Spectrally Sliced Optical Arbitrary Waveform Measurement (OAWM) Using a Photonic Multi-Chip Receiver Assembly

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Abstract: We demonstrate the first spectrally sliced OAWM receiver assembly that combines slicing filters and optical receivers in a hybrid multi-chip module. We prove the viability of the device by receiving a wavelength-division-multiplexed signal over a bandwidth of 320 GHz. © 2024 The Author(s)

1. Introduction

Full-field optical arbitrary waveform measurement (OAWM) [1] allows to capture signals with bandwidths of hundreds of GHz, thereby offering great potential for a variety of applications such as optical transmission at highest symbol rates [2-4], secure communications using optical spread-spectrum schemes [4], or ultra-broadband photonic-electronic analog-to-digital conversion (ADC) [5]. A well-established approach to OAWM relies on spectral slicing of the incoming waveform into multiple band-limited tributaries that are coherently detected by an array of in-phase/quadrature (IQ) receivers using an optical frequency comb (OFC) as a multi-wavelength local oscillator (LO). Harnessing the phase-locked nature of the comb tones along with redundant information in the spectral overlap regions between neighboring slices, the optical waveform can then be reconstructed through digital signal processing (DSP). However, so far, the potential of spectrally sliced OAWM has mainly been demonstrated in laboratory experiments that relied on conventional discrete components [3-5], whereas robust and compact implementation based on photonic integrated circuits (PIC) still represents a challenge. Specifically, high-quality slicing filters are difficult to integrate, in particular when high-index-contrast platforms such as silicon photonics (SiP) are to be used. Previous PIC-based demonstrations of spectrally sliced OAWM relied either on conventional arrayed waveguide gratings (AWG) that were implemented as comparatively large purely passive low-index-contrast planar lightwave circuits (PLC) [1] or on SiP coupled-resonator optical waveguide (CROW) structures [6] that needed sophisticated control schemes for thermal tuning. Moreover, all these demonstrations still relied on external IQ receivers, which were connected to the outputs of the slicing filters by optical fibers. This leads to setups which are still rather complex and thus not suited for practical applications of spectrally sliced OAWM.

In this paper, we demonstrate a fully optically packaged spectrally sliced OAWM module that combines compact silicon-nitride (Si_3N_4) arrayed waveguide gratings (AWG) with a SiP IQ receiver array in a chip-scale assembly. The slicing filters do not require any tuning and are connected to the receiver die by 3D-printed photonic wire bonds (PWB) [7,8]. Our integrated OAWM module offers an acquisition bandwidth of 320 GHz – to our knowledge the highest value so far demonstrated for a PIC-based spectrally sliced OAWM receiver. We experimentally demonstrate the viability of our assembly by combining it with an optically packaged Kerr-comb module and with a packaged comb-line-selection-and-flattening filter module, which allows to extract and manipulate individual comb tones prior to feeding them to the OAWM receiver. We use this system for reception of a wavelength-division-multiplexed (WDM) signal that essentially spans the entire acquisition bandwidth of 320 GHz. To the best of our knowledge, our demonstrations represent the first example of a spectrally sliced OAWM module having co-integrated photodetectors. We believe that our results represent an important step towards fully integrated spectrally sliced OAWM systems, which can be used in practical application scenarios, and which might offer better bandwidth-scalability than their non-sliced counterparts [9].

2. System concept and implementation

The concept of our spectrally sliced OAWM system is illustrated in Fig. 1(a). The optical signal of interest ('Sig') and the LO comb ('LO') are both fed to the OAWM receiver assembly Ⓐ, which is implemented as hybrid photonic multi-chip module (MCM). The OAWG MCM combines a SiP IQ receiver array (IQR1 … IQR4) with a pair of Si_3N_4-based arrayed-waveguide gratings (AWG), which serve as optical slicing filters for the incoming signal and the LO comb. The signal tributaries and the individual LO tones are then fed to the various IQR, each of which comprises a 2×4 multi-mode-interferometer (MMI) coupler acting as a 90° optical hybrid and a pair of silicon-germanium (SiGe) balanced photodetectors (BPD). The resulting electric signals are then digitized by an array of conventional electronic ADC, and the optical waveform is finally reconstructed by digital signal processing (DSP). The LO comb is derived from a dedicated frequency-comb generator (FCG) module Ⓒ, which contains an optically packaged Si_3N_4-based high-Q micro-ring resonator, pumped by an external continuous-wave (CW) laser. This can easily offer tens or even hundreds of phase-correlated comb tones. The generated Kerr comb is then fed to a line-selection-and-flattening filter (LSF) module Ⓑ, where the LO tones of interest are extracted, equalized in power, and finally recombined and routed to the OAWM MCM. The LSF is implemented by a series of Si_3N_4 ring filters that are coupled to a common pair of bus waveguides and that can be thermally tuned in wavelength to align with the desired comb tones. Power equalization of the comb tones is accomplished by slight detuning of the rings

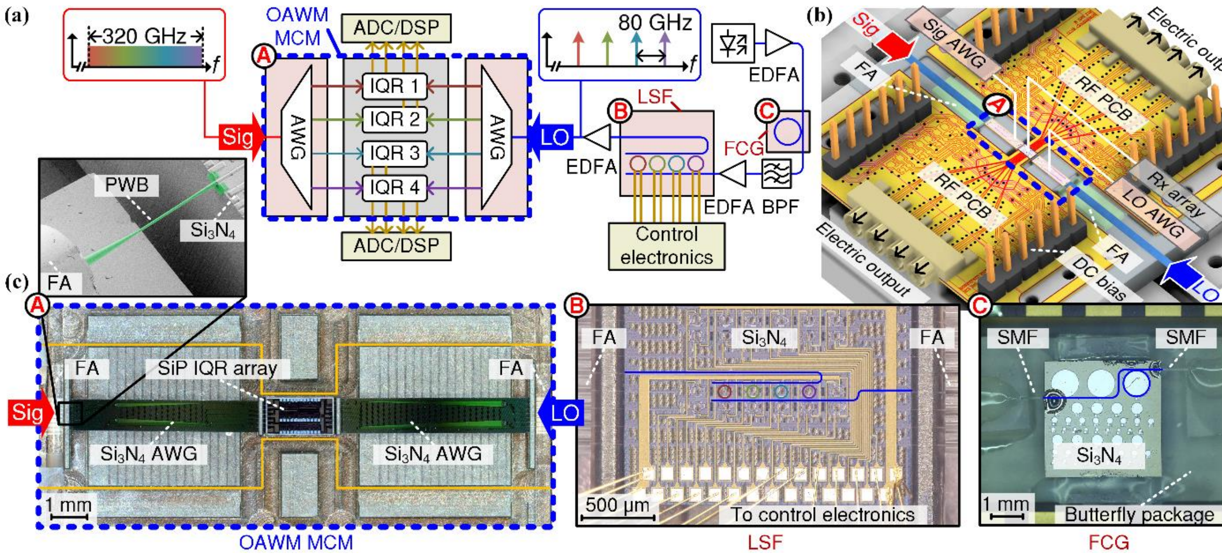

Fig. 1 (a) Concept and implementation of the spectrally sliced OAWM system, relying on an optically packaged multi-chip receiver module (OAWM MCM) Ⓐ, a line-selection-and-flattening filter (LSF) module Ⓑ, and frequency-comb generator (FCG) module Ⓒ. The OAWM MCM combines a pair of Si_3N_4-based arrayed-waveguide gratings (AWG) for spectral slicing of the incoming optical signal and for separation of LO with a silicon photonic (SiP) IQ receiver (IQR) array for coherent detection. **(b)** Illustration of an OAWM MCM, which is also electrically packaged using dedicated RF fan-out PCB. The PCB also contains biasing circuits for the BPD, which can be accessed through DC pin headers. The functionality of the PCB was tested and confirmed, even though the subsequent demonstration experiments still relied on RF probes. **(c)** The top views of the OAWM MCM, the LSF, and the FCG module. The OAWM MCM Ⓐ relies on in total 26 3D-printed photonic wire bonds (PWB) for internal optical chip-chip and fiber-chip connections, see Inset for an exemplary interface with PWB highlighted in false-color. The orange lines indicate the contours of the RF PCB, which themselves are not shown.

from the respective tones. The OAWM MCM, the LSF and the FCG module are connected by conventional optical fibers, which allows for flexible combination of these modules with each other and with other fiber-optic devices, such as bandpass filters (BPF) or erbium-doped fiber amplifiers (EDFA). In our current experiment, we used overall four channels having an optical bandwidth of approximately 80 GHz each, which leads to an overall acquisition bandwidth of 320 GHz. Note that the bandwidth of spectrally sliced OAWM receivers can be further increased by simply adding more channels, without any penalties regarding the signal quality. This is an advantage over easier-to-implement non-sliced OAWM schemes [9], where an increase of the channel count leads to a decrease of the RF power at the IQR outputs and may thus introduce additional noises and distortions [10]. Figure 1(b) shows an illustration of an OAWM MCM, which is also electrically packaged using dedicated RF fan-out PCB. We have designed such PCB with densely spaced pads close to the edge such that it can be connected to the SiP PIC via short electric wire bonds. The PCB also contains biasing circuits for the BPD, which can be accessed through DC pin headers. The functionality of the PCB and the associated RF interface to the silicon PIC was independently tested and confirmed, even though the subsequent demonstration experiments still relied on electrical probing of the optically packaged chips. Figure 1(c) shows top views of the OAWM MCM Ⓐ, the LSF module Ⓑ, and the FCG module Ⓒ. The OAWM MCM consists of a copper-tungsten (CuW) submount, which carries the SiP IQR array, the pair of Si_3N_4 AWG, and a pair of single-mode fiber arrays (FA). The Si_3N_4 AWG die is 5 mm long and 1 mm wide – much smaller than previously used PLC-based AWG with widths/lengths of several centimeters. Within the OAWM MCM, the optical devices are connected by a total of 26 photonic wire bonds (PWB) [7,8] that can efficiently interface to a wide range of integration platforms and that are hence key to flexible multi-chip assemblies. The PWB were printed with a commercially available machine (Sonata 1000, Vanguard Automation GmbH) using negative-tone resist (VanCore B, Vanguard Automation GmbH, refractive index n = 1.53). The losses of the PWB amount to approximately 2.4 dB per bond, which may be further reduced by applying a low-index overcladding. The orange lines in Ⓐ indicate the contours of the RF PCB, which themselves are not shown. The LSF filter module Ⓑ is also electrically connected to a breakout PCB via electric wire bonds.

3. Characterization and functional demonstration

To demonstrate the viability of the OAWM receiver assembly, we use it for receiving a broadband WDM signal. Figure 2(a) shows the spectrum of the Kerr comb (gray, FSR approx. 40 GHz) before the LSF module. The LSF module is adjusted to select every second comb line, marked in blue in Fig. 2(a), to obtain four LO tones spaced by 80 GHz with a suppression of 22 dB of the unwanted lines in between. These unwanted lines are further suppressed by the LO AWG integrated in the OAWM receiver assembly such that the rather limited suppression of the current LSF implementation is sufficient. Figure 2(b) shows for the measured on-chip transmission characteristics of the AWG pair used for LO-tone separation and signal slicing. The LO AWG, top panel of Fig. 2(b), is designed to have narrow-band transmission to avoid crosstalk between neighboring channels and to suppress the amplified spontaneous emission (ASE) noise introduced by the EDFA. In contrast, the signal AWG, bottom panel of Fig. 2(b), is designed to have a flat-top transmission along with spectral overlap regions between neighboring channels to provide redundant information for later spectral stitching. For seamless spectral stitching, it is beneficial to have –3 dB cross points, indicated by red circles in Fig. 2(b), at the overlaps between neighboring channels. The signal AWG features higher on-chip insertion loss of around 6 dB, in contrast to 3 dB found for the LO AWG. To match the spacing of the selected comb lines, both AWG are designed to have a channel spacing of 80 GHz. Correct absolute frequency alignment is ensured by placing the AWG pairs side-by-side in the fabrication layout to mitigate the impact of non-uniformity of the Si_3N_4 device layer thickness. In our experiment, we could not yet rely on the RF fan-out PCB and had to use RF probes to extract electric signals from the IQR array. The overall eight electric signals from four tributaries are then routed via coaxial cables to eight ADC provided by two synchronized high-speed real-time oscilloscopes (Keysight UXR series). The OAWM MCM is calibrated by sending an optical reference waveform with known amplitude and phase derived from a solid-state mode-locked femtosecond laser (Menhir-1550) to the signal input, see [6] for a more detailed explanation. This allows to extract the complex-valued opto-electric transfer functions of each channel, accounting for the optical characteristics of the PWB, the on-chip waveguides, the signal AWG filters, the on-chip IQR, and additional fiber-optic components, as well as for the electric characteristics of the RF probes and the subsequent coaxial cables. We use the calibrated system to acquired optical signal consists of three wavelength-division-multiplexed (WDM) 16QAM signals with symbol rates of up to 100 GBd covering an overall bandwidth of 320 GHz. Figure 2(c) shows the spectrum of the reconstructed signal (red) along with the receiver noise (gray), which was recorded in a separate measurement with all signals disconnected and the same DSP applied. The receiver noise spectrum indicates a strong frequency roll-off of each channel, which has to be compensated digitally and leads to noise enhancement toward to edges of each spectral slice. This roll-off results mainly from the GSG probes and long coaxial cables, which leaves a room for improvement by using the dedicated RF fan-out PCB. Still, the OAWM MCM works fairly well – constellation diagrams of the reconstructed WDM signals are shown in Fig. 2(c), and the bit error ratios (BER) are still well below the 7% soft-decision forward error correction (SD-FEC) limit [11]. To the best of our knowledge, the 320 GHz demonstrated in these experiments represents the highest bandwidth achieved so far in a PIC-based spectrally sliced OAWM system.

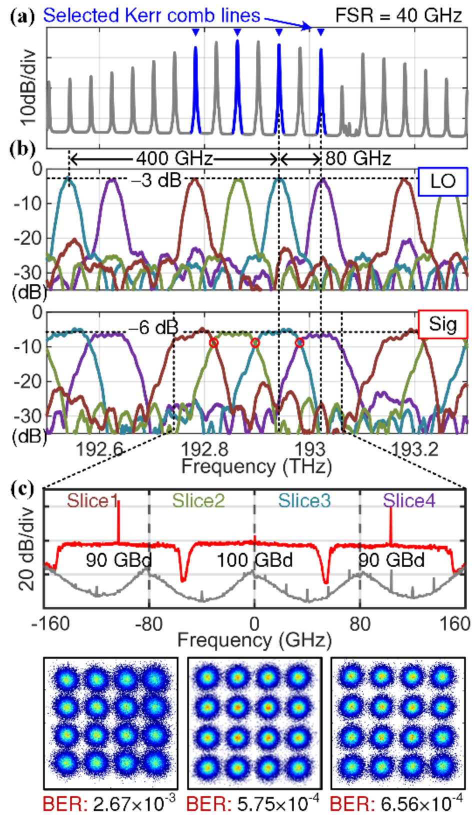

Fig. 2 Characterization and functional demonstration of the spectrally sliced OAWM system. **(a)** Optical spectrum of the Kerr soliton comb (FSR approx. 40 GHz) before the line-selection-and-flattening filter (LSF) module. For the OAWM experiment, we select every second comb line (indicated in blue), leading to a line spacing of 80 GHz. **(b)** Measured transmission curves of the LO (top) and signal (bottom) AWG filters. The LO AWG is designed to have good isolation, while the signal AWG is designed to have spectral overlaps between neighboring channels with –3 dB cross points (red circles). Both AWG have a channel spacing of 80 GHz to match with the selected comb tones. **(c)** Functional demonstration of the OAWM engine by receiving a 320 GHz WDM signal consisting of two 90 GBd and one 100 GBd 16QAM signal. The red curve represents the spectrum of the reconstructed signal merged from four spectral slices, while the gray curve shows the stitched receiver noise spectrum obtained in a separate measurement with all optical signals disconnected. All WDM channels can be demodulated with a bit error ratio (BER) below 7% soft-decision forward error correction (SD-FEC) limit [11]. The strong carriers visible for the two 90 Gbd signals was caused by a non-ideal biasing of the IQ modulator at the transmitter.

4. Summary

We have demonstrated the first optically packaged spectrally sliced OAWM receiver module that combines spectral slicing filters and IQ receivers in a hybrid multi-chip module (MCM). The assembly relies on 3D-printed photonic wire bonds (PWB), offering efficient single-mode interfaces to a wide range of PIC technologies. Our OAWM MCM offers a bandwidth of 320 GHz – the highest value so far demonstrated for PIC-based spectrally sliced OAWM systems. We believe our approach paves a path towards practical use of integrated spectrally sliced OAWM systems in various applications.

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