Photonic Analog-to-Digital Converters

Kenaish E. Al Qubaisi, Anatol Khilo

Institute Center for Microsystems (iMicro), Masdar Institute of Science and Technology,
Abu Dhabi, United Arab Emirates

Abstract

Photonic analog-to-digital conversion technology is considered a promising option to extend the performance of analog-to-digital converters (ADCs) to new levels by eliminating the bottleneck of aperture jitter. In this work, we review some important approaches to photonic ADCs and review recent developments in the field. We consider one particular scheme for photonic ADC conversion which uses optical sampling, wavelength demultiplexing, and electronic digitization; an important advantage of this scheme is that it can be implemented on a silicon chip as an electronic-photonic integrated circuit. We analyze important fundamental and practical limits to ADC performance which can be achieved with this scheme.

1. Introduction

Photonic ADCs has been a topic of research for several decades [1]. One advantage of photonic ADCs is that they are capable of eliminating the problem of electronic jitter, which is one of the most difficult problem facing further progress in electronic ADCs. Photonic ADCs do it by performing sampling in optical domain using ultra-stable optical pulse trains generated by mode-locked lasers [2-10]. Multi-channel operation can be achieved by using time- or wavelength-demultiplexing [3, 7, 8, 10], thus increasing the overall sampling rate of the ADC and eliminating the problem of comparator ambiguity. Time-stretching technique, which works by dispersive stretching of a modulated chirped optical signal, can increase the temporal resolution of photonic ADCs by orders of magnitude [4-6]. A different approach based on four-wave mixing in optical fibers has recently been demonstrated to enable highly accurate digitization of high-bandwidth RF signals [8]. The approach based on optical sampling with an electrooptic modulator and wavelength demultiplexing with filter banks [2, 3] has been shown to lead to high-performance ADCs [7]; an important advantage of this approach is that it can be realized on a monolithic silicon chip using recent advances in silicon photonic technology and electronic-photonic integration.

2. Optically-Sampled Analog-to-Digital Converters and Their Limits

In this work we consider an optically-sampled wavelength-demultiplexed photonic ADC; a conceptual layout of such ADC is shown in Fig. 1 [2, 3, 7].

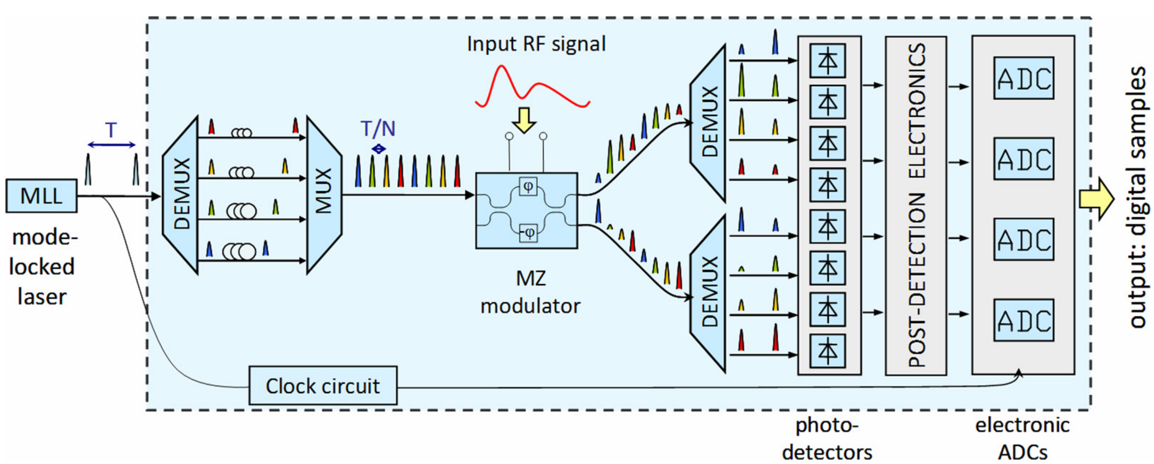

Fig. 1. An optically-sampled wavelength-demultiplexed ADC, converting an analog wideband RF input into digital samples at the output.

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A mode-locked laser generates a train of optical pulses with ultra-stable timing intervals between them. This pulse train is modulated in a fast electrooptic modulator with an RF signal which needs to be digitized; at the output of the modulator, the energy of each pulse is proportional to the value of the RF signal at the corresponding time moment. Because the time interval between optical pulses is very stable, this results in sampling with very low aperture jitter. The modulated optical pulses are then detected with photodetectors to generate pulses of current, which are then amplified and converted to digital samples using electronic ADCs. To improve the sampling rate of the photonic ADC, a scheme with multiple wavelengths is used. In this scheme, each pulse of the mode-locked laser is separated into *N* sub-pulses, each at different center wavelength, using a filter bank. These sub-pulses are then delayed by different amounts and re-combined into a single pulse train, which now has its repetition rate increased by a factor of *N*. After the modulator, different wavelengths are taken apart by a filter bank, and each wavelength is processed independently with its dedicated photodetector and electronic ADC.

To be a feasible competitor to electronic ADCs, it is highly desirable that a photonic ADC is implemented on a compact silicon chip. The scheme described above satisfies this criteria; all operations described above can be realized with silicon photonic components, except possibly for a mode-locked laser, which needs to be implemented separately, perhaps as another chip. With problem of aperture jitter removed, the accuracy of an integrated photonic ADC will depend on other factors, such as linearity of an electrooptic modulator, signal power at the photodetectors and signal-to-noise ratio (SNR), fluctuations of optical filter characteristics with temperature, and nonlinear optical phenomena in silicon waveguides. The nonlinear phenomena are most prominent inside the optical resonator filters because of the internal power enhancement. Inside the filter, two-photon absorption (TPA) leads to generation of free carriers; free carriers shift the filter resonance via free-carried dispersion (FCD) and absorb light via free-carrier absorption (FCA). This can reduce the accuracy of the ADC as illustrated in Fig. 2 for one example of photonic ADC parameters. In this work, we analyze the silicon nonlinearity and other factors which can limit the performance of an integrated photonic ADC, and discuss ways to overcome these limitations.

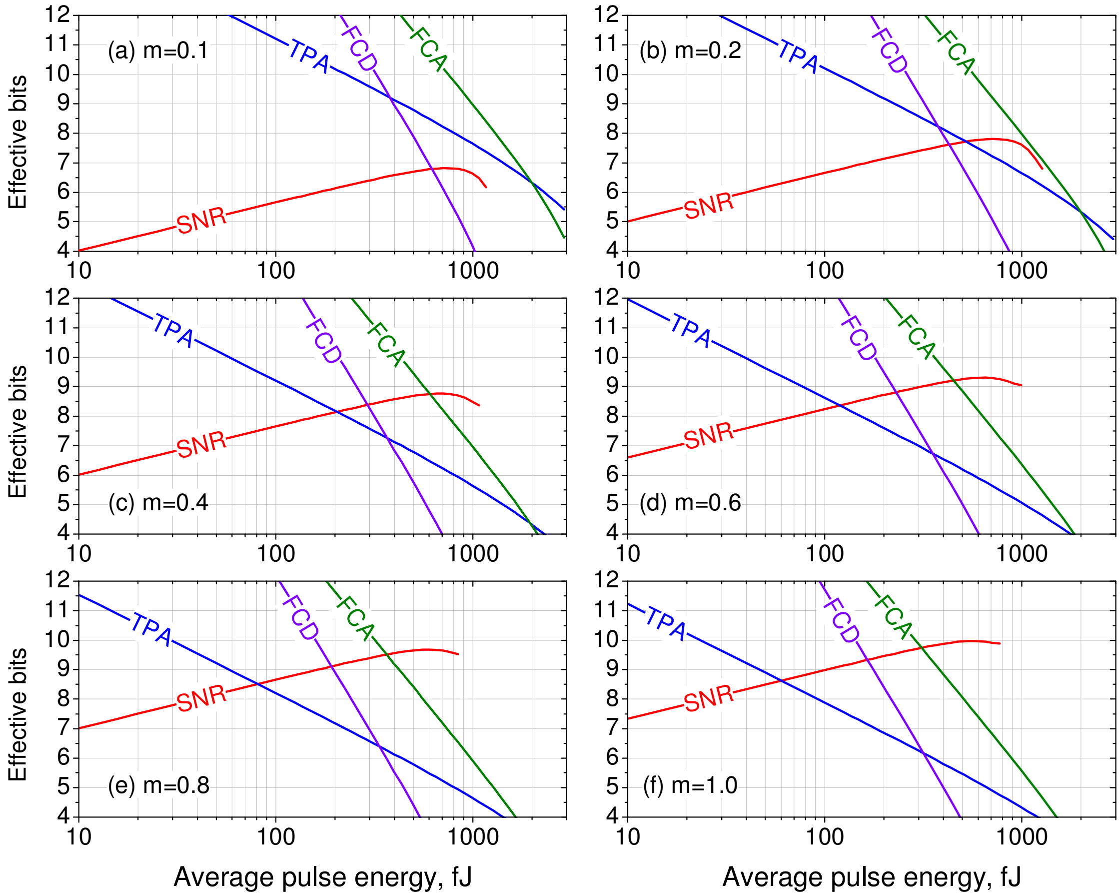

Fig. 2. Effective number of bit (ENOB) in a photonic ADC vs. average optical pulse energy at the output of a silicon micoring resonator filter with finesse=80. In (a)-(f), the modulation depth *m* is 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0, respectively.

3. References

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