Optical Fiber Communication Conference 2021 © OSA 2021

Optical Arbitrary Waveform Measurement (OAWM) on the Silicon Photonic Platform

Dengyang Fang[1], Andrea Zazzi[2], Juliana Müller[2], Daniel Drayß[3], Christoph Füllner[1], Pablo Marin-Palomo[1], Ali Tabatabaei Mashayekh[2], Arka Dipta Das[2], Maxim Weizel[4], Sergiy Gudyriev[4], Wolfgang Freude[1], Sebastian Randel[1], Christoph Scheytt[4], Jeremy Witzens[2], and Christian Koos[1,3]

(1) Institute of Photonics and Quantum Electronics (IPQ), Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
(2) Institute of Integrated Photonics (IPH), RWTH Aachen University, 52074 Aachen, Germany
(3) Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
(4) Heinz Nixdorf Institute (HNI), University of Paderborn, 33102 Paderborn, Germany
dengyang.fang@kit.edu, christian.koos@kit.edu

Abstract: We demonstrate optical arbitrary waveform measurement (OAWM) using a silicon photonic spectral slicer. Exploiting maximal-ratio combining (MRC), we demonstrate the viability of the scheme by reconstructing 100-GBd 64QAM signals with high quality.
OCIS codes: 070.1170 (Analog optical signal processing), 060.1660 (Coherent communications), 250.3140 (Integrated optoelectronic circuits)

1. Introduction

Optical arbitrary waveform measurement (OAWM) [1] has the potential to unlock a wide variety of applications, ranging from investigation of ultra-short events [2] and photonic-electronic analog-to-digital convertors (ADC) [3] to reception of communication signals with ultra-high symbol rates [4], elastic optical networking [5], and sliceable-bandwidth-variable transponders (SBVT) in cloud radio-access networks (C-RAN) [6]. OAWM has previously been demonstrated with an overall bandwidth of 228 GHz [4], exploiting spectral slicing of the incoming waveform into six tributaries that are coherently detected using an optical frequency comb (OFC) as multi-wavelength local oscillator (LO). Exploiting the phase-locking of the comb tones along with redundant information in spectrally overlapping regions of neighboring spectral slices, the optical waveform can be reconstructed through digital signal processing (DSP) in the base band [1]. However, while this led to an impressive 214 GBd dual-polarization QPSK reception with 856 Gbit/s line rate, the experiment was still based on discrete components such as fiber-pigtailed arrayed-waveguide gratings, limiting the robustness and scalability of the underlying hardware.

In this paper, we demonstrate OAWM using a highly compact silicon photonic circuit that exploits a bank of frequency-tunable coupled-resonator optical waveguide (CROW) filters for spectral slicing of the incoming signal. In our experiment, we demonstrate detection and stitching of four spectral slices, covering an overall bandwidth of 140 GHz. Our signal processing scheme accounts for the exact complex-valued transfer functions of the slicing filters and the subsequent IQ receivers, which are extracted in a one-time calibration measurement using a femtosecond laser (MENHIR-1550) with a known pulse shape. This allows using maximal-ratio combining (MRC) to spectrally stitch the four signal tributaries with minimum impairments. We demonstrate the viability of the scheme by receiving and accurately reconstructing a 100-GBd 64QAM signal with a single-polarization line rate of 600 Gbit/s, reaching a bit error ratio (BER) of 3.1×10^{-2} – well below the limit of soft-decision forward-error correction with 20% overhead. The demonstrated signal quality compares well to that obtained through single-slice detection using a broadband intradyne IQ receiver. To the best of our knowledge, our experiment represents the first OAWM demonstration using silicon photonics for spectral slicing, thereby paving the way towards monolithically integrated OAWM systems of unprecedented compactness and scalability.

2. Concept and experimental setup

The concept and the experimental setup are illustrated in Fig. 1. Figure 1 (a) shows a sketch of the envisioned silicon photonic (SiP) OAWM receiver, having an input port each for the broadband optical signal (Sig) and the LO comb. The signal is spectrally sliced by a first thermally tunable CROW filter bank [8], which is designed and tuned to provide a flat passband, a steep roll-off, as well as sufficient spectral overlap between adjacent channels for spectral stitching. The comb lines are isolated and equalized in power using either simple ring resonators or a second CROW filer bank. The signal slices are then routed to an IQ receiver array for coherent detection, using the corresponding phase-locked comb-tones as LO. The in-phase (I) and quadrature (Q) components of the signal slices are detected by on-chip balanced photodetectors (BPD) and digitized by highly scalable CMOS ADCs. By increasing the number of CROW filters, BPDs, and ADCs, the overall detection bandwidth of the system can be scaled to the THz range.

As a first step towards a fully integrated system, we realized the SiP slicing circuit with four integrated CROW filters and used it in a proof-of-concept experiment, see Fig. 1 (b). For evaluating the performance, we use broadband 100 GBd QAM signals, generated by a lithium-niobate IQ modulator that is driven by a benchtop-type arbitrary-waveform generator (AWG, Keysight M9536A). The optical test signal is sliced by an array of CROW filters, which are thermally tuned to provide a flat passband with a 3 dB bandwidth between 30 GHz and 40 GHz. For adjusting the

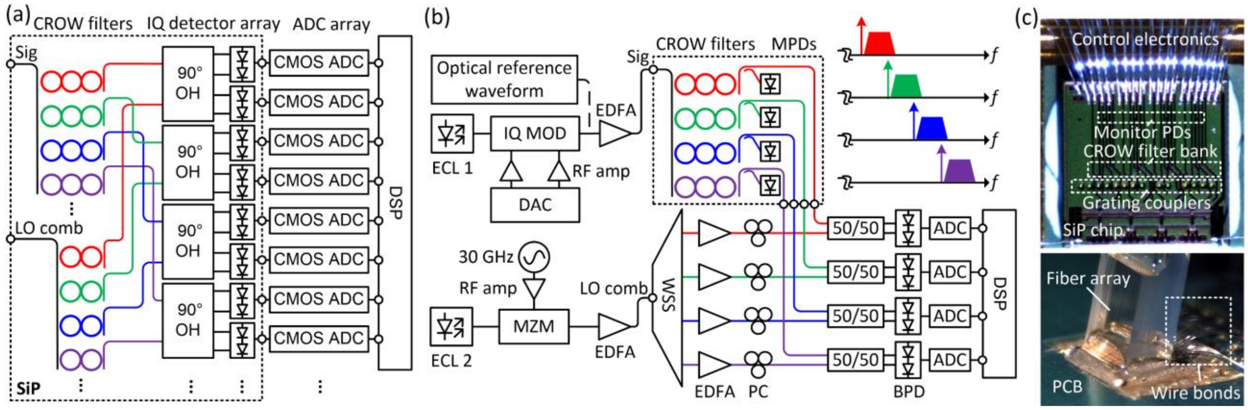

Fig. 1 Concept and realized elements of a silicon photonic (SiP) optical arbitrary waveform measurement (OAWM) system. **(a)** Envisioned fully integrated OAWM system with input ports for the optical signal (Sig) and the LO comb. Signal slicing and comb-line separation relies on thermally tunable CROW filter banks. Coherent detection is accomplished in an IQ receiver array based on 90° optical hybrids (OH) and on-chip balanced photodetectors (BPD). Once digitized by highly scalable CMOS ADC, the signal tributaries are stitched through digital signal processing (DSP) to reconstruct the incoming waveform. **(b)** Experimental setup of our proof-of-concept demonstration. For testing, we use a 100-GBd 64QAM signal, generated by a lithium-niobate IQ modulator that is driven by a benchtop-type arbitrary-waveform generator (AWG, Keysight M9536 A). The test signal and is spectrally sliced by an array of thermally tunable 3rd-order CROW filters on a SiP chip. The LO comb tones, generated by a Mach-Zehnder modulator (MZM) and an external-cavity laser (ECL 2), are separated and equalized using a wavelength selective switch (WSS) and then sent to four balanced heterodyne receivers, which are connected to a high-speed real-time oscilloscope with four ADC channels. **(c)** Top: Microscope image of the SiP chip with CROW filter bank and on-chip monitor diodes for adjusting the filters. Bottom: Side-view photograph of the CROW chip attached to a printed circuit board (PCB) comprising control electronics. A fiber array is used to couple light to the SiP chip.

CROW filter bank, we feed it with continuous-wave (CW) laser tones of known frequencies and make use of feedback signals that are obtained from on-chip monitor photodiodes (MPD) connected to the filter outputs through 17 %-taps. On the LO side, our experiment relies on a frequency comb generated by a Mach-Zehnder modulator (MZM) that is driven by a 30 GHz sinusoidal RF signal. The selected comb lines are separated and equalized using a wavelength selective switch (WSS) and amplified by erbium-doped fiber amplifiers (EDFA). The polarization is then aligned by polarization controllers (PC) before each comb tone is combined with the corresponding signal slice in a 50/50 couplers, followed by a balanced photodetector with a 3 dB bandwidth of 43 GHz. The photocurrents are digitized using four ADC channels of a high-speed real-time oscilloscope. Note that, in contrast to the IQ reception scheme shown in Fig. 1 (a), our current experiment relies on balanced heterodyne detection due to limitations of the available ADC channels, see Fig. 1 (b), and that the LO tones are thus positioned on the edge of corresponding signal slices.

3. Experimental demonstration and waveform reconstruction

To accurately reconstruct the original broadband signal from the spectral slices, the complex-valued transfer functions of the associated signal paths need to be measure. We separate each transfer function into a time-invariant frequency-dependent part, representing, e.g., the characteristics of the CROW filter, the group delay introduced by the various fibers and the EDFA, as well as the electric response of photodiode and ADC, and into a slowly time-variant frequency-independent complex-valued factor accounting for the amplitude and phase fluctuations of the comb lines and the random phase drift in the optical fibers. For precisely measuring the time-invariant part, we use a novel one-time calibration method that relies on feeding the system with an optical reference waveform, generated by an ultra-stable mode-locked laser (MENHIR-1550) (repetition rate ~ 250 MHz, pulse duration < 200 fs), see dashed line in Fig. 1 (b). The amplitude and phase profiles of this reference pulse are known from a frequency-resolved optical gating (FROG) measurement. At the coherent receivers, we detect the slices of the reference waveform and extract the associated amplitude and phase. By comparison with the known spectrum of the reference waveform, we can then derive the time-invariant transfer function of each detection path. For estimating the time-variant frequency-independent complex-valued factors, we correct for the time-invariant frequency-dependent transfer functions and then compare the resulting complex-valued spectra in a 500 MHz-wide spectral overlap region between adjacent slices. Note that the time-variant change of these factors arises from rather slow fluctuations of the comb lines and of the fibers and can thus be assumed constant during a single signal recording. With the complete complex transfer functions at hand, the incoming waveform can then be reconstructed by offline DSP. To this end, the digitized signal slices are first frequency-shifted according to the spacing of the LO comb tones, see Fig. 2 (a). Figure 2 (b) shows the corresponding data after compensating for the time-invariant transfer functions of the various signal paths. The dotted lines indicate the position of the 500 MHz-wide overlap regions that are used to estimate the frequency-independent complex factors associated with neighboring slices. Note that the position of these regions is defined by the crossing points of the slightly non-uniform CROW transfer functions, which are not strictly equidistant. For merging the signal tributaries, we consider our receiver as a single-input multiple-output (SIMO) system and use maximal-ratio combing (MRC) [9] to maximize the SNR of the reconstructed waveform, see Fig. 2 (c) for the reconstructed spectrum of a 100 GBd

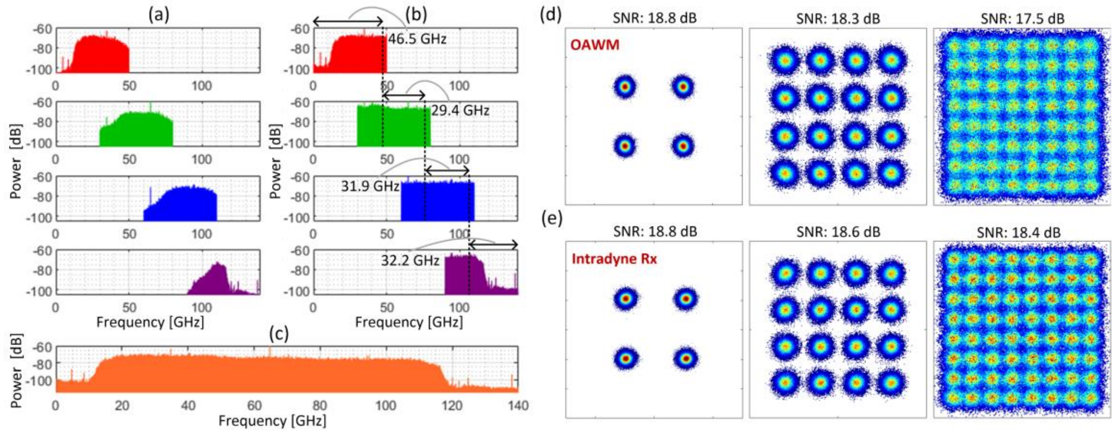

Fig. 2 Signal processing procedure and the experimental results. **(a)** Digitized frequency-shifted spectral slices. (b) Spectral slices after compensating for the time-invariant transfer functions. The dotted lines indicate the used overlap regions for estimating the frequency-independent complex factors. **(c)** Reconstructed spectrum of a 100-GBd 16QAM signal, obtained through merging the signal tributaries by maximal-ratio combing (MRC). **(d, e)** Comparison of 100-GBd signal data signals with different modulation formats, obtained by OAWM-based detection (top row) and by single-slice single-polarization intradyne coherent receiver (Intradyne Rx, bottom row). For OAWM reception, we observe less than 1 dB SNR penalty for 100-GBd 64QAM and negligible penalty for 100-GBd QPSK and 16QAM, while the ADC bandwidth requirements are greatly reduced.

16QAM test signal. In the example shown in Fig. 2 (a-c), the spectral widths of the four signal slices amounts to 46.5 GHz, 29.4 GHz, 31.9 GHz, and 32.2 GHz, leading to an overall bandwidth of 140 GHz. Note that the bandwidth of our heterodyne receivers amounts to approximately 50 GHz and thus exceeds both the comb line spacing of 30 GHz and the width of the CROW passband, which amounts to approximately 40 GHz. As a consequence, the spectral slices in our experiment exhibit significant overlap, see Fig. 2 (a) and (b). We find that reducing this overlap by omitting parts of the digital spectra does not have any detrimental impact on the quality of the stitched waveform. The scheme could hence have implemented with reduced electronic acquisition bandwidths.

To estimate the performance of our OAWM scheme, we analyze the quality of received data signals with different modulation formats and compare it to single-polarization single-slice intradyne coherent reception, see Fig. 2 (d) and (e). For a fair comparison, we use identical DSP algorithms in both cases, and we extract the constellation signal-to-noise ratio (SNR), which is related to the error-vector magnitude (EVM). For OAWM reception, we observe less than 1 dB SNR penalty for 100-GBd 64QAM and negligible penalty for 100-GBd QPSK and 16QAM, while the ADC bandwidth requirements are greatly reduced. For the SNR of 17.5 dB measured for the 100-GBd 64QAM signal, we estimate a bit error ratio (BER) of 3.1×10^{-2}, well below the limit of soft-decision forward-error correction with 20% overhead [7]. To the best of our knowledge, our work does not only represent the first OAWM demonstration using silicon photonics for spectral slicing, but also the first OAWM-based reception of 16QAM and 64QAM signals. Our scheme can be scaled to higher bandwidths by increasing the number of parallel ADC channels.

4. Summary

We have demonstrated optical arbitrary waveform measurement (OAWM) using a highly compact silicon photonic circuit for spectral slicing. Our signal processing scheme accounts for the exact complex-valued transfer function of the slicing filters and the subsequent receivers, which are extracted in a one-time calibration measurement using a known optical reference waveform. Exploiting maximal-ratio combining (MRC) for spectral stitching, we demonstrate accurate reconstruction of 100-GBd QPSK, 16QAM and 64QAM signals. The signal quality compares well to that obtained using a broadband single-slice intradyne IQ receiver, while greatly reducing the electronic bandwidth requirements. To the best of our knowledge, our experiment corresponds to the first OAWM demonstration using silicon photonics for spectral slicing and thus represents an important step towards a fully integrated on-chip OAWM system.

Acknowledgements: This work was supported by the Deutsche Forschungsgemeinschaft (DFG) project PACE (no. 403188360) within the Priority Programme "Electronic-Photonic Integrated Systems for Ultrafast Signal Processing" (SPP 2111), by the project TeraSlice (no. 863322) under European Union's Horizon 2020 Research and Innovation Programme, by European Research Council (ERC) consolidator grant TeraSHAPE (no. 773248), by the Alfried Krupp von Bohlen und Halbach-Stiftung, and by the Max-Planck School of Photonics (MPSP)

References

[1] N. K. Fontaine *et al.*, "Real-time full-field arbitrary optical waveform measurement," Nature Photon. **4**, 248–254 (2010).

[2] D. Solli, C. Ropers, P. Koonath *et al.* "Optical rogue waves," Nature **450**, 1054–1057, (2007).

[3] A. Zazzi *et al.*, "Fundamental limitations of spectrally-sliced optically enabled data converters arising from MLL timing jitter," Opt. Express **28,** 18790–18813, (2020).

[4] N. K. Fontaine *et al.*, "228-GHz coherent receiver using digital optical bandwidth interleaving and reception of 214-GBd (856-Gb/s) PDM-QPSK," European Conference on Optical Communication, ECOC 2012, Paper Th.3.A.1.

[5] R. Proietti *et al.*, "Elastic optical networking by dynamic optical arbitrary waveform generation and measurement," J. Opt. Commun. Netw. **8,** A171–A179, (2016)

[6] L. Velasco *et al.*, "Meeting the requirements to deploy cloud RAN over optical networks," J. Opt. Commun. Netw. **9**, B22–B32, (2017).

[7] K. Schuh, *et al.*, Single Carrier 1.2 Tbit/s Transmission over 300 km with PM-64 QAM at 100 GBaud, Proc. Optical Fiber Communications (OFC), Th5B.5, San Diego, CA (2017)

[8] S. Romero-García *et al.*, "Wideband multi-stage CROW filters with relaxed fabrication tolerances," Opt. Express **26**, 4723 - 4737, (2018).

[9] D. G. Brennan, "Linear Diversity Combining Techniques," in Proceedings of the IRE **47**, 1075-1102 (1959), doi: 10.1109/JRPROC.1959.287136.