Traveling Wave Spatial Quantized Analog-to-digital Conversion

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ABSTRACT — An analog-to-digital converter (ADC) architecture that extracts the required quantization energy directly from the input analog signal and sampling clock through a spatial quantization scheme is presented. We experimentally demonstrate 8-level quantization consuming only 7.2pJ per quantization operation with 18GHz bandwidth. Measured 8ps full-width half-maximum photodetector output voltages, promises the potential of realizing a 3bit 125GS/s ADC through this system.

Index Terms — Analog-to-digital converter, mode-locked laser, quantum-confined Stark effect, INL, DNL, SNDR.

I. INTRODUCTION

With rapidly increasing signal bandwidths along with predominance of digital technologies and techniques, the need for higher speed analog-to-digital conversion arises in order to interface between the analog and digital domains. Apart from major technical challenges in obtaining high sampling frequencies, in combination with the increasing tendency towards conservation of energy, the maximum available energy unfortunately, places an upper bound on the sampling frequency in conventional interfaces between analog and digital [1, 2]. To date, the fastest ADC that has been demonstrated experimentally consumes 3.8W power to achieve 40GS/s sampling rate and 3bits of resolution [3] (i.e., 95pJ per sample), which is much higher than the available power for a battery-powered portable device.

A number of photonic sampling techniques have been proposed to overcome the limited timing jitter of electronic sampling circuits. Many of the proposed photonic ADCs take advantage of mode-locked lasers with sub-picosecond pulse-widths and aperture jitter of few tens of femtoseconds [4]. Equally significant is the relative ease of optical clock distribution without a consequential increase in amplitude and phase noise, due to the robust nature of photons for transmitting information. Utilizing electronic quantization circuits in these optically sampled ADCs unfortunately limits the sampling speed due to the ambiguity of comparator circuits [2].

Here, we present an analog-to-digital conversion technique, which in contrast to the conventional ADCs eliminates any intermediate sample-and-hold and quantization circuit by directly launching the optical sampling pulses at spatial positions corresponding to quantization levels, and is consequently capable of achieving sampling frequencies as high as mode-locked laser pulse repetition rates. The conversion technique is unique in the sense that the required sampling and quantization energy is obtained from the analog input and sampling signal. We experimentally demonstrate 8-

level quantization consuming only 7.2pJ per quantization operation with 18GHz bandwidth. Measured 8ps full-width half-maximum photodetector output voltages, promises the potential of realizing a 3bit 125GS/s ADC through this system.

II. OVERVIEW OF THE ADC SYSTEM

The architecture of the proposed ADC is shown in Figure 1a. An optical input from a mode-locked laser is first coupled into an input waveguide. The optical pulse is then split and propagated down two waveguide branches of partial Mach-Zehnder-like interferometer. A phase modulator is integrated in one of the branches to vary the phase of the optical pulses according to the electrical signal to be digitized.

Fig. 1. (a) Schematic of the 3-bit spatially quantized ADC (b) Simulated power distribution on the image plane of a 350 μm free propagation region

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 in which the beams from the two branches can diverge and interfere. The resulting interference pattern from the two optical pulses forms a spot on an effective image plane, a spot whose position varies as the phase difference between the two optical pulses changes. In effect, the combination of the phase modulator and the free-propagation region together constitute an imaging beam-deflection system whose deflection is determined by the phase difference between the two optical pulses entering the free-propagation region and, more specifically, by the modulating electrical signal. Placing photodetectors at appropriate positions along the image plane

enables measurement of the spatial distribution of optical power. Moreover, connecting photodetector arrays in a binary fashion allows resolution of the output bits of the ADC. Figure 1b shows the simulated optical power distribution on the image plane of a 350 μm free propagation region as a function of the introduced phase shift.

III. PHASE MODULATOR AND PHOTODETECTOR

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 [5]. In this work, multiple quantum well layers are designed as integral parts of the intrinsic region of a p-i-n diode integrated inside the optical waveguide, which is designed for single transverse mode operation for wavelengths longer than 860 nm. The phase-modulating electric signal, which in combination with the substrate bias generates the electric field across the multiple quantum well layers, propagates on a coplanar waveguide (CPW) along the optical waveguide. Traveling wave phase modulation allows a long modulation path while maintaining a small junction area [6]. Consequently, the bandwidth-efficiency tradeoff is reduced and higher modulation bandwidth and efficiency will be achieved at the same time.

Fig. 2. Schematic of the traveling wave phase modulator

The schematic structure of the traveling wave phase modulator (TWPM) is shown in figure 2. Light is launched into the optical waveguide formed in the junction of a p-i-n diode. The epitaxial layers grown on a semi-insulating GaAs substrate are composed by a 0.1 μm -thin layer of multiple quantum wells sandwiched between two nominally undoped $\text{Al}_{0.05}\text{Ga}_{0.95}\text{As}$ layers of 0.4 μm thickness forming the intrinsic region of a p-i-n diode. A 1- μm thick, p ($5 \times 10^{17} \text{ cm}^{-3}$ Be) $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}$ layers followed by a 1- μm thick, p⁺ ($2 \times 10^{19} \text{ cm}^{-3}$ C) $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}$ layer, and a 2- μm thick, n ($5 \times 10^{17} \text{ cm}^{-3}$ Si) $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}$ serve as upper and lower cladding layers, respectively.

The CPW metal electrode structure comprised of metal on top of the optical waveguide and ground planes to either side is designed to have a characteristic impedance of 50 Ω and a

propagation constant set to allow for the phase modulating electric signal to travel in phase synchronism with the light. The complex characteristic impedance, $Z_0 (= \sqrt{Z/Y})$, and the complex propagation constant, $\gamma_c (= \sqrt{ZY})$, can be determined knowing the transmission line impedance per unit length, Z , and admittance per unit length, Y . The line impedance per unit length is characterized by a conventional coplanar waveguide inductance and resistance per unit length. The line parallel plate capacitance and the waveguide diode depletion region capacitance, while operated at reverse bias, together with a series resistance modeling the semiconductor losses associated with transverse current flow represent the line admittance per unit length. The 50 Ω CPW termination is fabricated using a part of the waveguide semiconductor.

Photodetectors, monolithically fabricated along the output waveguides, consist of an active region terminated through 6 μm metal spacing on either side, equivalent to 50 Ω . The generated photocurrent along the active region is a function of MQW reverse bias set by substrate bias voltage. Absorption of the photodetector is calculated by the overlap of optical mode with the quantum well layers. The power absorption density along the waveguide photodetector is set to be locally low by the small confinement factor of the guided light in the 0.1 μm -thin multiple quantum well absorption layer. This improves the photodetector efficiency along large device lengths by reducing the field screening effect [7] caused by the high concentration of photo-generated carriers at high optical pulse peak powers. The simulation results suggest an optical absorption coefficient of 1.5 mm^{-1} along the photodetector under 6V reverse-bias. The combination 0.218fF/ μm capacitive parasitic along the photodetector active region and the 50 Ω termination resistance, suggests a bandwidth of 36GHz and the corresponding FWHM pulse width of 5.5ps for a 400 μm photodetector.

IV. FABRICATION AND EXPERIMENTAL RESULTS

GaAs/AlGaAs p-i-n layers are grown by molecular beam epitaxy on a (100) semi-insulating GaAs substrate. The 2 μm -wide ridge waveguides are defined by Cl reactive ion etching. Au/Ni/Ge/Au n-contact metal region with total thickness of about 0.5 μm was formed by standard lift-off and then rapid-thermal annealed (RTA) at 415 $^{\circ}\text{C}$ for 30s. A Benzo Cyclo Butene (BCB) layer was spun on the device and etched back up to the top of the waveguide for planarization of the etched surface such that the microwave coplanar waveguide (CPW) lines can be placed on top. A Ti/Pt/Au evaporation and lift-off step forms the metallization of the CPW and the p-type metal contact.

CPW scattering parameters of a 1mm-long phase modulator, and the extracted characteristic impedance and propagation constant are shown in figure 3.

The extracted characteristic impedance is quite close to 50 Ω , within 6% deviation throughout the measurement range. This impedance level allows the modulator input/output to be easily

connected to conventional 50Ω RF systems. The reasonably good agreement between the experimental RF index and the desired 3.2 optical index verifies less than 2% microwave-optical velocity mismatch for the frequencies lower than 50GHz. The experimental RF attenuation is also shown in figure 3. The device performance would improve if the attenuation would be further reduced by increasing the center strip width to reduce the metal microwave loss.

Fig. 3. CPW characteristics calculated from CPW scattering parameters

The introduced phase shift $\Delta\phi$ in the optical mode is given by:

$$\Delta\phi = \chi V_m L \frac{1 - e^{-\alpha L}}{\alpha L} e^{-\left(\frac{t}{T_{\text{settling}}}\right)} \quad (1)$$

where χ is the phase modulation efficiency ($^{\circ}\text{V}^{-1}\text{mm}^{-1}$), V_m is the modulating electric voltage, L is the length of modulator, α is the microwave attenuation, and T_{settling} is given by [6]:

$$T_{\text{settling}} = 2.2 \frac{d}{V} + 2\pi \frac{\rho\epsilon}{d} + 2\pi L \frac{V_o - V_c}{V_o V_c} \quad (2)$$

where d is the depletion region depth, V is the carrier average drift velocity across the depletion region, ρ is the p-i-n diode contact resistivity, and V_o and V_c are the velocities of the optical wave and the microwave, respectively. By calculating the CPW propagation constant from scattering parameter measurements as a function of frequency an electric field settling time of 2.1 ps is estimated for a 1.5 mm long phase modulator. The expected operation bandwidth of the quantization system utilizing this phase modulator is 30 GHz, where the microwave attenuation of the CPW is the primary bandwidth-limiting mechanism.

Fig. 4. Traveling wave phase modulator phase/amplitude modulation characteristics

In order to investigate the phase modulation characteristics, we convert phase modulation to intensity modulation by inserting a phase modulator in one arm of an asymmetric Mach-Zehnder interferometer and observe 180° phase shift at each minimum/maximum intensity transition. Phase modulation sensitivity as a function of reverse bias is obtained by calculating interferometer $V\pi$ at each 180° phase transition and illustrated together with the associated intensity modulation in figure 4. At the operating optical wavelength of 870 nm, a relatively linear phase change of $270^{\circ}\text{V}^{-1}\text{mm}^{-1}$, and optical loss variations of less than $0.28\text{dBV}^{-1}\text{mm}^{-1}$ are achieved, about a 2.1V reverse bias voltage. Using a 1.5mm-active region phase modulator allows the achievement of 2π phase shift over a $\pm 450\text{mV}$ input analog signal range.

A die micrograph of the fabricated ADC is shown in figure 5a. The phase modulator is 1.5mm long and the free propagation region is 350μm long. Lengths of 50μm, 150μm and 400μm are chosen for the 1st, 2nd and 3rd bit detector arrays respectively. Optical sampling pulses from a Ti-sapphire mode-locked laser operating at 870 nm, driving 150fs pulses are coupled into the input waveguide. The resolved ADC bits within $\pm 100\text{mV}$ voltage range, at an input energy of 300fJ per optical pulse are shown in Figure 5b. Depending on the digital technology, we can adjust the optical pulse energy or utilize high gain stages prior to digital circuits to match the output voltage with the technology logic levels.

Fig. 5. (a) ADC micrograph (b) ADC resolved bits at an input energy of 68fJ per optical pulse (c) Photodetector transient response to a 150fs-wide optical pulse

Figure 5c shows the transient pulse response of a 400μm detector, measured by pump-probe electro-optic (EO) sampling technique [8]. The measured 8ps full-width half-maximum (FWHM) value at 6V reverse-bias indicates the capability of photo-detector to detect optical pulse train with up to a 125GHz repetition rate.

A performance summary of the fabricated ADC is shown in figure 6. Because of the limited mode-locked laser repetition rate, the bandwidth performance of the ADC is investigated by monitoring the frequency response of ADC LSB bit to a 6dBm sinusoidal analog source under laser continuous-wave operation. The measured frequency response, shown in figure 6a, 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 6b 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 partial Mach-Zehnder interferometer increase nonlinearity.

Fig. 6. (a) ADC LSB response to a 6 dBm analog input (b) INL and DNL (c) Measured FFT spectrum for $f_s=80$ MS/s

For a mode-locked sampling clock of 80MHz, a signal-to-noise plus distortion ratio (SNDR) of 17.8dB (equivalent to 2.67 effective bits) and 18.5dB (equivalent to 2.78 effective bits) is obtained for input signal frequencies of 10MHz and 30MHz, respectively (figure 6c). The limited repetition rate of the available mode-locked laser unfortunately did not allow SNDR measurements at sampling rates higher than 80MHz. Power consumption of the ADC is investigated by looking at the quantization and sampling power consumptions, separately. The spatial quantization power is supplied by the input analog signal performing the phase modulation within the ± 0.45 V voltage range, corresponding 4mW maximum analog input power, eliminating any static ADC power consumption. As mentioned before, the optical pulses from mode-locked laser not only provide the low jitter ADC sampling clock, but are also recycled in the spatial quantizer to resolve ADC output bits. As a result, the input optical pulse power directly affects the amplitude of the ADC resolved bits and the ADC resolution. For an input optical energy of 300fJ per pulse, about 25fJ 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, including optical power for quantization operation and electrical power 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 quantization circuits with similar specifications.

VII. CONCLUSION

The spatially quantized analog-to-digital conversion is an extremely power efficient technique for interfacing analog and digital domains, while overcoming the sampling speed restrictions of traditional ADCs. This is a valuable direction for increasing flexibility of electronic systems by eliminating many performance limiting components along the way to digital processors. Realization of some of the electronic systems, like software radio, which were previously not practically feasible due to the need for directly digitizing a large portion of the RF spectrum at the antenna will be possible by utilizing such an analog-to-digital conversion technique.

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