al proposed a time-interleaved optical ADC using TDM technology in 2013. In their work, the repetition rate of the optical pulse generated by the mode-locked laser was 400MHz [1, 2].

In order to advance the bandwidth and accuracy of ADC further, in this paper, a high-speed optical sampling system is presented, which consists of an optical switching matrix and a cavity-less pulse source based on modulators. A high-quality optical pulse with a repetition rate of 10GHz and a pulse width of 9.4ps is demonstrated, and used as the optical source of the high-speed optical sampling system.
with a high repetition rate up to 10GHz and 2.5GHz in each channel, also with an SNR of 30dB. This sampling system can be used into the advancements in radar and telecommunication systems with higher bandwidth and precision requirements.

2. Principle

2.1. Principles of the optical switching matrix

In the following section, the basic principle of the optical sampling time interleaved ADC will be introduced, as well as the main source of its nonlinearity. The selection of the system optical source should meet the following conditions: high pulse repetition rate, low time jitter, and narrow pulse width. The RF signal is optically sampled by the combination of D-MZMs with large bandwidth. And then, the sampling pulse is divided into four parallel signals with low sampling rate by TDM technology. This can significantly reduce the bandwidth, sampling rate and other demands of the related electronic equipments in the subsequent steps.

The main source of system nonlinearity comes from the optical modulator. According to the modulation depth, information about the input RF signal and its higher order harmonics is contained in the optical samples [2]. Other spurious tones of the optical switching matrix are given by:

\[
f = \left( k \frac{F_s}{M} \pm \sum_{n} f_{RF}^n \right) |_{k=1}^M
\]  

(1)

In which \( F_s \) is the system sampling rate, \( M \) is number of output channels, and \( f_{RF}^n \) are the RF signal harmonics calculated by:

\[
f_{RF}^n = n f_{RF} \mod \frac{F_s}{2}
\]  

(2)

While \( f_{RF} \) is the signal frequency. The principle above shows that both the sampling frequency and the RF signal harmonics affect the frequency of the spurious tones [1].

2.2. Principles of the cavity-less pulse source

When a chirped Gaussian pulse beam is transmitted in a dispersive medium, if the product of the chirp parameter and the group velocity dispersion parameter is positive, the pulse broadens as the transmission distance increases. If the product of chirp parameter and group velocity dispersion parameter is negative, the pulse begins to compress and then broadens with the increase of propagation distance. The chirped pulse is generated by a MZM and a PM series system, both of which are driven by a 10GHz sinusoidal pulse. The bias voltage is adjusted slightly below the quadrature bias point to slightly compress the pulse in the MZM, and then the pulse is frequency chirped in the PM. The chirped pulse is finally compressed in the dispersive fiber [7, 8].

It should be noticed that the width and the waveform of the production pulse are affected by the bias voltage of MZM, the amplitude of input signal, the phase difference between MZM and PM, the amplitude of PM input signal and the total dispersion. The cavity-less pulse source based on the above principle is applied to the sampling system, and the experimental setup of the whole system is shown in Figure 1, which consists of a cavity-less pulse source and an optical switch matrix.
3. Simulation
The simulation is built in Optisystem 15.0.0 and is mainly divided into two parts, a 10GHz cavity-less pulse source and a 10GHz TDM optical switching matrix.

3.1. Simulation of the cavity-less pulse source
The cavity-less pulse source uses a 1550nm CW laser as the optical source. An RF pulse source generates a 10GHz sinusoidal signal with 50% duty ratio, which is divided into two channels by a 6dB splitter, and one channel is launched into the MZM 1 after power adjustment, with its RF Vpi of 3.9 volts, bias Vpi of 4.6 volts, and the input signal power is determined to be 18.8 dbm by calculation. The other channel is launched to the PM after power adjustment at a value of 30dBm. According to the calculation, the total dispersion of the system is \( 2.483 \times 10^{-2} \) ps. The SM-DCF with dispersion rate of \(-80\) ps / nm / km is selected. The simulation results show that the pulse width is 9.4ps with the repetition rate of 10GHz. The simulation results of cavity-less pulse source in time domain are shown in Figure 2.

3.2. Simulation of the optical switching matrix
The optical source above is used to generate optical pulses with a repetition rate of 10GHz and a pulse width of 9.4ps, and a sine pulse with a duty cycle of 50% and a repetition frequency of 10 GHz is generated by the electrical RF pulse source. Two low-noise divide-by-2 frequency dividers are used to divide the sine pulse. The sine pulse is divided into a repetition rate of 5 GHz and 2.5 GHz and then put
into the first and second stage of D-MZM 1 to D-MZM 3 respectively with the RF Vpi of 3.9 volts and the bias Vpi of 4.6 volts. In order to ensure the effect of TDM and frequency division, suitable adjustable time-delays are added before the first and second stage of optical switching matrix the respectively, and make the two pulse phases after frequency division consistent with the carrier phase. An erbium-doped fiber amplifier (EDFA) is used to compensate the total optical loss of about 12dB in the two-stage D-MZMs. This work focuses on the output results from four channels and mainly divided into two parts, the quality of the single channel output result and the consistency of the total four output results. According to the basic principle of the modulator, especially in order to ensure the consistency of four output results, both the RF input and the bias input of the D-MZMs should be strictly calculated and controlled, and the RF inputs of the D-MZMs are finally determined to a value of 15.8dBm. The final simulation results of four outputs are consistent, and with the pulse width of 9.4ps and the repetition rate of 2.5GHz as expected. The simulation results of the whole system in time domain are shown in Figure 3. Only the results of 2 channels are shown in the figure and an additional phase difference is added between the channels to facilitate the display of the results.

![Figure 3. Simulation of the optical switching matrix in the time domain. Blue solid line: channel one; red dashed line: channel two.](image)

### 3.3. A relevance between system SNR and phase difference

A phase difference due to the wires, the fibers and other components is quite common in the experiment and may finally affect the performance of the sampling system strongly according to its effect on the SNR. An optical pulse with lower pulse width could reduce this and make the system more stable. A relevance between the output SNR and the phase difference of D-MZM 1 is shown in Figure 4 and it changes in period. It is noted that this period is mainly determined by the stage of the optical switching matrix with 200ps on the first stage of D-MZM 1 and 400ps on the second stage of D-MZM 2 and D-MZM 3 respectively, and it may be more unpredictable with phase differences on both stages.

![Figure 4. Output SNR affected by phase difference.](image)
4. Experimental demonstration

In the experiment, most of the parameters are calculated in the same way as those in the simulation system and will not be repeated here, and the whole system is built according to the experimental setup above (Figure 1). It is noticed that due to the different lengths of the wires and the fiber, additional time-delays needs to be added to reduce the phase difference and ensure that the effect of the frequency division meets the requirements. Another difficulty is that due to the large number of electrical components used in the experiment and their different losses, it is difficult to control the electrical RF input power of the first and second stage of the D-MZMs to be fixed at 15.8dBm, therefore, two combinations of fixed power amplifiers and adjustable attenuators are used in the experiment. Photodetectors with power gain function are used in the experiment, and the results are observed on an oscilloscope with a sampling rate of 40GHz/s and a high-performance spectrum analyzer.

When the optical input power of the CW laser is 18dBm and the electrical input sinusoidal pulse amplitude is 11dBm, the SNR of the sampled pulse is about 30dB. Like the simulation, only the results of 2 channels are shown in the figure and an additional phase difference is added between the channels. The experiment results of the whole system in time domain and in frequency domain are shown in Figure 5 and Figure 6.

![Figure 5](image1.png)

**Figure 5.** System outputs in the time domain. Blue solid line : channel one; red dashed line : channel two.

![Figure 6](image2.png)

**Figure 6.** System outputs in the frequency domain.

5. Conclusion

Our work presents a high-speed TDM optical sampling system that can be used in laboratory or industrial design. The system is simulated in Optisystem 15.0.0 and brought about in experiments. It can be applied to various occasions that require high-speed optical sampling technology. The cavity-less pulse source provides high-quality optical pulses with a pulse width of 9.4ps and a repetition rate of 10GHz. The frequency division of high-speed RF signals is achieved through two-stage D-MZMs, and finally four channels with a repetition rate of 2.5GHz and an SNR of 30dB are obtained. Compared with the previous optical switch matrix based on TDM, our optical source used in this system maintains a low cost, and the repetition rate also increases from 400MHz to 10GHz. This sampling system can be
scaled to larger bandwidth, higher accuracy and used into the advancements in radar and telecommunication systems.

Acknowledgement
This work has been supported by the NSFC #61801037.

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