Photonic analog-to-digital converter using soliton self-frequency shift and interleaving spectral filters

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We propose a novel ultrafast photonic analog-to-digital converter that uses the soliton self-frequency shift in an optical fiber as an optical power-to-frequency conversion mechanism and a set of interleaving spectral filters as the optical comparators. Our method does all the signal processing in the optical domain and requires binary receivers in only the electronic domain. In contrast to the usual exponential scaling, the simultaneous binary search architecture that we propose results in a flash analog-to-digital converter with remarkable linear scaling between the number of comparators and the number of bits resolved. © 2003 Optical Society of America

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Analog-to-digital converters (ADCs) are widely viewed as a bottleneck in high-performance communication and radar. Although the speed of signal processing has improved tremendously in the past decade or so, improvements in ADC speed and resolution have been much slower.[1] The growing gap between processing speed and ADC speed underscores the need for brand new concepts and revolutionary improvements in ADC performance.

Photonic ADCs have attracted much attention recently.[2] The main advantage of photonic ADCs over electronic ADCs is the ultrastable optical sampling pulses.[2] There are several techniques for applying optics in ADCs.[3–6] Although the time-division multiplexing concept[7,8] is straightforward, it typically requires a large number of active switches for demultiplexing of the signal, and thus the issues of synchronization and extinction ratio arise. Wavelength-division multiplexing techniques are attractive because of their completely passive demultiplexing,[9,10] but they are hampered by the requirement for a complex source that must generate a periodically repeating multiwavelength pulse train with very precise interpulse spacing at a very high repetition rate.[10]

Here we propose a novel photonic ADC method that does all the signal processing in the optical domain and requires binary receivers in only the electronic domain. Our design in large part parallels that of a dense wavelength-division multiplexing transmission system and takes advantage of the recent advances in fiber-optic communication, generating synergies between the two fields.

Soliton self-frequency shift (SSFS) is a well-understood phenomenon in fiber-optic communications. First discovered approximately 16 years ago in soliton transmission experiments,[11,12] SSFS recently attracted renewed attention.[13–15] The availability of short-pulsed sources and optical amplifiers, together with some novel fiber structures, has made SSFS easy to observe.[14,16]

Figure 1 illustrates the design of our high-sampling-rate, N-bit-resolution, all-optical ADC. The ADC consists of a high-repetition-rate (for example, 40 GHz), short-pulse (pulse width of 2 ps) optical source for sampling. The electrical-to-optical conversion may be carried out in a $\mathrm{LiNbO_3}$ Mach–Zehnder (MZ) modulator or some other electrical-to-optical transducer. After the modulator, the intensity modulated pulse train is amplified and then sent to a highly nonlinear fiber (HNLF, a fiber with a small core size and low dispersion). Because the amount of spectral shift in SSFS depends on the pulse power, SSFS can be used as a power-to-frequency converter, analogous to a voltage-controlled oscillator in the electronic domain. A $1 \times N$ fiber-optic splitter (N is the total number of bits resolved by the ADC) is placed at the fiber output after the SSFS. Each output is then sent through a passive periodic spectral filter that serves as a comparator with periodic reference levels. These filters can serve as the wavelength-channel interleavers that are routinely used in a dense wavelength-division multiplexing network (interleaving filters). The transfer function of the filter, i.e., the transmission band and stop band, is illustrated schematically in

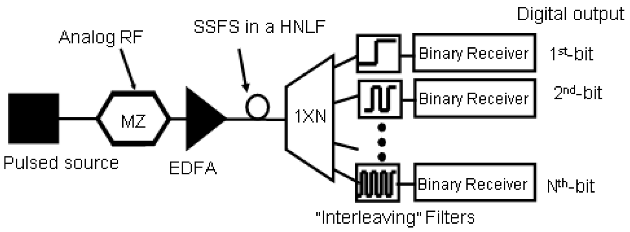

Fig. 1. (a) Illustration of an ultrafast, N-bit ADC with a SSFS and interleaving filters. EDFA, erbium-doped fiber amplifier.

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Fig. 2. Figure 2 also shows the principle of achieving 3-bit resolution with only three comparators. The scheme is essentially a simultaneous binary search: Filter 1 determines the most significant bit, filter 2 determines the next-to-highest significant bit, and so on. Although the binary search may seem to be analogous to successive or pipeline ADCs in the electronic domain, our method does not involve any successive steps or subsequent digital-to-analog conversion, and there is no pipeline. All the ADC action is carried out in a single step.

The binary receiver and the optical-to-electrical transducer response limit the sampling rate. Bandwidths near 100 GHz have already been demonstrated for modulators[17] and binary receivers, and 50-GHz devices are now commercially available. Thus, the sampling rate far surpasses the speed of traditional electronic ADCs. We also note that one can combine WDM parallel processing with our technique to increase the sampling rate to well beyond that of the binary receivers.[10]

One of the challenges for our photonic ADC is the resolution. The resolution of our system is determined by the amount of SSFS that is practically achievable and the resolution of the optical filter. The requirement for a set of well-calibrated interleaving filters should not be a major issue: Dense wavelength-division multiplexing fiber-optic transmission today can have channel spacing less than 25 GHz, and the frequency stability of these filters can be controlled to be within a fraction of a gigahertz. However, it is known that short-duration pulses and high peak powers are both required for achieving a large amount of SSFS.[11,13] Thus, there is a trade-off between the narrow filter width and the sampling-pulse temporal width. Here we propose a spectrum breathing technique that reduces the power requirement for SSFS and simultaneously solves the conflicting requirements of having a short temporal pulse desired for SSFS and a narrow spectral content needed for high-resolution optical comparison.

We realize that a short pulse is needed for the sampling and the subsequent SSFS and is not essential in the optical comparator and binary receiver. (After the SSFS, the information lies entirely in the frequency domain.) Thus, one can devise a scheme that uses short pulses for sampling and SSFSs and longer pulses with narrow spectral bandwidths for optical comparison and binary detection. There are several standard nonlinear optics methods for achieving the pulse width (and therefore pulse spectrum) oscillation, i.e., breathing. We propose to use dispersion-decreasing fiber [DDF; dispersion D varies from 5 to 0.5 (ps/km)/nm] to adiabatically compress the pulse by a factor of 10. Such a short pulse (~200 fs) is very efficient for achieving a large SSFS. After the SSFS, we use dispersion-increasing fiber (DIF) to adiabatically restore the original pulse spectrum. Note that we can use the same DDF as a DIF by reversing the propagation direction via a circulator (Fig. 3), which also reduces the physical length of the HNLF by a factor of 2. A Faraday rotating mirror (Fig. 3) will be used to suppress the polarization-dependent effects in the fiber so that polarization-maintaining fiber may not be necessary.[15] Figure 4 shows the numerical simulation results of the spectral evolution with the parameters illustrated in Fig. 3. For an estimation of the resolution, we show numerical simulation results in Fig. 5. With a 35-nm total SSFS, 5-bit resolution can be obtained. The resolution can be further improved by additional pulse-spectrum compression. For example, one can add an adiabatic spectrum-compression stage by using distributed loss in a standard single-mode fiber [SSMF; $D = 17$ ps/(nm/km)]. The loss of the SSMF can be intentionally made as high as 1 dB/km by microbending or macrobending of the fiber so that the soliton will further compress its spectrum. Because the soliton period of an 8-ps soliton in SSMF is approximately 1 km, spectral compression by another factor of 4 should be obtainable without using excessively long SSMF. Thus, there is the promise of resolution greater than 6 bits.

We realize that, as the center frequency of the pulse starts to shift as a result of the SSFS in the optical fiber, the pulse timing starts to walk off because of the

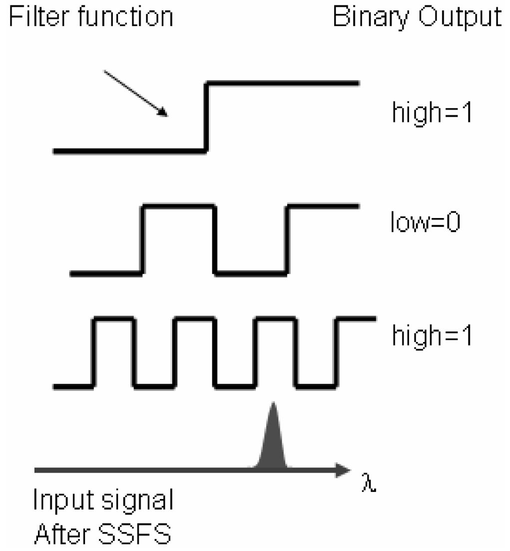

Fig. 2. Binary search with interleaving filters. Only three comparators instead of the usual eight (2^3) are needed for 3-bit ADC resolution.

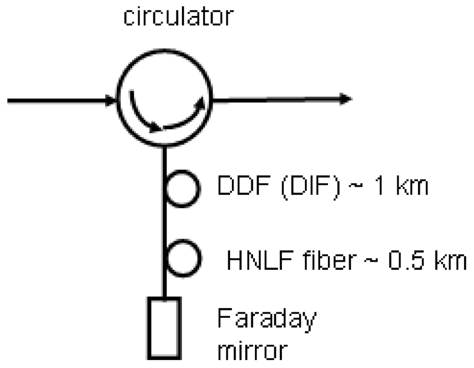

Fig. 3. (a) Schematic illustration of the spectrum breathing setup. Approximately 1 km of DDF (DIF) and 0.5 km of HNLF are necessary.

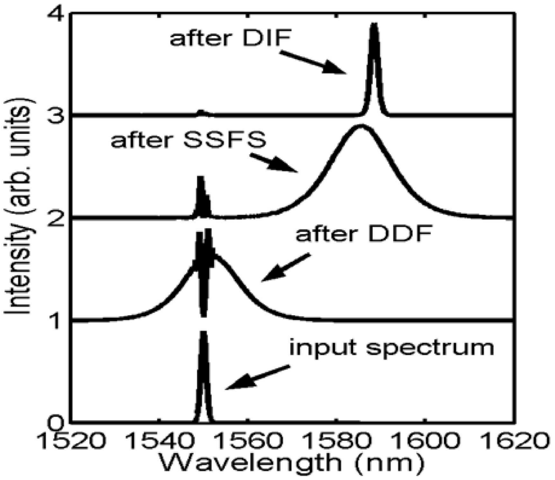

Fig. 4. Numerical simulation of the spectral evolution of an input pulse propagating through the fiber setup in Fig. 3 (DDF–HNLF–DIF). The input pulse width is 2 ps.

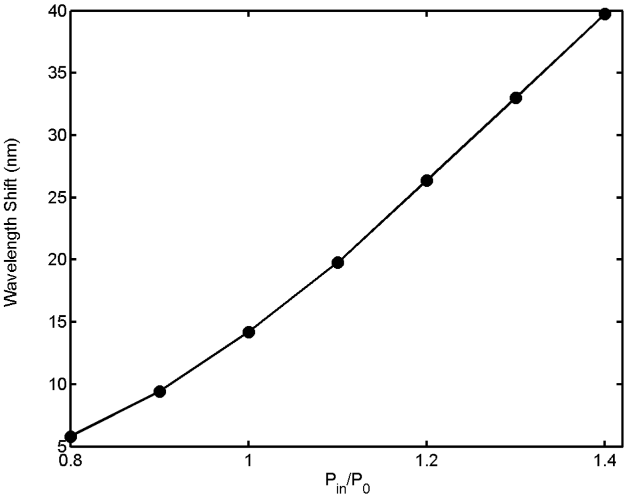

Fig. 5. Numerical simulation of SSFS as a function of input pulse power (P_{in}). P_0 is the fundamental soliton power needed at launch.

local dispersion, introducing a frequency-dependent timing shift. Fortunately, such a timing shift can be completely compensated for by dispersion-management techniques. Soliton collisions should not occur in the HNLF if we limit the total spectral shift to less than 40 nm and use a low-dispersion fiber (which is also necessary for the power budget). In addition, because the timing-jitter tolerance increases exponentially with the decreasing number of bits, a binary receiver can tolerate a fairly large amount of timing jitter.[1,2] Amplitude noise due to amplified spontaneous emission should be negligible because of the high pulse energy.

Although the SSFS has been used as an optical power-to-frequency converter in the past,[18] our method differs significantly from that in the previous report. Our spectrum breathing technique makes possible a large SSFS while maintaining a narrow spectral bandwidth and, thus, high sampling rates with high resolution. More importantly, our proposed signal processing method using a set of interleaving filters results in a flash ADC with remarkable linear scaling between the number of comparators and the number of bits resolved, instead of the usual exponential dependence. Finally, we note that the 1 × N splitter and the interleaving filters can potentially be integrated on the same wafer, making our proposed scheme more compact and robust.

In summary, we have proposed a novel photonic ADC method that does all the signal processing in the optical domain and requires binary receivers in only the electronic domain. Our idea centers on using the SSFS in an optical fiber as an optical power-to-frequency converter. The resulting optical output is processed by a set of interleaving filters that serve as the optical comparators. Because the final optical output is already in a digital binary format, one can use digital linearization techniques and clock recovery without adding any system complexity. Based on our numerical simulations, a resolution of greater than 6 bits can be achieved at 40 Gsamples/s with existing commercial devices.

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