

Continuous, Real-Time, Full-Field Waveform Measurements via Spectral Slicing and Parallel Digital Coherent Detection

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Abstract: Single-shot, amplitude and phase characterization of 160-GHz bandwidth optical waveforms with 2- μ s record lengths using a bandwidth- and time-record scalable technique based on parallelized balanced four-quadrature homodyne detection and DSP reconstruction.

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1. Introduction

Current optical fiber systems are achieving terahertz bandwidths by employing advanced amplitude/phase modulation formats and coherent optical techniques [1, 2], making the capability to characterize the full-field (amplitude and phase) of wide-bandwidth optical waveforms with high sensitivity a crucial factor in the development of high performance optical communications technologies. In many of the modulation formats, it is not sufficient to quantify only the temporally varying optical intensity, instead the full-field optical waveforms must be measured [2]. Also, since it is often necessary to investigate bit-pattern dependent and time-varying effects, measurements for long record lengths (time duration) in a single-shot are particularly advantageous.

The availability of gigahertz bandwidth electronic digitizers has renewed interest in optical digital coherent receivers [3] for fiber-optic communications. This is primarily because high-speed sampling of the received signals has enabled optical reference phase estimation without the use of phase-locked loops (PLLs) [2, 3]. It is possible for optical digital coherent receivers to measure the full optical field of a signal waveform by digitizing the photodetected signals from a phase-diversity (multiport) homodyne receiver [4] and then reconstructing the in-phase (I) and quadrature-phase (Q) signals (i.e., full field) using digital signal processing (DSP) [5]. However, the total measurement bandwidth is limited by currently available digitizers to just a few tens of gigahertz and direct scaling to larger optical bandwidths relies solely on the relatively slow progress of analog-to-digital converter (ADCs) performance. This paper describes a parallelized implementation of the optical digital coherent receiver to perform continuous, real-time full-field optical waveform measurements with scalable bandwidth. We demonstrate greater than 160 GHz of instantaneous bandwidth with 2 μ s record lengths (500 kHz spectral resolution), which is the largest record-length-to-resolution ratio (>320,000) of any single-shot, full-field waveform characterization method.

2. Real-time OAWM concept and experimental implementation

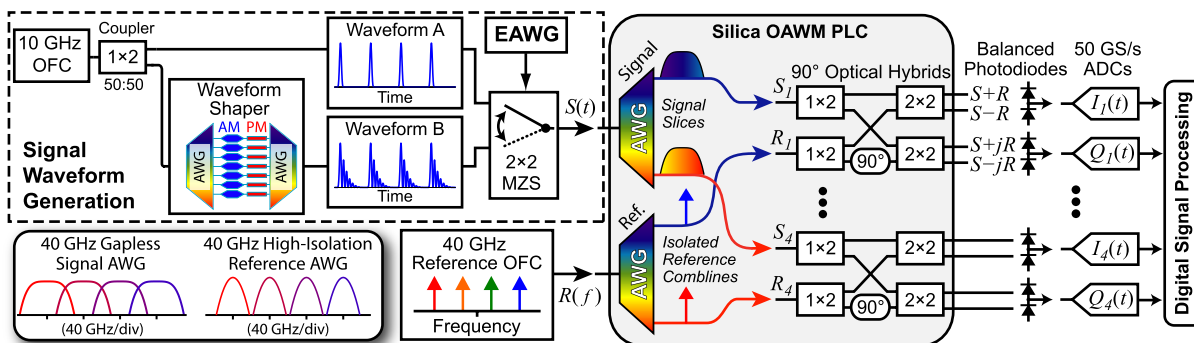


Fig. 1. Illustration of the real-time optical arbitrary waveform measurement (OAWM) concept and demonstration. Inset shows idealized passband transmissions for the signal and reference AWGs on the silica OAWM PLC. EAWG; electrical arbitrary waveform generator.

Since this measurement technique is analogous to optical arbitrary waveform generation (OAWG) [6], we refer to it as real-time optical arbitrary waveform measurement (OAWM). Broadly speaking, OAWM uses spectral slicing of the optical signal with parallel optical homodyne detection using an optical frequency comb (OFC) as a reference. Spectral slicing is conceptually similar to bandwidth interleaving or frequency interleaving [7] techniques used in some high-speed digitizers. Starting with the silica OAWM planar lightwave circuit (PLC) of Fig. 1, a gapless arrayed-waveguide grating (AWG) spectrally slices (demultiplexes) the large optical bandwidth, time-varying signal waveform, $S(t)$. Simultaneously, a narrow-passband AWG strongly isolates each line of the reference OFC, $R(f)$. In

a parallel manner, each spectral slice, centered on a single combline, is demodulated to baseband I/Q signals using homodyne four-quadrature coherent balanced detection in the time-domain [4]. The I/Q signals of each slice's are digitized and then digital signal processing (DSP) directly reconstructs the measured signal waveform. Of course, knowledge of the signal multiplexer's transmission function, the photodiodes' and digitizers' electronic responses, and the reference OFC amplitude and phase (obtainable by various multi-shot characterization techniques or even through self-calibration) are all required for accurate reconstruction.

A clear demonstration of real-time OAWM requires sufficiently complex, yet stable and predictable optical signal waveforms that contain both wide bandwidths and slowly varying temporal features. The left side of Fig. 1 (dashed box) shows how complex signal waveforms are created by time interleaving Waveform A and Waveform B [8] using a 30 GHz 2×2 Mach-Zehnder switch (MZS) driven by a 10 GHz electrical arbitrary waveform generator (EAWG). Waveform A is a 160 GHz-wide, transform-limited, sinc^2 -like pulse with a rectangular spectral envelope and a flat spectral phase directly from the 10 GHz OFC. While Waveform B is crafted via static OAWG (i.e., line-by-line pulse shaping) [9] using a 10 GHz silica PLC based waveform shaper [10]. The intensity and phase of the 16 OFC combines are adjusted to create a waveform with a Gaussian spectral envelope, cubic spectral phase and 160 GHz full optical bandwidth. The output of the 2×2 MZS is a waveform which is composed of various sequences of waveforms A and B (e.g., all As, all Bs, ABAABBAAA..., etc.), whose repetition rate and pattern are controlled by the EAWG which allows pseudo-random A-B sequences of word lengths up to $2^{23}-1$.

A separate, but spectrally overlapping, 4 line \times 40 GHz OFC provides the OAWM reference signal, $R(f)$. The real-time OAWM experiment employs a custom designed silica PLC which integrates all passive optical components necessary to implement spectral slicing and parallel four-quadrature optical coherent detection. Single-mode fiber arrays couple signals in and out of the PLC. Balanced detection (i.e., homodyne downconversion) and digitizing occur off-chip using 40 GHz balanced photodiodes and eight 50 GS/s ADCs that are part of two separate four-channel real-time oscilloscopes. The OAWM PLC incorporates the two arrayed-waveguide gratings (AWG) spectral demultiplexers and an array of 90° optical hybrids. Both AWGs have the same center frequency and 40 GHz channel spacing to match the reference OFC. However, each AWG is designed to serve a distinct function; one as a high-isolation demultiplexer for the reference comb and the other as a gapless demultiplexer for signal slicing (see inset of Fig. 1). Each of the signal spectral slices (i.e., S_1, S_2 , etc.) are directed to the signal input of an optical hybrid and each reference combline (i.e., R_1, R_2 , etc.) goes to the reference input of the corresponding optical hybrid. Then, each hybrid combines a spectral slice in four quadrature phases with a single reference combline where $I_+ = S + R$, $I_- = S - R$, $Q_+ = S + jR$, and $Q_- = S - jR$. The I_+/I_- and Q_+/Q_- signals are routed to balanced photodiodes to generate their respective I and Q signals, then the eight signals are digitized at 50 GS/s with 8 bits of resolution. In DSP, these digitized signals are Fourier transformed to the frequency domain and processed as follows to obtain the full optical field of that spectral slice. The field in the i -th slice is $S_i(f - f_i) = H_i(f) \times [E_{I_i}(f)I(f) + jE_{Q_i}(f)Q(f)] / R_i^*$ where f_i is the frequency of the i -th reference combline, $H_i(f)$ is the inverse signal spectrum filter, $E_{I_i}(f)$ and $E_{Q_i}(f)$ are the inverse electrical filters for $I(f)$ and $Q(f)$ components and R_i is the phase and amplitude of the i -th reference combline. The processed spectral slices then are combined to reconstruct the final measured waveform.

3. Demonstration and Measurement Examples

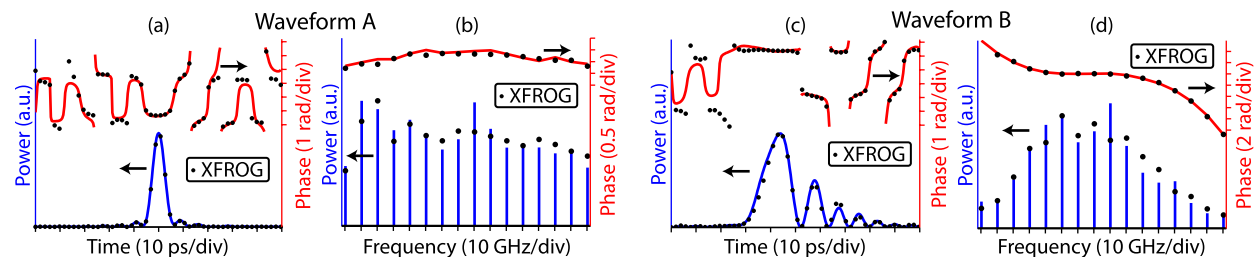


Fig. 2. A comparison between real-time OAWM and XFROG measurements of repetitive waveforms. (a) Temporal and (b) spectral match of Waveform A. (c) Temporal and (d) spectral match of Waveform B.

Measurement demonstrations of real-time OAWM which show its fidelity and capabilities are based on different waveform examples. Fig. 2 shows a comparison between cross-correlation frequency-resolved optical gating (XFROG) and real-time OAWM for a repetitive Waveform A and then Waveform B (10 GHz repetition rate). The solid lines and stems are the averaged signal from a $2 \mu\text{s}$ time record (intensity and phase of each 10 GHz combline) measured by real-time OAWM and the dots are the XFROG results (FROG error, $G < 0.005$ for a 128×128 array) [11]. For both waveforms, the match is extremely close considering that this is an initial demonstration of OAWM.

Fig. 3(a) shows a $2 \mu\text{s}$ time record of a complex waveform as a 2D histogram (similar to an eye diagram) of the intensity by overlaying each consecutive 4 ns frame from the original $2 \mu\text{s}$ single-shot time record into one 4 ns

window (500 windows), one of the few practical methods for showing the full temporal record in a small figure. To better understand the complex waveform and to highlight some of the measurement results, Fig. 3(b) shows the single-shot temporal intensity of the first half of a 4 ns frame starting at 1 μ s with sample points (6.25 ps interval) highlighted. Fig. 3(c,d) and show the same frame with either Waveform B blocked (Fig. 3(c)) or Waveform A blocked (Fig. 3(d)). The switch maximized the extinction of Waveform B between its on and off states rather than Waveform A. In Fig. 3(b), coherent interference effects between Waveform A and Waveform B can be seen when the intensity of the two waveforms are comparable.

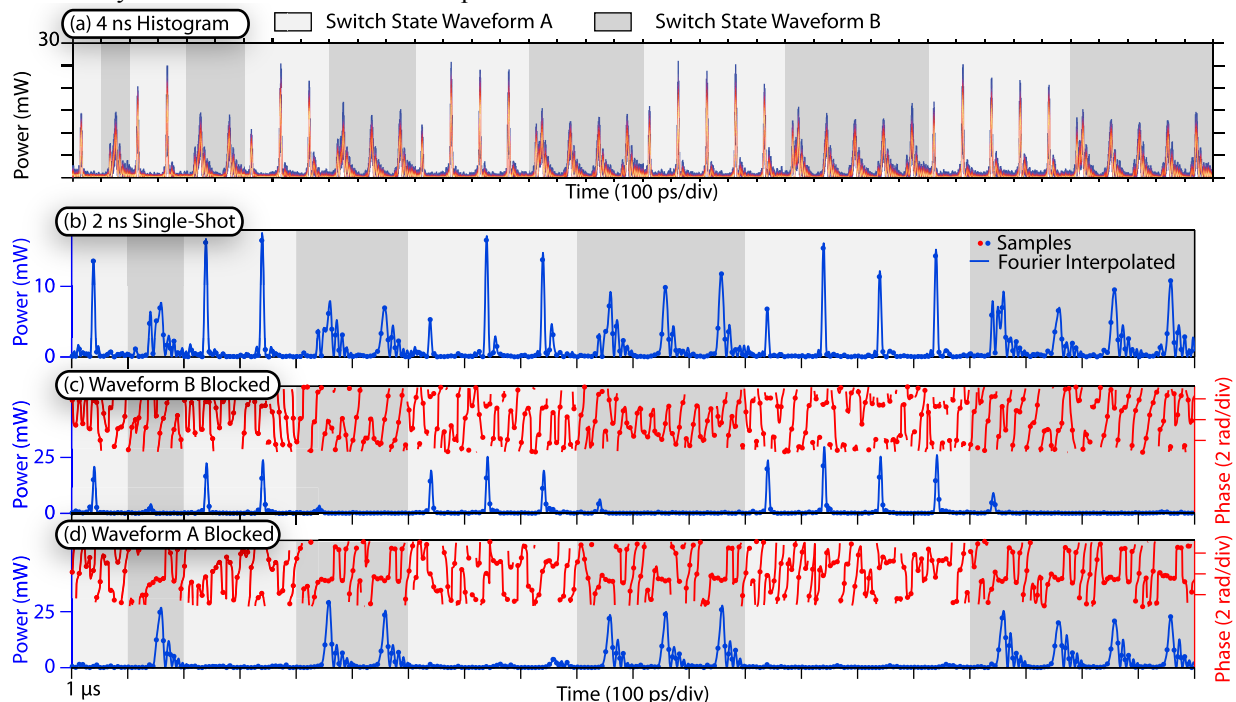


Fig. 3. Real-time OAWM measurement data for a complicated waveform pattern. (a) A histogram of the waveform intensity for the 4 ns pattern created from 2 μ s of total data (phase information not shown for clarity). (b) A 2 ns frame from (a) showing the detailed waveform pattern through all of the A-to-B transitions. (c) Measurement when Waveform B is blocked. (d) Measurement when Waveform A is blocked.

4. Conclusion

We demonstrate full-field waveform characterization with 160 GHz of instantaneous bandwidth and 2 μ s record lengths using a bandwidth- and time-record scalable technique. This approach is passive, does not require any optical nonlinearities and potentially achieves shot-noise-limited sensitivity. It is extendable to other regions of the optical spectrum, scalable to much larger bandwidths with current technologies, and suitable for further integration.

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