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Investigation of all-optical analog-to-digital quantization using a chalcogenide waveguide: A step towards on-chip analog-to-digital conversion

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ABSTRACT

We have investigated all-optical analog-to-digital quantization by broadening the pulse spectrum in a chalcogenide (As_2S_3) waveguide and subsequently slicing the measured spectrum using an array of filters. Pulse spectral broadening was measured for 8 different power levels in a 6 cm long As_2S_3 waveguide and used to analyze an 8-level all-optical quantization scheme employing filters with full-width at half-maximum (FWHM) bandwidth of 2 nm. A supercontinuum spectrum with −15 dB spectral width up to 324 nm was observed experimentally at large powers. This large spectral broadening, combined with filtering using a 128 channel arrayed waveguide grating (AWG) with 2 nm filter spacing, has the potential for all-optical quantization with 7-bit resolution. In order to encode the quantized signal we propose an encoder scheme which can be implemented using optical Exclusive-OR gates. Demonstrating all-optical quantization using a planar waveguide is an important step towards realizing all-optical A/D conversion on a chip.

1. Introduction

Storage, processing and analysis of commonly occurring signals such as the human voice, temperature fluctuations, Radar signals, etc., require data conversion from the analog-to-digital domain. Analog-to-digital converters (ADCs), therefore, form a key component of the signal-processing toolbox and use a three-step process: (i) sampling; (ii) quantization; and (iii) encoding as shown in Fig. 1. Current ADCs work in the electronic domain; however, the limited bandwidth of electronics makes processing of large bandwidth signals challenging. Photonic ADCs have, therefore, been explored to make use of the inherently large bandwidth of optics [1]. Several schemes have been proposed to achieve sampling, quantization and encoding optically, many relying on nonlinear optical effects in kilometer length optical fibers [2–5]. Although excellent performance has been achieved [2], fiber based schemes are not compatible with compact, low-cost, integrated solutions. Recent progress in highly nonlinear photonic integrated circuits suggests that a monolithic Photonic ADC is feasible. In particular, we recently demonstrated on-chip optical sampling at 640 Gbps and broadband supercontinuum (SC) generation in 7 and 6 cm long chalcogenide waveguides, respectively, the building blocks for Photonic ADCs [6,7].

In this paper, we analyze all-optical quantization by filtering the supercontinuum spectrum generated by propagating 715 fs duration pulses at 1544 nm through a 6 cm long As_2S_3 waveguide. The filtered spectra were analyzed at 8 different power levels and used for 8-level quantization. We generated a supercontinuum spectrum with a −15 dB bandwidth of up to 324 nm, which would allow 128-level quantization using filters with a 2 nm bandwidth. Optical quantization using spectral broadening in a planar waveguide and subsequent filtering is a key step towards realizing an all-optical ADC chip. However, in order to realize an optical chip equivalent to an electrical ADC, on-chip implementation of encoding logic is also required. To this end, we propose an encoding scheme, which can be implemented using optical Exclusive-OR (XOR) gates, which have been demonstrated using fiber optical parametric amplifiers [8] and semiconductor optical amplifiers (SOA) [9]. Further, as the main focus of this paper is to demonstrate all-optical quantization for enabling chip-level analog-to-digital conversion, we focus only on the demonstration of optical quantization and present the proposed XOR-gate based encoding scheme in Section 3. The paper is divided into four sections. In Section 2, we introduce the concept of all-optical quantization based on spectral slicing of the supercontinuum spectrum followed by experimental results for 8-level quantization. In

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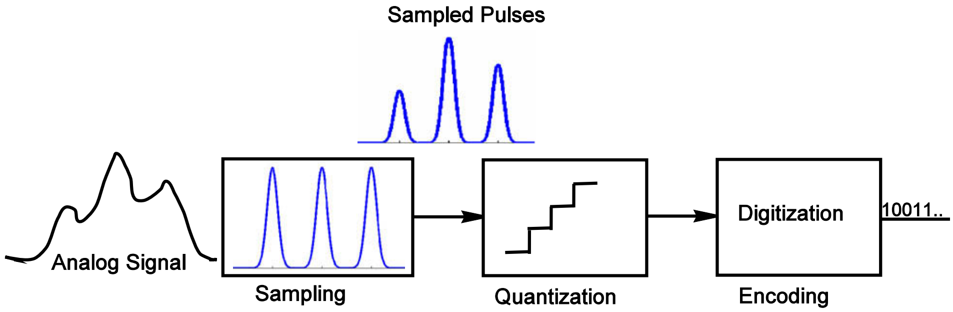

Fig. 1. Schematic of an analog-to-digital converter showing different components sampler, quantizer, and encoder.

Section 3, we present a discussion on XOR-gate based encoder followed by conclusions.

2. Concept and experiment

2.1. Concept

The on-chip, all-optical quantizer analyzed here works on the principle of mapping an input power to a number of ON ports with each port defined by a filter with a different center wavelength [4]. Fig. 2 shows a schematic of the chip-based all-optical quantization scheme. Pulses input to the As_2S_3 waveguide experience spectral broadening as a result of the self-phase modulation and higher-order nonlinear effects such as Raman effect, where the width of the output pulse spectrum increases with pulse power. To achieve N-level quantization, the spectrally broadened pulses at the output of the As_2S_3 waveguide are input to an array of N filters (AWG), where the center wavelength of the first filter is closest to the input pulse wavelength and the Nth filter farthest from the input wavelength. As the pulse power is increased to P_1, the increased spectral broadening causes output of the first filter, at wavelength λ_1, to cross the detection threshold and this output port is turned ON, which is represented by a '1' in Table 1. With increasing pulse power, the output ports are turned ON successively resulting in the generation of output port matrix (see Table 1). Thus, this technique achieves quantization by mapping the input pulse power to the number of ON ports. Next, we present our experimental results for all-optical quantization using spectral broadening in a 6 cm long chalcogenide waveguide.

2.2. Experiment

In our experiment, we investigated 8-level optical quantization by measuring the pulse spectrum for 8-different power levels using an OSA and applying multiple filter functions in software with 2 nm bandwidth placed ≈3 nm apart. Fig. 3 shows a schematic of the experimental set-up for studying pulse spectral broadening

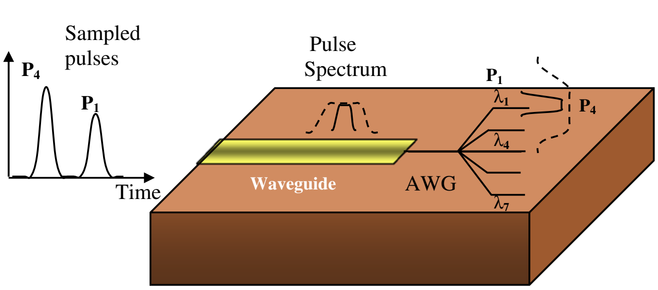

Fig. 2. Schematic of an all-optical quantization scheme based on pulse spectral broadening in As_2S_3 waveguide and subsequent filtering by an array of filters.

Table 1
Output of filters for increasing the pump power from P_1 to P_7.

	P_1	P_2	P_3	P_4	P_5	P_6	P_7
λ_1	1	1	1	1	1	1	1
λ_2	0	1	1	1	1	1	1
λ_3	0	0	1	1	1	1	1
λ_4	0	0	0	1	1	1	1
λ_5	0	0	0	0	1	1	1
λ_6	0	0	0	0	0	1	1
λ_7	0	0	0	0	0	0	1

in a waveguide. Optical pulses from a Calmar mode-locked laser were attenuated to generate the sampled pulses. The measured pulse width was 715 fs, the input pump wavelength 1544 nm, and the repetition rate of the laser 10 MHz. The output of the laser was coupled via a 99/1 splitter to the chalcogenide waveguide using lensed fibers with the 1% port connected to a detector to measure the power at the input to the waveguide. The nonlinear and dispersion parameters of the waveguide were $\gamma = 9786$ $(\text{W km})^{-1}$ and 29.2 (ps/km nm) at 1550 nm, respectively. The coupling losses are approximately 6 dB per facet and the propagation loss ≈3 dB. The input pulse peak power coupled to the laser was varied from 22 W to 40 W in order to generate pulse spectra with different spectral widths.

Fig. 4a shows the measured output spectra for different input powers. From Fig. 4a, we note that the −15 dB bandwidth increases with power. Fig. 4b shows the experimental (squares) −15 dB spectral bandwidth as a function of the input peak power along with a linear fit. The experimental results show that the increase in bandwidth is nearly linear for input power in the range from 22 W to 40 W, however, better waveguide design and optimization of experimental parameters is required in order to realize a better linearity.

The experimentally measured output spectrum was used to quantize the sampling pulse using seven filters on the Stokes side of the pump. The vertical lines in the inset of Fig. 4a show the center wavelengths of the filters and the horizontal line shows the −15 dB power point. As the input sample pulse amplitude was increased to P_1, the spectral broadening caused power at the first port (λ_1), labeled by vertical line in the inset of Fig. 4a, to cross the threshold value leading to an 'ON' state at the first output port. As the power of the sample pulse was continuously increased, the pulse spectrum broadened further and the output at other ports crossed the threshold generating the sequence shown in Table 1. Fig. 5 shows the transfer functions obtained from the measured pulse spectra. The different lines in Fig. 5 show the outputs of seven different filters, which define the seven different output ports, as functions of input power. Because the center wavelength of the filters at different output ports are different (as shown in the inset of Fig. 4a), the ports cross the threshold successively with increas-