3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

User-friendly, reconfigurable all-optical signal processing with integrated photonics

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Abstract

The development of reconfigurable, integrated all-optical signal processors on will enable low-cost and accessible platforms for key technologies such as bio-medical imaging, telecommunications and quantum optics. We demonstrate, that simple, user-friendly, programmable integrated circuits in combination with evolutionary optimization algorithms can constitute an essential pillar in the field of smart-photonics.

1 Introduction

The fusion of guided optimization techniques and photonic systems is an emerging and increasingly popular research field at the interface to machine-learning (dubbed 'smart'-photonics) with the goal of offering high customizability and advanced device functionality[1]. Towards this aim, there are several key 'ingredients' such systems require to find use: i) the implementation of adaptive and programmable elements to control the system output, ii) the adaption of algorithms from computer science, and iii) fast, efficient and reliable detection schemes for the feedback signals.

Until now, the majority of implementations make use of free-space or fiber-based approaches utilizing, for example, spatial-light modulators or electronic polarization controllers to alter the system dynamics[2]. In order to boost device compactness, environmental robustness, and processing speeds, photonic integrated circuits (PICs) are appealing for achieving cutting-edge performance in a small footprint with the potential for mass-production and scalability. Lately, PICs have allowed progress in reconfigurable 'smart'-devices, such as photonic field programmable gate arrays[3] or intelligent telecommunications processors[4].

Here, we demonstrate that integrated, reconfigurable circuits can be an essential cornerstone in the field of smart-photonics, by enabling advanced device functionalities beyond single-application uses. In detail, we show that a simple cascaded Mach-Zehnder interferometer design can be utilized towards different applications such as on-demand tailoring of broadband light sources and reconfigurable picosecond pulse shaping.

2 Results

The key element in our implementation is a chip-integrated pulse splitter consisting of concatenated balanced and unbalanced Mach-Zehnder interferometers. The platform is based on a silicon-oxy-nitride glass that offers exceptionally low linear (< 0.06 dB/cm) and negligible nonlinear losses[12], and is fiber-coupled to standard single-mode fibers for ease of use. The unbalanced interferometers of our chip features bit-wise increasing delays (i.e., 2^n for n=0...7) from 1 ps up to 255 ps. The individual delays can be accessed and controlled over a micro-controller which drives the pulse splitting via on-chip electric heaters.

The short delays of our chip sample allows to maintain femtosecond pulse widths in order to drive adjacent highly nonlinear processes in highly-nonlinear fibers such as supercontinuum generation[5]. Indeed, supercontinuum spectra with hundreds of nanometer bandwidth are a sought-after sources for spectroscopy and bio-medical imaging applications. However, such sources are generally static in their spectral energy distribution, i.e., the spectrum is defined by the pump laser and fiber parameters[10]. In our implementation, the integrated pulse-splitter is used to split a femtosecond pulse into several pulse copies of varying delays and amplitudes. During the propagation inside a highly nonlinear fiber (HNLF), these pulse copies can experience different inter- and intra-pulse interactions, depending on their splitting ratios, which can lead to drastically changed output spectra. The experimental setup is shown in Fig. 1.

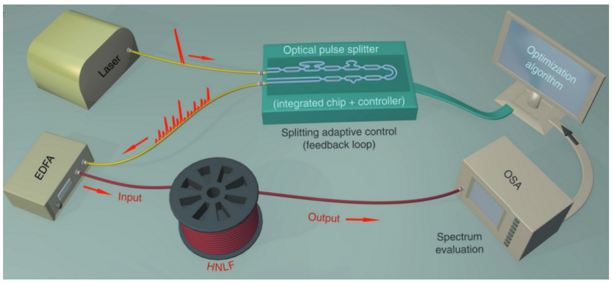

Figure 1. Experimental setup for customized supercontinuum generation. EDFA = erbium-doped fiber amplifier, HNLF = highly nonlinear fiber, OSA = optical spectrum analyzer.

By employing a guided optimization algorithm in the form of the popular genetic algorithm (GA), the process of supercontinuum generation can be altered towards a specific target output (e.g., maximizing the intensity in one or more wavelength bands). Specifically, the spectrum is readout using an optical spectrum analyzer, and subsequently evaluated for a targeted performance via a loss function metric. Then, the settings for the amplitude splitting are updated until a specific termination criterion for the feedback loop is met. Fig. 2 shows the results for such optimization towards maximal optical power in different wavelength bands, which is especially important for applications that require high power densities in specific spectral domains. From the results, it is evident that for a single pulse the method significantly outperforms the control experiment (dashed spectra).

Another application that can benefit from this kind of reconfigurability and optimization is picosecond pulse-shaping, which is important for controlling nonlinear dynamics[6] or for information encoding in telecommunications[7]. However, to date, the narrow linewidth of sub-nanosecond sources has inhibited any demonstration of an efficient and adaptable scheme.
In our work[8], we demonstrate that the same integrated pulse-splitter can be repurposed towards reconfigurable picosecond pulse-shaping using temporal coherence synthesis[11]. In detail, a picosecond input pulse (here ≈22 ps) will experience self-interference in the pulse-splitter. By adjusting the individual amplitude ratios between the interfering pulse splittings, customized output waveforms can be obtained. The experimental setup is shown in Fig.3.

In order to efficiently and unambiguously monitor the output waveform, we implemented an all-optical sampling scheme based on seeded degenerate four-wave mixing in a HNLF[9]. The measured sampling signal is then evaluated on a computer using a Hilbert transform for envelope retrieval. The cosine-similarity between the retrieved and a targeted waveform is used as a loss function. In contrast to the customized supercontinuum generation experiment, here we utilized a nature-inspired particle swarm optimiza-

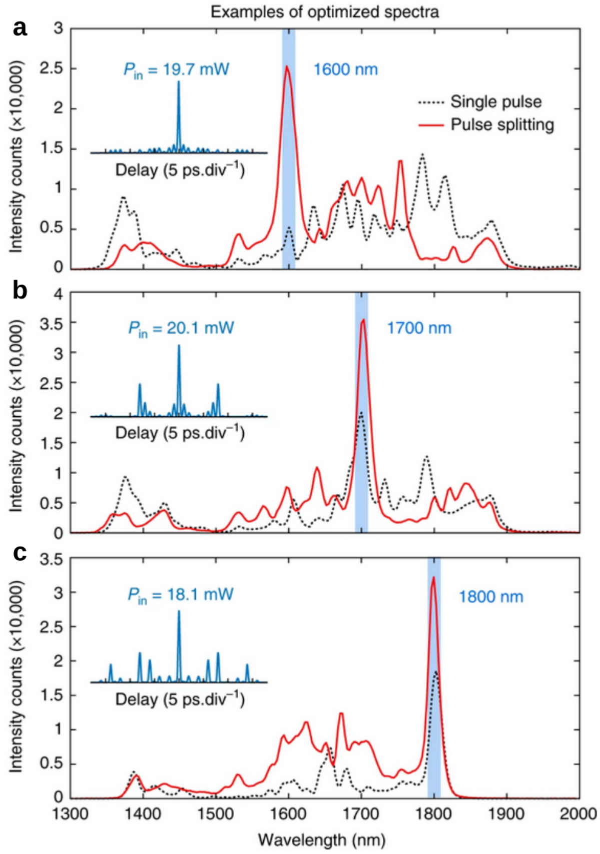

Figure 2. Results of the customized supercontinuum generation. **a-c** Intensity maximation at 1600 nm, 1700 nm and 1800 nm, respectively. The blue bar indicates the target wavelength window. The insets show the autocorrelation trace for each case.

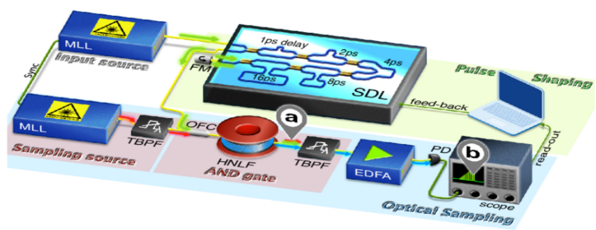

Figure 3. Setup for an autonomous pulse-shaper using an integrated pulse-splitter and an all-optical sampling scheme (a). The shaped and sampled signal is detected by an oscilloscope (b), and a computer mediates the evaluation and optimization of the integrated pulse-splitter. SDL = split-and-delayline, FM = Faraday mirror, MLL = mode-locked laser, TBPF = tunable bandpass filter, OFC = optical fiber coupler, PD = photodiode

tion algorithm (PSO) for the optimization, which turned out to converge significantly faster for this particular application than the GA. The obtained results for different waveforms (square, triangle or sawtooths) are depicted in Fig. 4, which are of relevance to the telecommunications sector.

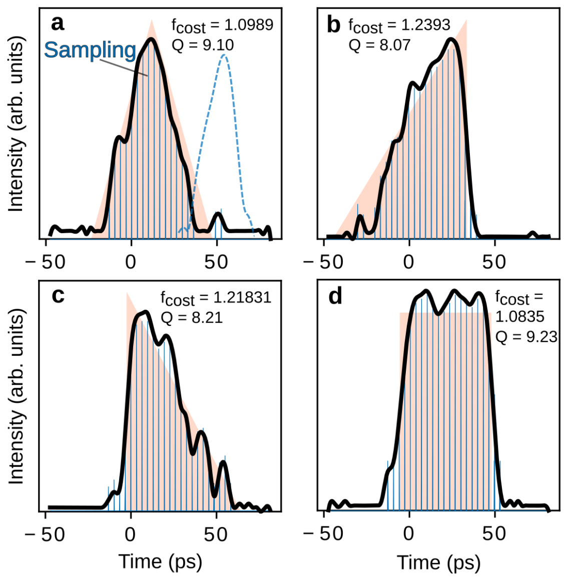

Figure 4. Experimental results for the reconfigurable picosecond pulse-shaper. **a** Triangular **b** Positive sawtooth, **c** Negative sawtooth, **d** Flattop waveform. The target waveform is shown in pink, the measured sampling signal and retrieved envelope are solid blue and black lines, respectively. The blue dashed line in **a** depicts the input pulse.

3 Conclusion

We demonstrate that the time and length scales accessible in integrated photonics play an enabling role towards the next generation of optical signal processing. Making use of a reconfigurable interferometer network, we demonstrate its utility towards signal optimization in both the spectral (i.e., custom supercontinuum generation) and temporal (i.e., custom temporal waveform generation) domains. GA and PSO algorithms are broadly able to guide the reconfiguration of the circuit towards the application cases, when coupled with effective readout methods. Moreover, the results demonstrate the unprecedented capabilities of machine learning approaches for repurposing existing photonic hardware, ultimately reducing the need for time consuming and financially expensive photonic device fabrication. Our work suggests that development into such combinations of reconfigurable circuits, optimization, and fast readout may play a pivotal role in enhancing signal processing capabilities while maintaining user friendliness, low setup complexities and footprints, and costs.

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