200 GBd 16QAM Signals Synthesized by an Actively Phase-Stabilized Optical Arbitrary Waveform Generator (OAWG)

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Abstract: We implement an optical arbitrary-waveform generator (OAWG) that relies on spectrally sliced signal synthesis with well-defined feedback-stabilized phase relations. We demonstrate the viability of the approach by generating high-quality 16QAM signals with record-high symbol rates of up to 200 GBd.

1. Introduction

Optical arbitrary waveform generation (OAWG) based on frequency combs [1–3] has the potential to unlock a wide variety of applications, ranging from generation of high-symbol-rate data signals and elastic optical networking [1, 2] to photonic-electronic digital-to-analogue conversion (DAC) [4] and quantum optics [5]. In contrast to line-by-line pulse shaping, which is based on static adjustment of individual comb tones in amplitude and phase [6] and typically leads to time-periodic signals, generation of truly arbitrary waveforms [1–3] requires high-speed modulation of comb tones to produce a continuous spectrum with the desired phase and amplitude. However, while broadband modulation of comb tones has been demonstrated, e.g., for generating high-symbol rate communication signals [1, 2, 7], phase-stabilized superposition of the resulting tributary signals still remains a challenge. As a consequence, the waveforms generated in previous experiments [1, 2, 7] were subject to unwanted distortions, which, in case of optical data transmission, required either a selection of data signals with correct phase relations [2] or non-standard data-aided signal processing techniques at the receiver [7]. None of these approaches can be transferred to practical optical communication systems, where receiver implementations should be independent from the specifics of the transmitter.

In this paper, we demonstrate an OAWG system that relies on real-time phase control for coherent superposition of spectrally sliced tributary signals with the desired phase relations. The scheme exploits passive combiner elements with multiple output ports to continuously monitor interference signals, that are generated by overlapping spectral portions of neighboring spectral slices and that are used as a feedback to stabilize the phase relations between the superimposed tributary signals in a closed control loop. Our approach allows for precise continuous synthesis of the desired arbitrary waveforms and is scalable to THz bandwidths by cascading signal combiners in a tree-like structure. We demonstrate the viability of the scheme by generating a 200 Gbd 16QAM waveform from two separate 102 GHz-wide tributary signals. To the best of our knowledge, this is the highest symbol rate so far achieved for true 16QAM signaling.

2. Concept of active phase stabilization

The concept of the actively stabilized OAWG system is depicted in Fig. 1(a). Narrowband tones at frequencies f_1, f_2 ... f_N derived from an optical frequency comb generator (OFC) are separated by a demultiplexing (DEMUX) filter and individually modulated by an array of N in-phase/quadrature modulators (IQM $1 \dots N$), which are driven by an array of $2N$ digital-to-analogue converters (DAC). The tributary spectral slices generated by the IQM are then combined in a binary tree of $(N-1)$ signal-combining elements (SCE), each merging two spectrally neighbouring slices see Fig. 1(b,e). In the following, the targeted optical waveform obtained by merging all tributaries is represented by its analytic time-domain signal $\underline{a}_\mathrm{s}(t)$ or the corresponding Fourier transform $\underline{\tilde{a}}_\mathrm{s}(f)$, and the various tributary signals are denoted accordingly as $\underline{a}_\nu(t)$ and $\underline{\tilde{a}}_\nu(f)$, respectively, $\nu = 1 \dots N$. Each SCE contains a passive combiner with multiple output ports, where the targeted optical waveform is formed at one of the ports ('signal port') whereas the other ports are used to generate the monitoring signals that are needed for continuous phase control ('monitoring ports'). In the implementation used in this work, the SCE relies on a 90° optical hybrid as a widely available device, see Fig. 2(c). Note, however, that the scheme can also be implemented with passive signal combiners, such as 3×3 multi-mode interference couplers (MMI) where only two input ports are used. To generate the desired feedback signal for phase control, neighboring tributary signals are designed to have slightly overlapping spectra, see Fig. 1(e), that lead to phase-sensitive interference signals at the monitoring ports of the passive signal combiner. For an implementation based on a 90° optical hybrid (OH), we denote the various output ports by '+1', '−1', '+j', and '−j', depending on the relative phase with which the two input signals are superimposed, see Fig. 1(c). Output '+1' serves as the signal port, whereas Output '−1' is left unused and Outputs '+j' and '−j' serve as monitoring ports, being connected to the two input ports of a balanced photodetector (BPD) to generate the desired feedback signal. This feedback signal is processed in a controller, which drives a phase shifter (PS) at one of the input ports of the OH. In the following, we consider exemplarily the SCE that merges tributary signals $\underline{a}_1$ and $\underline{a}_2$, see Fig. 1(c). $\Delta\varphi$ denotes the deviation from the desired phase, with which

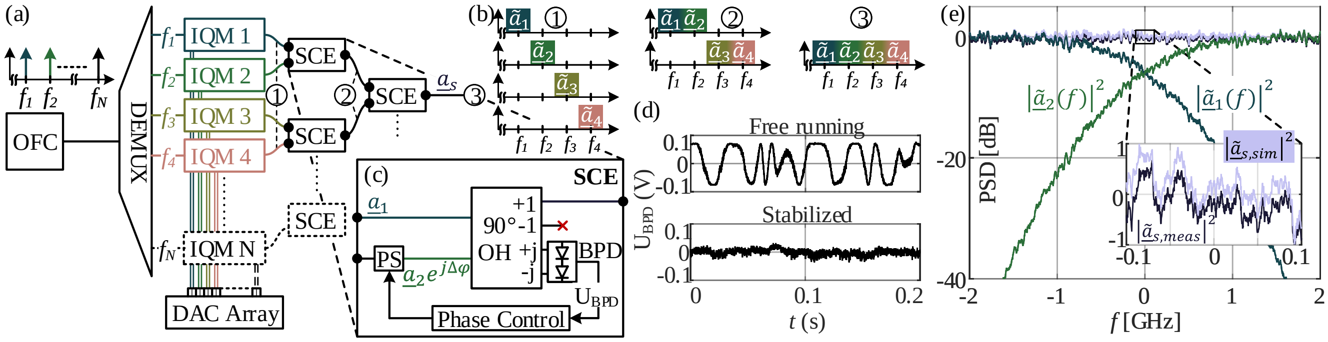

Fig. 1. (a) An optical frequency comb (OFC) provides N frequency tones, which are separated by a demultiplexing (DEMUX) filter and modulated by an array of $2N$ IQ-modulators (IQM), driven by an array of digital-to-analog converters (DAC). After the modulators, the spectral slices are combined by a binary tree of signal-combining elements (SCE) to ultimately form the full OAWG output signal $\underline{a}_S(t)$. (b) Spectral representation of the signal spectra at stages ①-③ indicated in Subfigure (a). (c) Detailed representation of a SCE implemented based on a 90° optical hybrid (90° OH) as passive optical combiner. The superimposed optical waveform is formed at Output '+1', whereas Outputs '+j' and '−j' are connected to a balanced photodetector (BPD) to generate the feedback signal. A controller and optical phase shifter (PS) complete the feedback control system. (d) Feedback signal u_{BPD} for a free-running and stabilized SCE. (e) Overlap region of neighbouring spectral slices for the case of a 16QAM signal synthesized from two tributaries. $|\tilde{\underline{a}}_1(f)|^2$ and $|\tilde{\underline{a}}_2(f)|^2$ denote the simulated spectra for the signal tributaries, and $|\tilde{\underline{a}}_{s,\mathrm{meas}}(f)|^2$ is the simulated superimposed waveform, which shows excellent agreement with its measured counterpart, recorded at the ouput of a single-stage SCE, see inset. All PSD are normalized to the the average PSD in flat-top spectrum area. For better visibility, all spectra were smoothed with a moving-average filter with 100 taps.

the tributary signals $\underline{a}_1$ and $\underline{a}_2$ should be superimposed at the signal port (Output '+1'),

$$\underline{a}_s(t) = \underline{a}_1(t) + \underline{a}_2(t)e^{j\Delta\varphi(t)} \tag{1}$$

The optical signals at Outputs +j and -j can then be written as

$$\underline{a}^{(+j)}(t) = \underline{a}_1(t) + j\underline{a}_2(t)e^{j\Delta\varphi(t)}, \qquad \underline{a}^{(-j)}(t) = \underline{a}_1(t) - j\underline{a}_2(t)e^{j\Delta\varphi(t)} \tag{2}$$

Exploiting the fact that only spectrally overlapping signal components of $\underline{a}_1(t)$ and $\underline{a}_2(t)$ contribute to the low-frequency components processed by the control loop, the output $u_{\mathrm{BPD}}(t)$ of the BPD can be expressed as

$$u_{\mathrm{BPD}}(t) = C\sin(\Delta\varphi(t)) \approx C\Delta\varphi(t) \tag{3}$$

where the proportionality constant C includes various linear factors like the power of the tributary signals within the overlap region, the responsivity of the BPD, or the trans-impedance amplifier gain. The linear approximation in Eq. (3) is valid for $\Delta\varphi \ll 1$, i.e., in the vicinity of the desired operating point of the phase control loop, such that the problem can be addressed by a simple linear PI controller. The effectivity of the control loop is illustrated in Fig. 1(d), where the monitor signal $u_{\mathrm{BPD}}(t)$ is recorded for the free-running system with disabled PI controller (top) and for the stabilized system with the PI controller activated (bottom).

Note that the control scheme described above relies on tributary signals that have approximately constant spectral power in the overlap region, which is the case for the data signals considered in the next section. For arbitrary signals that have no or only strongly time-dependent spectral components in the overlap region, the phase control can also rely on pilot tones that are added to the tributary signals and that cancel in the superimposed waveform, while leading to a constant non-zero amplitude factor C of the control signal according to Eq. (3).

3. Functional demonstration: 200 Gbd 16QAM signaling

We demonstrate the viability of our approach by synthesizing a 200 Gbd 16QAM signal from two tributary signals, see Fig. 2(a). Including the roll-off, the spectrum of the synthesized data signal is 202 GHz wide, and the spectral width of each slice amounts to approximately 102 GHz, thus leading to 2 GHz of spectral overlap, see Fig. 2(b) for the spectra of the tributary signals. To generate the underlying comb tones, we use a Mach-Zehnder Modulator (MZM) that is fed by a narrow-linewidth external-cavity laser (ECL) and that is operated at the null point by a radio-frequency oscillator (RF-Osc) with a sinusoidal 50 GHz tone. This leads to two tones spaced by 100 GHz, which are separated by a wavelength-selective switch (WSS) and sent to two IQM for generating the two tributary signals $\underline{a}_1(t)$ and $\underline{a}_2(t)$. The IQM are driven by an electric arbitrary-waveform generator (AWG, Keysight M8194A) featuring four DAC channels with nominal 3 dB-bandwidth of 45 GHz. The AWG is synchronized to the RF oscillator driving the MZM, thus ensuring stable frequency spacing between the tributary signals. After the IQM, each tributary signal is amplified, filtered to reduce out-of-band amplified spontaneous emission (ASE) noise of the EDFA, and then sent to the SCE for phase-controlled superposition. The SCE relies on a 90° optical hybrid, see Fig. 1(c). The control algorithm is implemented on an FPGA development platform (XilinX Zynq UltrasScale+), and a piezo-based fiber phase shifter (model FPS-003, General Photonics Corp., VA, USA) with an effective system bandwidth of approximately 20 kHz is used to adjust the phase of the second tributary signal. The AWG are configured to repeat the stored waveforms,

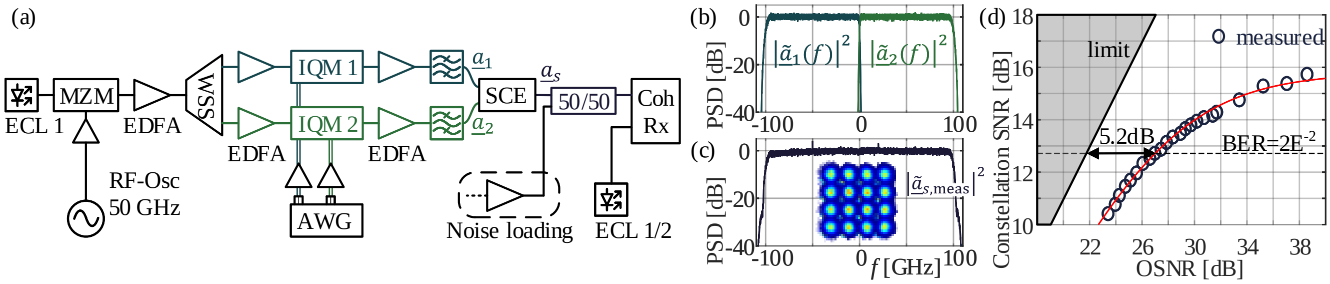

Fig. 2. Measurement setup and results (a) Experimental setup: The tone of an external-cavity laser (ECL 1) is modulated by Mach-Zehnder modulator (MZM) and an RF oscillator (RF-Osc) to generate two carriers, that are separated by wavelength-selective switch (WSS). IQ-modulators (IQM) and electric arbitrary-waveform generators (AWG) are used to generate the optical tributary signals. A signal-combining element (SCE), Fig. 1(c), is used to superimpose the tributaries with the desired phase relation, and the resulting waveform $\underline{a}_{\mathrm{S}}(t)$ is the fed to a high-speed coherent receiver (Coh Rx). The generated signal can optionally be loaded with additional noise power. (b) Simulated power spectral density (PSD) of the spectral slices $|\underline{\tilde{a}}_1(f)|^2$ and $|\underline{\tilde{a}}_2(f)|^2$. (c) Measured PSD and constellation diagram of a generated 16QAM signal. (d) Constellation SNR measurements for different optical signal-to-noise power ratios (OSNR). The implementation penalty amounts to 5.2 dB.

thus generating continuous tributary signals. Due to the rather low bandwidth of the BPD and the subsequent control loop, the amplitude C of the feedback signal in Eq. (3) corresponds to an average over thousands of 'symbols' and can thus be considered essentially constant. To adjust the optical signal-to-noise power ratio (OSNR), the generated waveform $\underline{a}(t)$ at the output of the SCE is loaded with flat-top additive white Gaussian noise (AWGN) with variable optical power density before being sent to a high-speed coherent receiver (Coh Rx) that comprises another 90° optical hybrid and a high-speed BPD with a nominal bandwidth of 100 GHz (Fraunhofer HHI, Berlin). As a local oscillator (LO), we either use the transmit laser (ECL 1) or and independent device (ECL 2). Homodyne reception with ECL 1 as LO turned out to simplify precise calibration of the frequency-dependent transfer function of the AWG and associated IQM, which were operated at their bandwidth limits. Once calibrated, the system can be operated in intradyne mode without any performance penalties. The output of the BPD is digitized by a high-speed real-time oscilloscope (Keysight UXR1004A), having a nominal bandwidth of 100 GHz, and then processed further by offline digital signal processing (DSP). The DSP chain contains standard coherent receiver algorithms including timing recovery, equalizer, carrier recovery and post-equalizer. Figure 2(b) shows the simulated spectra of the two tributary signals $\underline{a}_1(t)$ and $\underline{a}_2(t)$, recorded by homodyne reception, and Fig. 2(c) shows the measured spectrum of the combined signal with the corresponding constellation diagram. The evolution of the constellation signal-to-noise ratio (SNR) of our received signal as a function of the OSNR is depicted in Fig. 2(d). We find that the OSNR penalty of our recovered signal compared to the theoretical limit is only 5.2 dB, measured at a constellation SNR of approximately 13 dB, which corresponds to a BER of 2×10^{-2}. To the best of our knowledge, the demonstrated 200 GBd is the highest symbol rate achieved for true 16QAM signalling [8], outperformed only by OTDM-based schemes, where subsequent symbols do not have a fixed phase relationship [9].

4. Summary

We demonstrated an OAWG system that relies on precise superposition of spectrally sliced tributary signals with the desired phase relationships. The scheme exploits interference signals generated by spectrally overlapping portions of neighboring slices for feedback-stabilization of the phase relations and allows for precise synthesis of signals over arbitrary length. We demonstrate the viability of the scheme by generating a 200 Gbd 16QAM signal at an implementation OSNR penalty of 5.2 dB. To the best of our knowledge, this is the highest symbol rate so far achieved for true 16QAM signaling.

Acknowledgements: This work was supported by the DFG project GOSPEL (no. 403187440) within the Priority Programme SPP 2111, by the ERC Consolidator Grant TeraSHAPE (no. 773248), by the BMBF project Open6GHub, by the EU H2020 Marie Skłodowska-Curie Innovative Training Network MICROCOMB (no. 812818), by the Alfried Krupp von Bohlen und Halbach Foundation, by the Max-Planck School of Photonics (MPSP), and by the Karlsruhe School of Optics & Photonics (KSOP).

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