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► To cite this version:

Mario Chemnitz, Bennet Fischer, Benjamin Maclellan, Piotr Roztock, Robin Helsten, et al.. All-optical Sampling for Adaptive On-Chip Picosecond Pulse-Shaping. Nonlinear Optics 2021, Aug 2021, Online, United States. hal-03418007

HAL Id: hal-03418007

<https://hal.science/hal-03418007>

Submitted on 17 Nov 2021

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All-optical Sampling for Adaptive On-Chip Picosecond Pulse-Shaping

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Abstract: We present autonomous pulse-shaping based on on-chip temporal coherence synthesis empowered by passively detuned, nonlinear optical sampling. Our scheme enables robust, efficient and reconfigurable picosecond waveform shaping with low detection requirements and low computational power. © 2021 The Author(s)

1. Introduction

Control over the temporal shape of picosecond optical pulses is essential for many application fields, for example to boost the efficiency of all-optical telecommunication methods [1] or nonlinear light-matter interactions [2]. Most techniques process the pulse in the spectral domain, which is very powerful for femtosecond and few-picosecond pulses [3]. Unfortunately, such methods become increasingly impractical for larger pulse durations. Several systems for picosecond pulse-shaping have been developed with a recent focus on integrated approaches [4,5], as these offer smaller footprints, better energy efficiencies, and a potential for mass fabrication. However, current approaches have two main disadvantages: Firstly, they rely predominantly on *a priori* sample design towards a specific shaping tasks, thus lacking reconfigurability; Secondly, they do not feature optical output monitoring for easy deployment and usage. Adaptive solutions, especially ones based on machine-learning algorithms, are an attractive means to greatly increase reconfigurability [6], but are hindered by the absence of efficient and inexpensive monitoring solutions. Here, we demonstrate an on-chip system for temporal coherence synthesis [7] for 3–100 ps pulse-shaping. The backbone of our method is an all-optical sampling technique alongside a particle swarm algorithm for parameter optimization, enabling effortless reconfigurability and autonomous operation with minimal detection requirements.

2. Results and Discussion

Figure 1a shows the experimental implementation of our adaptive pulse-shaping device. The source is a commercial fiber laser (Pritel FFL) that emits pulses with ~22 ps FWHM (full width at half maximum) pulse duration at a repetition rate of $f_{rep,1} = 10$ MHz. The optical chip for the pulse-shaping is based on silicon-oxi-nitride glass that offers exceptionally low optical losses [8]. The chip consists of a concatenation of multiple unbalanced Mach-Zehnder interferometers with bit-wise increasing delays [9], as illustrated in Fig. 1a. Here, at each interferometer, the incoming pulse is split into two copies, with the splitting ratios controlled by applied heater voltages. While one copy propagates in a longer path (illustrated with different colors in Fig. 1a), the other copy takes a shorter one. Afterwards, the two parts interfere in another controllable waveguide coupler to create a new temporal waveform.

For reading out the waveform, we make use of an all-optical sampling scheme based on four-wave mixing in a highly nonlinear fiber (OFS Fitel, zero dispersion wavelength 1546nm, 1km length) [10] (see Fig. 1b). The sampling source is a spectrally filtered, mode-locked fiber laser (Menlo FC1500-250-WG) which emits pulses with 4.4 ps duration (FWHM) at a repetition rate of $f_{rep,2} = 250.27$ MHz. Inside the highly nonlinear fiber, an optical idler is generated only when the pump (i.e., shaped pulse) and seed (i.e., short sampling pulse) temporally overlap. Fig. 1c shows an output spectrum of the HNLF with the generated idler (sampled output) in blue. A suitably chosen slight mismatch in the repetition rates of the pump and seed (i.e., $f_{rep,2} = nf_{rep,1} + \delta f$ with rate detuning δf) enables the passive scanning of the sampling pulse over the created waveform (pump) with each repetition of the pump pulse. Assuming a constant pulse shape, this passive method generates sampling points at kilohertz rates (i.e., with a sampling period of $\Delta T = (1/\delta f) > 1\mu s$), which are easy to filter and measure using a slow photodiode. A continuous waveform is then retrieved by using the Hilbert transform to obtain the envelope over the sampling points.

To confirm the calibration of our sampling method, we compared it against auto-correlation results. The measurements in Fig. 1d show that the retrieved envelope width from the sampling matches the pulse width measured with the auto-correlator very well. Hence, this scheme allows for unambiguous detection of the pulse

shape in the picosecond domain with reduced experimental complexity and straight-forward low-bandwidth electronics.

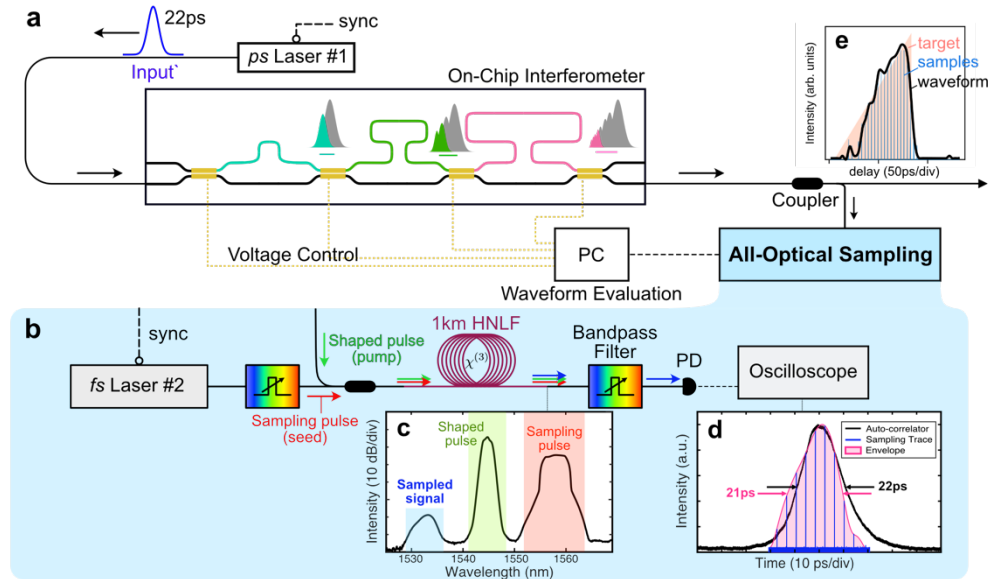


Fig. 1 **a)** Concept for the autonomous pulse shaper based on the concatenation of on-chip interferometers with ascending delays (in color). PC = personal computer, Solid lines = optical paths, dashed lines = electrical paths; **b)** All-optical sampling scheme. HNLF = highly nonlinear fiber, PD = photo diode. **c)** Output spectrum of HNLF. **d)** Sampling of the 22 ps input pulse compared to its measured auto-correlation. The time scale is corrected for the respective scaling factors. **e)** Measured pulse shaper output (optical samples and reconstructed waveform) after optimization for a positive sawtooth shape (target).

Finally, the optical sampling was used in combination with a metaheuristic particle swarm optimization (PSO) algorithm to find the optimal coupler splitting ratios for each on-chip interferometer. For waveform evaluation in the PSO, we defined a cost function based on the cosine similarity (i.e., a measure for the similarity between two vectors, here the target and measured waveform). This way, the split-and-delay procedure could be steered such that the output pulse shape matched a given target waveform. The combination of an optimization algorithm with an efficient measurement technique provides broad reconfigurability over a vast range of targeted pulse widths, even though the platform is not specifically designed for this particular task. In our experiments, we tested and achieved standard waveforms such as negative/positive sawtooth, square and triangular shapes (e.g., see Fig. 1e). Simulation results (incl. PSO) further reveal a functional operation range from 3 to >100 ps target duration, with significant improvements in the waveform shape when phase control in the pulse-copy recombination is added to the system.

3. Conclusion

In conclusion, we have demonstrated an autonomous pulse-shaping device based on the unique combination of on-chip temporal coherence synthesis, all-optical sampling, and an evolutionary optimization algorithm. The sampling technique allowed us to unambiguously distinguish between symmetric and asymmetric waveforms (e.g., sawtooth and triangle) with 20–50 ps widths, which is particularly challenging with auto-correlators. The full scheme can easily be integrated on a photonic chip platform, using spiral waveguides for optical sampling, and hence paves the way to compact, user-friendly ps-pulse shapers for telecom applications, among others.

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