18 wavelengths 83.9Gs/s optical sampling clock for photonic A/D converters

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Abstract: In this paper, a simple approach to generate the time-wavelength interleaved sampling clock for photonic A/D converters is proposed using commercially available mode-locked femtosecond fiber laser and optical wavelength/time division multiplexing (WDM/OTDM) techniques with low cost passive optical components. A time and wavelength mapping module is configured using specially designed wavelength division multiplexer and mechanical tunable fiber stretchers. OTDM modules with low optical insertion loss and flexibly configurable multiple factor are implemented with the fused-biconical optical fiber couplers. Experiment is carried out using 18 WDM channels and 128 times OTDM to demonstrate the generation of 83.9Gs/s time-wavelength interleaved sampling clock.

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1. Introduction

In order to overcome the limitation of electronic analog-to-digital converters (EADCs) in ultra high speed applications, such as high performance communications, advanced radar and electronic instrumentation, etc., photonic ADCs (PADCs) have been proposed as a promising

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alternative with the unique features of ultra stable and high-speed sampling, broad bandwidth, and nearly lossless signal remoting [1,2]. In many schemes studied so far, the wavelength-division multiplexing(WDM) based photonic ADC, which employs time-wavelength interleaved optical sampling and electronic quantization, is one of the most practically feasible methods [2,3]. Its crucial issue is the generation of time-wavelength interleaved sampling clock [3,4]. Multiple lasers with different wavelength, multiple wavelength laser, and spectral slicing of single broad bandwidth laser are three typical ways to generate such clock [5–7]. Spectral slicing approach is relatively cost-effective and mature. Unfortunately, broadband lasers with high repetition rate are not commercially available yet. There are two methods to solve the problem. One is to use super continuum generation to broaden the spectral width of mode-locked picosecond fiber laser with gigahertz repetition rate [8]. The other is to increase the repetition rate of broadband femtosecond fiber laser by optical time division multiplexing (OTDM). In this paper, we present a simple approach to generate high-repetition-rate time-wavelength interleaved sampling clock with channels more than ten using commercially available broadband femtosecond fiber laser and low cost optical passive devices. The relative key techniques such as low loss and braodband WDMs, large multiple factor OTDM and the low cost precise delay control are studied. An 18 channels 83.9Gs/s time-wavelength interleaved sampling clock is generated. The number of channels is important for achieving WDM based PADCs with high sampling rate since the sampling rate of the single channel is limited by the sampling rate of EADCs used in back end, whose ENOB(effective number of bits) of EADCs decreases with its bandwidth. The state-of-art resolution of commercially available EADCs is about 8 around 4 Gs/s, e.g. EV10AQ190 from e2v (8.7 @ 5 Gs/s). In order to reach 80Gs/s PADC system with ENOB of 8, about 20 channels are needed.

2. System architecture

The architecture of photonic ADC based on WDM is shown in Fig. 1. The multiple wavelength interleaved pulse generator (MWPG) is used to generate time-wavelength interleaved optical sampling pulse train. The optical sampling pulse train inputs to an electro-optic modulator (EOM) to sample the RF signal, and then is demultiplexed to multiple wavelength channels. On each wavelength channel, the sampling optical signal is detected by a photo detector (PD) and quantized by EADCs. The quantized data on each channel are combined to form the digitized result of the RF analog signal in digital processing unit.

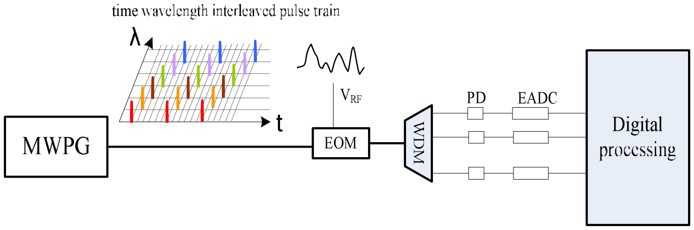

Fig. 1. The architecture of photonic ADC based on WDM

Figure 2 shows the proposed architecture of MWPG. Pulses from a broadband mode-locked femtosecond fiber laser (MLFLL) at the repetition rate of f are input to a time and wavelength mapping module (TWMM), which spectrally slices each input pulse into N pulses of different wavelengths and maps the sliced pulses to different time positions with appropriate fiber delay lines (FDLs) to form a pulse train as shown in Fig. 2. The output pulse train from TWMM is then sent to an OTDM module with multiple factor of M to generate the time-wavelength interleaved sampling clock with the interval $1/(f \times N \times M)$.

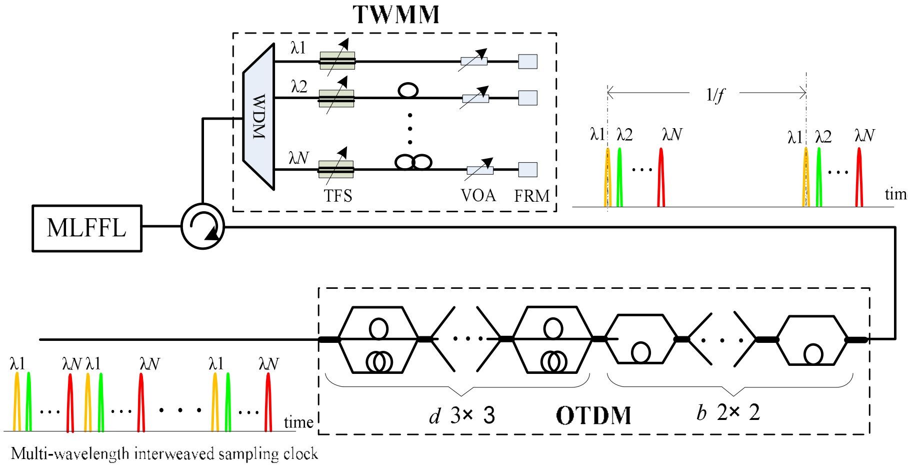

Fig. 2. Experimental setup of the time-wavelength interleaved sampling clock generator (FRM: Faraday Rotation Mirror, VOA: Variable Optical Attenuator, TFS: Tunable Fiber Stretchers)

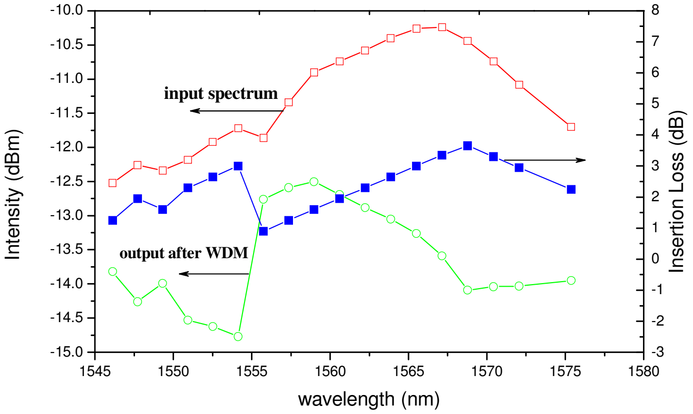

Fig. 3. The insertion loss of a specially designed 18-channel WDM according to the spectrum of MLFFL used

In order to generate the optical sampling clock with equal amplitude, the power balance is needed. Theoretically, Variable optical attenuators (VOAs) with fine resolution can be used to solve the problem. However, it brings about extra loss and may limit the resolution, especially when the power difference is large. The insertion loss difference between WDM ports and the nonuniformity of the laser optical spectrum are two main factors leading to the unequal pulse amplitude. The power difference between channels will be enhanced when the effects of the two factors are positively added. Therefore attention should be paid in parameter selection and implementation of devices, including WDM, Faraday rotation mirror, tunable fiber stretchers, etc. We employed TTF (thin film filter) based WDM. As is known, such WDM has nonuniform channel insertion loss due to cascaded configuration. We arranged the channels according to the laser spectrum, rather than the wavelengths, in such a way that channels with larger insertion loss (which undergo more reflections) are located at the wavelengths that have higher power in the laser spectrum. Figure 0.3 shows the insertion loss (IL) of each port of a specially designed 18-channel WDM with channel spacing of 200GHz according to the spectrum of the femtosecond fiber laser we used. It can be seen that the loss is worsen unseriously.

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The OTDM module in Fig. 2 consists of b and d stages of 2 × 2 and 3 × 3 cascaded optical fiber couplers, respectively. Hence appropriate M ($= 2^b + 3^d$) can be obtained flexibly by selecting b and d. The fused-biconical 2 × 2 fiber couplers are placed before the 3 × 3 ones. In such arrangement, the optical power loss, IL_{OTDM} , of the OTDM module consists only of the excess loss of each coupler and the insertion loss of the last coupler. If the excess loss of each coupler is the same, we have:

$$IL_{OTDM} = \sum_{i=1}^{b} EL_i^{2\times2} + \sum_{i=1}^{d} EL_i^{3\times3} + IL^{l\times l} \tag{1}$$

where $EL_i^{2\times2}$ and $EL_i^{3\times3}$ are the excess loss of the 2 × 2 and 3 × 3 couplers, respectively; $IL^{l\times l}$ is the insertion loss of the last coupler ($l = 2$ for 2 × 2 coupler and $l = 3$ otherwise). In addition to provide flexibility in determining M, the use of 3 × 3 couplers can also minimize the coupler stages [9].

3. Experimental results and discussion

An 83.9Gs/s time-wavelength interleaved sampling clock is generated using 18 WDM channels and 128 times OTDM based on above architecture. The mode-locked femtosecond fiber (Precision Photonics, FFL1560) laser used in the experiment produces 70-fs pulses at a repetition rate of 36.44 MHz with average power of 40 mW. Its central wavelength is at 1560nm with 45 nm full width at half maximum (FWHM). The 18 channels WDM specially designed for the TWMM has channel spacing of 200GHz with 3dB bandwidth of 1.2nm. A WDM construct with two skip filters (8-skip-0 and 8-skip-3) is adopted to guarantee the maximum port insertion loss is less than 3.6dB. The 128 times OTDM module is implemented using 8 fused-biconical 2 × 2 cascaded fiber couplers with excess loss less than 0.15 dB and uniformity less than 0.08dB. In such arrangement, the average optical power loss of the OTDM module is less than 4.2dB according to Eq. (1). In order to minimize the effect of the fiber dispersion on the timing jitter, the OTDM is implemented based on the central wavelength of the spectrum used, and the residual dispersion induced time jitter in OTDM is compensated in the WDM part through the method proposed in ref [10]. The precise fiber delay in TWMM and OTDM module is implemented by a manipulation method with precision around 2 ps [11] and manually tunable mechanical fiber stretchers (MTMFS) which can work stably with resolution of 0.04ps [10]. Fiber based VOAs, rather than space optical based ones, are used to reduce the back reflected interference.

Figure 4 shows the OTDM pulse output for one WDM channel observed using a 50GHz photodetector (PD) and a 60GHz digital sampling oscilloscope (Tektronix, TDS8200). The sampling rate is about 4.66Gs/s, corresponding to a pulse interval of 1/(36.44 × 128) = 214.39ps. The full width at half maximum of pulses is broadened from 4.18ps (measured using autocorrelator FR-103XL) to about 14ps [see Fig. 4(b)] due to the limited bandwidth of the PD and the oscilloscope used, which make us unable to record 18 wavelengths 83.9Gs/s sampling clock using the 60GHz oscilloscope directly.

In order to observe the 18 wavelengths 83.9Gs/s sampling clock, we measure the optical pulse train of even number channels and odd number channels referring to a common pulse, respectively, then display them together using the WaveStar software from Tektronix, Inc. Figure 5(a) shows the pulse trains of 9 even channels and 9 odd channels, respectively. Figure 5(b) shows the corresponding spectrum in the two cases. Figure 6 shows the spectrum of time-wavelength interleaved sampling clock of 18 wavelengths and the composed 18 channels 83.9Gs/s pulse train.

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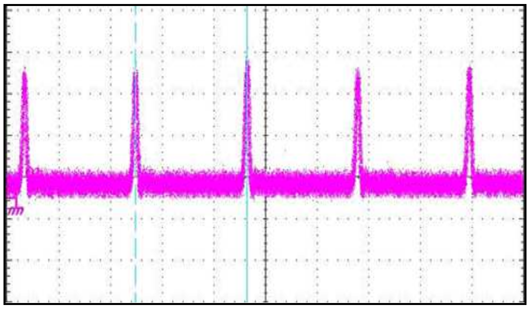
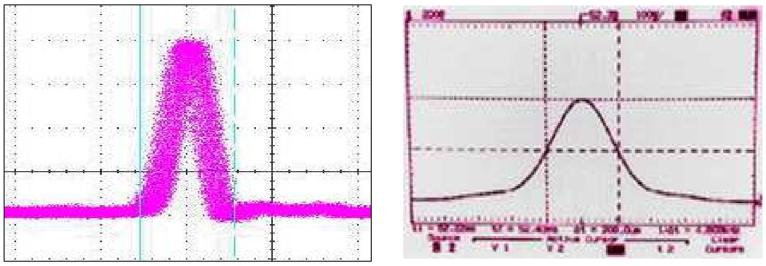


time (100 ps/div)

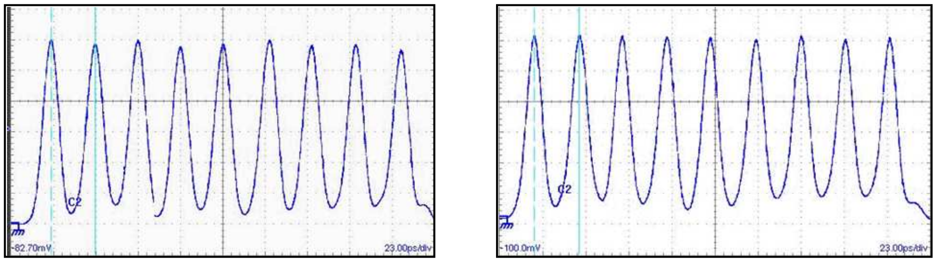
(a)



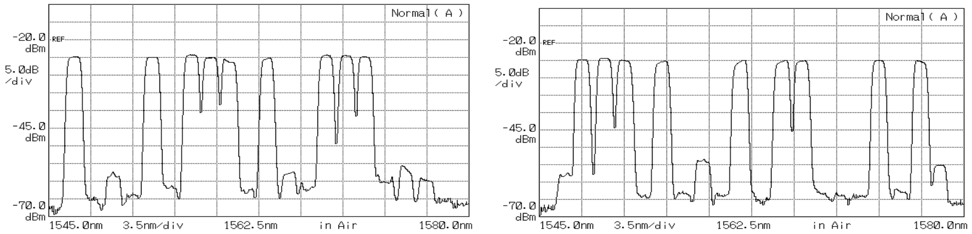
time (20 ps/div)

(b)

Fig. 4. OTDM pulse output for one WDM channel. (a) 4.66Gs/s pulse train measured using digital sampling oscilloscope. (b) pulse width observed by a digital sampling oscilloscope (left) and its autocorrelator curve (right).



time (23ps/div) (a) time (23ps/div)



(b)

Fig. 5. (a) The optical pulse trains of 9 channels with even number (left) and 9 channels with odd number (right). (b) Corresponding spectrum.

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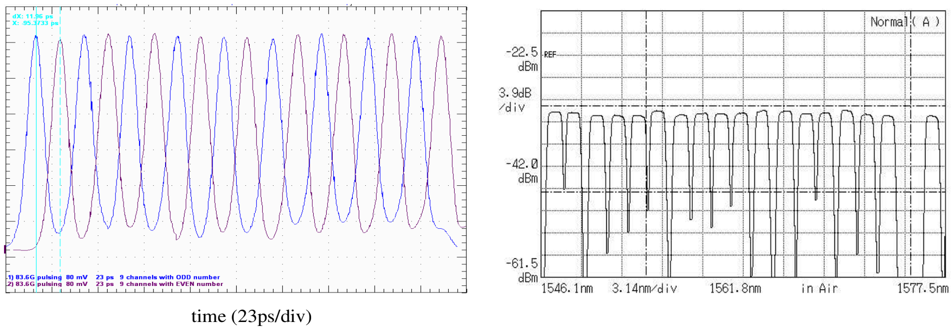

(a) (b)

Fig. 6. The composed 18 channels 83.9 Gs/s pulse train (a) and the spectrum of time-wavelength interleaved sampling clock (b).

The timing jitter and amplitude jitter of the optical clock in Fig. 3(a) and Fig. 6, which have an important impact on the performance of the photonic ADC [12], are approximately 200fs and 2.66%, respectively measured using TDS8200. The main sources of timing jitter are from the laser source, the fiber dispersion, and the precision in delay control. The timing jitter and the amplitude instability of laser in our experiment, which is random, are less than 150fs and 1%, respectively. The timing error related to the fiber dispersion and delay control precision is deterministic and has been reduced from over 1ps to less than 100fs in our previous work [10]. Therefore, less than 100fs timing jitter may be reached by using a broadband laser source with time jitter less than 10fs. The amplitude fluctuation is mainly caused by nonuniformity of couplers and the difference of insertion loss on different paths in the OTDM. For this reasons, we used 8 stages of 2 × 2 coupler to build 128 times OTDM since it is more difficult to control the coupling coefficient of 3 × 3 couplers. Furthermore, the amplitude error related to the nonideal component is deterministic, which can be greatly reduced by the calibration of PADC systems [13]. Figure 7 shows the preliminary result on the correction of deterministic amplitude errors in our system by calibration. The calibration is based on the measured amplitude fluctuation of the optical clock in corresponding wavelength channel. The fluctuation is than removed from the sampling result (in our experiment a standard sine is used as the sampled signal) as a fixed background error. From the Fig. 7, we can see that the amplitude errors can be suppressed obviously after calibration. The root mean square (RMS) of the amplitude errors is reduced by about 50%.

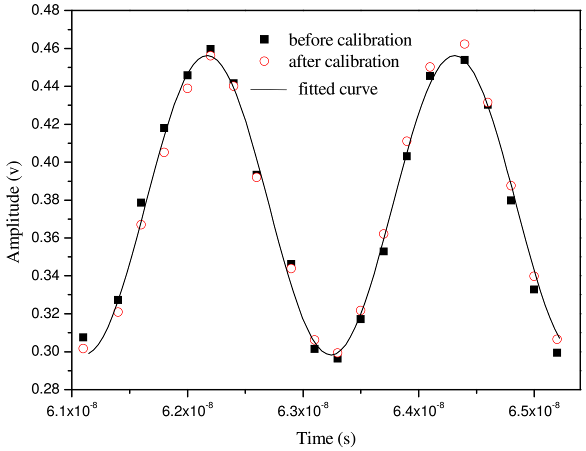

Fig. 7. The correction of amplitude errors in sampling a standard sine signal.

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4. Conclusion

The generation of time-wavelength interleaved sampling clock is one of the key issues for WDM based photonic ADC. We presented a simple approach to generate high repetition rate time-wavelength interleaved sampling clock with channels larger than ten by combining a commercially available broadband low-repetition-rate femtosecond fiber laser and optical wavelength/time division multiplexing techniques. A time and wavelength mapping module is configured using a specially designed 200GHz-channel-spacing WDM and manually tunable mechanical fiber stretchers. An OTDM module with low insertion loss and flexible multiplexing factor is proposed with the low cost fused single-mode fiber couplers. Generation of 18-wavelength 83.9Gs/s time and wavelength interleaved optical sampling clock is demonstrated using an 18-channel WDM and a 128 times OTDM.

Acknowledgments

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