Optical Spatially Quantized High Performance Analog-to-digital Conversion

Mona Jarrahi, David A. B. Miller, R. Fabian W. Pease, Thomas H. Lee
SMIRC Lab, Stanford University, Stanford, CA, 94305-4070
Tel: (650) 497-0565, Fax: (650) 735-3383

Abstract: We present an optical spatial quantized analog-to-digital converter (ADC) and experimentally demonstrate 8-level quantization consuming only 7.2pJ per quantization operation. Measured 8ps full-width half-maximum photodetector outputs, promises the potential of realizing a 3bit 125GS/s ADC.

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A number of photonic sampling techniques have been proposed that avoid the jitter of electronic sampling by using mode-locked laser technology [1]. Those ADC's employ electronic quantization which limits the sampling speed due to the ambiguity of comparator circuits [2]. Power consumption also limits ADC operating frequency [2, 3]. Here, we describe a photonically-sampled ADC in which quantization is accomplished by using the analog voltage to steer the sampling pulse to different regions of an array of detectors. We experimentally demonstrate 8-level quantization consuming only 7.2pJ per quantization operation with a bandwidth of 18GHz and 8ps full-width half-maximum (FWHM) photodetector outputs, thus showing the potential of realizing a 3bit 125GS/s ADC.

Each optical pulse from a mode-locked laser is coupled into an input waveguide and is then split and propagated down two waveguide branches (fig. 1a). A traveling wave phase modulator is integrated in one of the branches to vary the phase of the optical pulses according to the analog voltage. After passing through the interferometer arms, the optical beams from the two branches enter a slab waveguide region allowing free propagation in the lateral direction that permits the beams from the two branches to diverge and interfere. The resulting interference pattern forms, on an effective image plane, a spot whose position depends on the phase difference between the two optical pulses. In effect, the phase modulator and the free-propagation region together steer the spot according to the modulating voltage. Placing photodetectors at appropriate positions along the image plane enables measurement of the spatial distribution of optical power. Moreover, connecting photodetectors in a binary fashion allows us to resolve the output bits of the ADC.

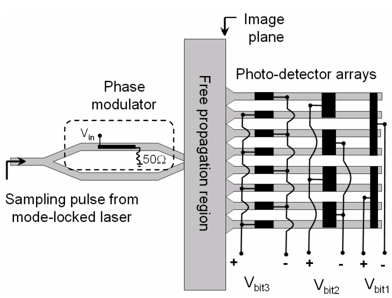

Fig1. Architecture of the 3-bit spatially quantized ADC

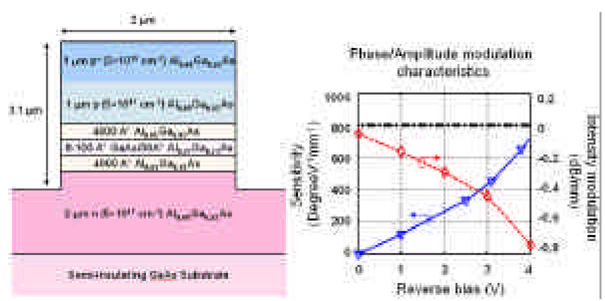

Fig2. Phase modulator cross section and modulation characteristics

The phase modulation mechanism is based on the quantum-confined Stark effect, in which an applied perpendicular electric field induces a shift in the absorption spectrum, and an accompanying shift in the refractive index of a multiple quantum well structure [4]. Multiple quantum well layers are designed as integral parts of the intrinsic region of a p-i-n diode integrated inside the optical waveguide. The phase modulating electric signal propagates on a coplanar waveguide (CPW) along the optical waveguide, allowing a long modulation path while maintaining a small junction area for achieving high modulation bandwidth and efficiency at the same time. The CPW metal electrode structure is designed to have a characteristic impedance of 50ohm and a propagation constant set to allow for the phase modulating electric signal to travel in phase synchronism with the light. A schematic diagram showing the cross-sectional view of the waveguide phase modulator and the measured phase/amplitude modulation characteristics at the wavelength of 870nm are shown in figure 2. Photodetectors, monolithically fabricated along the output waveguides, consist of an active region with a 50ohm termination.

A die micrograph of the fabricated ADC is shown in figure 3a. The phase modulator is 1.5mm long and the free propagation region is 350um long. Lengths of 50um, 150um and 400um are chosen for the 1st, 2nd and 3rd bit detector arrays respectively. 150fs optical sampling pulses from a Ti-sapphire mode-locked laser operating at 870 nm are coupled into the input waveguide. The resolved ADC bits within a $\pm$100mV voltage range, at an input energy of 68fJ per optical pulse are shown in Figure 3b. In order to realize a complete ADC, we can utilize high gain stages prior to digital circuits to match the output voltage with the technology logic levels. Figure 3c shows the transient pulse response of a 400um detector, measured by a pump-probe electro-optic (EO) sampling technique [5]. The measured 8ps full-width half-maximum (FWHM) value at 6V reverse-bias indicates the capability of the photo-detector to detect optical pulse trains at up to a 125GHz repetition rate.

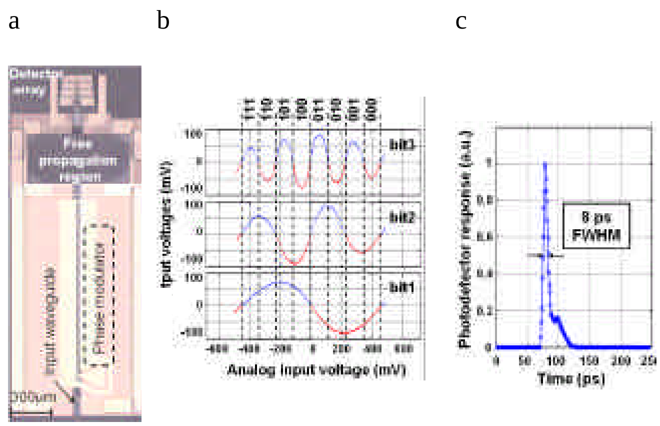

Fig3. (a) ADC micrograph (b) ADC resolved bits at 68fJ per input pulse energy (c) Photodetector transient response to a 150fs-wide pulse

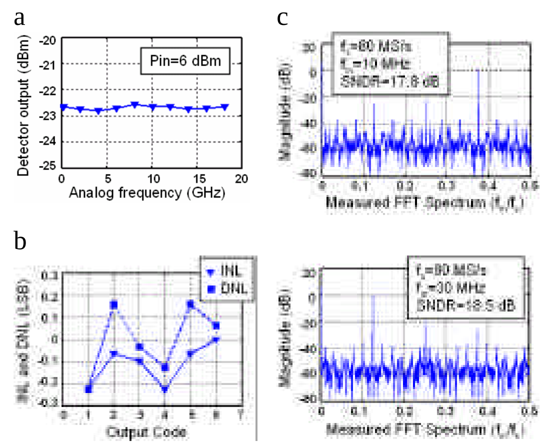

Fig4. (a) ADC bandwidth (b) INL/DNL (c) Measured FFT spectrum for f_s=80MS/s

Because of the limited mode-locked laser repetition rate, the bandwidth performance of the ADC is investigated by monitoring the frequency response of the ADC least significant bit (LSB) to a 6dBm sinusoidal analog source under laser continuous-wave operation. The measured frequency response, shown in figure 4a, indicates an instrument-limited operational bandwidth of 18GHz. The linearity of the ADC is characterized by measuring the differential nonlinearity (DNL) and integral nonlinearity (INL) during ADC DC operation. Figure 4b shows the static INL and DNL error of less than 0.2LSB. The main source of nonlinearity is the phase modulation nonlinearity with respect to the modulating voltage. In addition, optical loss in the phase modulator branch and all other sources of mismatch between two arms of the interferometer increase nonlinearity. For a mode-locked sampling clock of 80MHz, a signal-to-noise plus distortion ration (SNDR) of 17.8dB (equivalent to 2.67 effective bits) and 18.5dB (equivalent to 2.78 effective bits) is obtained for an input signal frequency of 10MHz and 30MHz, respectively (figure 4c). The limited repetition rate of the available mode-locked laser unfortunately, did not allow SNDR performing measurements at sampling rates higher than 80MHz. The spatial quantization power is supplied by the input analog signal performing the phase modulation within the $\pm$0.45V voltage range, corresponding 4mW maximum analog input power. For an input optical energy of 68fJ per pulse, about 45fJ is consumed to resolve 8 quantization levels, while the rest of the optical energy is dissipated along modulator waveguides and free propagation region. The total energy for each quantization operation, including optical energy and electrical energy dissipation in the photodetectors, is 7.2pJ per quantization operation. Such energy consumption is more than two orders of magnitude lower than that predicted for a traditional electrical ADC with similar specifications.

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