Near Quantum-Limited Single-Shot Full-Field Measurements of Arbitrarily Shaped Optical Waveforms

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Abstract: This paper demonstrates single-shot, four-quadrature balanced homodyne detection in the spectral domain for full field measurements of 500-GHz bandwidth 150-aJ optical waveforms with 200-ps record lengths. Results indicate essentially quantum-limited performance.

OCIS codes: (320.5540) Pulse shaping; (320.7100) Ultrafast measurements; (120.5050) Phase measurement.

The capability to measure arbitrarily-shaped ultra-wideband optical waveforms on a single-shot basis, in full amplitude and phase, with near quantum-limited (QL) performance is attractive for many applications including LADAR signal processing, telecommunications, physics, and chemistry. Here we investigate single-shot optical arbitrary waveform measurement (SS-OAWM) employing four-quadrature balanced homodyne detection in the spectral domain[1, 2] (FQSD) for full-field measurement combined with high-extinction ratio (ER) time-gating for single-shot isolation. With a strong ‘reference-waveform’ $\boldsymbol{R}$ FQSD becomes insensitive to noise fluctuations of $\boldsymbol{R}$ allowing near QL measurements[2] over a large dynamic range.

Fig. 1(a,b) show the experimental setup. It consists of optical arbitrary waveform generation (OAWG) to generate a ‘signal-waveform’ $\boldsymbol{S}$ for measurement using SS-OAWM. The OAWG here manipulates a coherent optical frequency comb (OFC) on a spectral line-by-line basis with precise amplitude and phase control [this is known as static line-by-line Fourier synthesis OAWG (FS-OAWG)] to create waveforms with specification of the electric field approaching THz bandwidths[3, 4]. Fig. 1(c-f) depict representative waveforms at key locations. Fig. 1(c) presents a frequency-resolved optical gating (FROG) measurement of the 10 GHz × 55-line OFC (λ_{center} = 1551 nm). The 10 GHz OFC is crafted into a 100-ps repetitive $\boldsymbol{S}$ via FS-OAWG with a 64-channel single-loopback silica arrayed-waveguide grating waveform shaper[5]. Fig. 1(c-e) illustrate line-by-line control on an OFC [Fig. 1(c)] to craft a fully specified spectrum [Fig. 1(d)] which is an arbitrarily-shaped waveform in the time-domain[Fig. 1(e)].

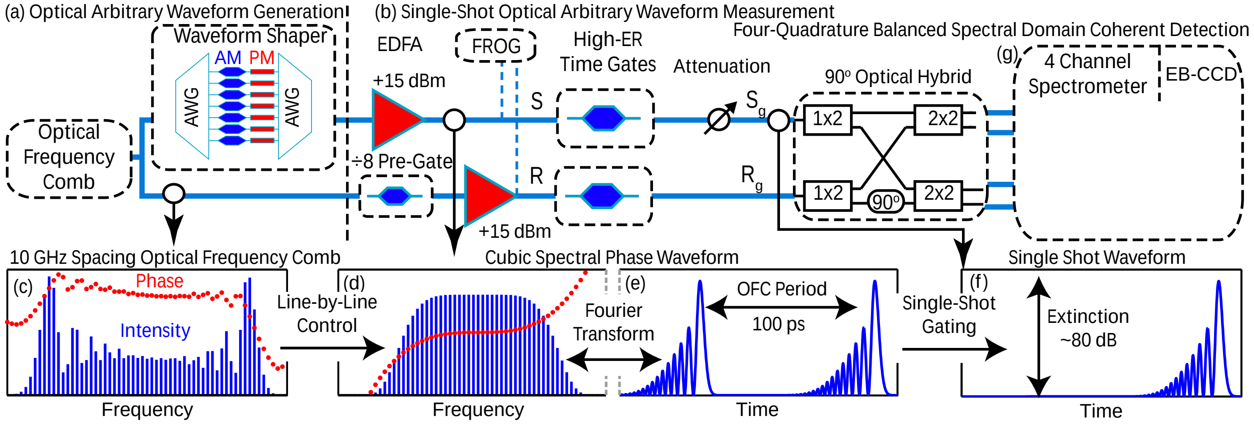

Fig. 1. Experimental arrangement for OAWG and SS-OAWM showing waveforms at key points. (a) Line-by-line FS-OAWG setup. (b) Schematic of SS-OAWM. (c) Measured OFC output spectrum. (d) Example spectrum of a shaped waveform and (e) its time-domain representation. (f) Gated single-shot shaped waveform to be measured. (g) Example measured four-quadrature spectra.

SS-OAWM involves three important steps to measure $\boldsymbol{S}$: 1) isloating a single pulse from $\boldsymbol{R}$ (i.e., $\boldsymbol{R_g}$) and a temporal region of interest from $\boldsymbol{S}$ (i.e., $\boldsymbol{S_g}$) by separate high-ER time gates, 2) accurately measuring the amplitude and phase of $\boldsymbol{R}$ using FROG, and 3) measuring $\boldsymbol{S_g}$ against $\boldsymbol{R_g}$ using FQSD. $\boldsymbol{R}$ is prepared by pre-gating (50 ps wide gate) and amplifing one out of every eight pulses from the OFC producing a 1.25 GHz reference pulse train. For step 1, $\boldsymbol{S_g}$ and $\boldsymbol{R_g}$ are isolated from their corresponding repetitive waveform trains ($\boldsymbol{S}$ and $\boldsymbol{G}$) using two cascaded Mach-Zehnder modulators (MZM) driven by a 10 Gb/s pulse-pattern generator which is synchronized to the OFC via a common 10 GHz oscillator. The cascaded MZMs have a dynamic ER of >80 dB when used on $\boldsymbol{S}$ and $\boldsymbol{R}$. The time gate transmission function is nearly flat across the center 100 ps with rise and fall times of 40 ps. For step 2, $\boldsymbol{R}$ is measured with FROG and an OSA. Ideally, $\boldsymbol{R_g}$ should be characterized however it is far too weak (−100 dBm), and the pre-gating prior to the high-ER time-gating ensures that $\boldsymbol{R}$ and $\boldsymbol{R_g}$ are nearly identical. FQSD (step 3) uses a

90° optical hybrid (OH) to combine $\boldsymbol{R_g}$ in all four-quadratures with $\boldsymbol{S_g}$ and a four-channel spectrometer which uses a gated electron-bombarded (EB)-CCD image intensifier (20 µs gate time, Q.E. of 30%, and gain of 150) to capture the four-quadrature spectra [Fig. 1(g) I_+, I_-, Q_+, Q_-]. Then, the in-phase (I) and quadrature-phase (Q) components of $\boldsymbol{S_g}(\omega) = [I_+(\omega) - I_-(\omega) + jQ_+(\omega) - jQ_-(\omega)]/\boldsymbol{R_g}(\omega)$ are determined by subtracting the two I-quadrature spectra $I_{+(-)}(\omega) \propto |\boldsymbol{R_g}(\omega)|^2 + |\boldsymbol{S_g}(\omega)|^2 + (-)2\mathrm{Re}\{\boldsymbol{S_g}(\omega)\boldsymbol{R_g^*}(\omega)\}$ and Q-quadrature $Q_{+(-)}(\omega) \propto |\boldsymbol{R_g}(\omega)|^2 + |\boldsymbol{S_g}(\omega)|^2 + (-)2\mathrm{Im}\{\boldsymbol{S_g}(\omega)\boldsymbol{R_g^*}(\omega)\}$ followed by division by $\boldsymbol{R_g^*}(\omega)$. The subtraction removes all common noise sources. FQSD with this spectrometer resolution (better than 3 GHz) supports 400 ps record lengths, however $\boldsymbol{S_g}$ is intentionally limited to 200 ps to ensure complete characterization. After all losses (time gates, OH, spectrometer, etc.), 4×10^6 photons (500 fJ) in $\boldsymbol{R_g}$ and up to 80,000 photons (<12 fJ) in $\boldsymbol{S_g}$ are incident on the EB-CCD.

The SS-OAWM system measures $\boldsymbol{S_g}$ (a single-shot of $\boldsymbol{S}$) every 50 ms (20 Hz rate). For each waveform, 200 shots of $\boldsymbol{S_g}$ are recorded for comparison of the measured waveforms' intensity and phase fluctuations to theoretical QL waveforms' fluctuations due to quantum noise (QN). To demonstrate the accuracy of the SS-OAWM technique, Fig. 2(a) shows a comparison between the average of 200 SS-OAWM measurements of a transform-limited waveform shaped using SS-OAWM feedback and independently measured spectral intensity (OSA) and phase (FROG). Note, the SS-OAWM measures a single-shot spectrum ($\boldsymbol{S_g}$) which must be continuous (no temporal periodicity), whereas the FROG and OSA measure a repetitive waveform ($\boldsymbol{S}$) and thus yields discrete frequency comb lines.

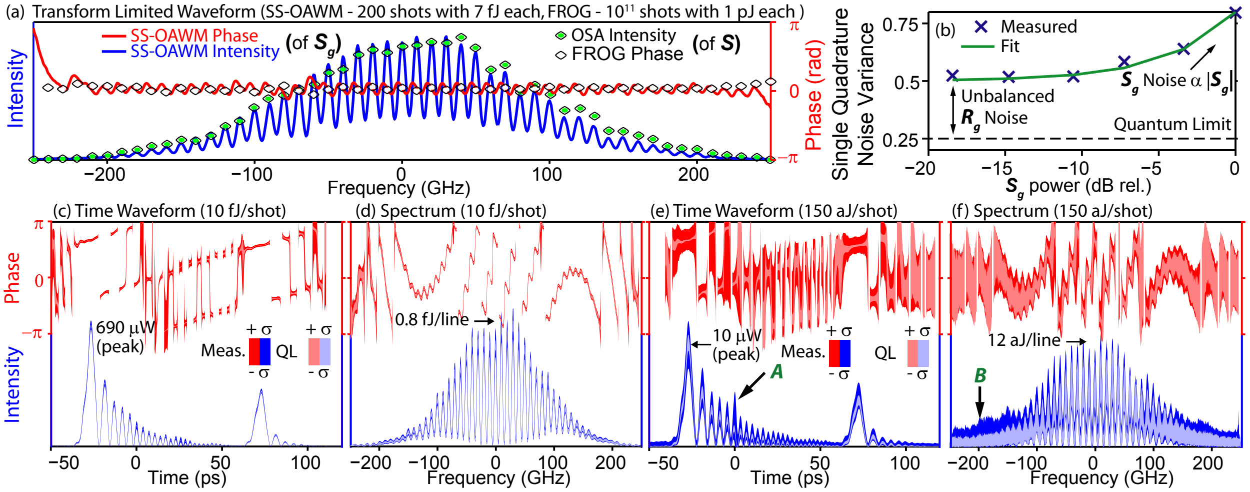

Fig. 2. (a) Comparison of $\boldsymbol{S_g}$ measured with SS-OAWM to independent measurement of $\boldsymbol{S}$. (b) Noise in a single spectral bin. (c,d,e,f) Measured cubic spectral phase waveform and QL simulations. $\boldsymbol{A}$ and $\boldsymbol{B}$ indicate systematic $\boldsymbol{R_g}$ noise introduced through partially unbalanced OH.

Following[2], each mode of the electromagnetic field at a specific frequency (i.e., a spectral bin for $\boldsymbol{S_g}$ or a spectral line for $\boldsymbol{S}$) has a QN variance of ¼ per field quadrature when expressed as a photon number. Fig. 2(b) shows the single-quadrature noise variance within one spectral bin (~1 GHz) while attenuating $\boldsymbol{S_g}$. At weak signal levels QN and $\boldsymbol{R_g}$ noise contributed via imperfect balancing of the OH are dominant. At strong signal levels the excess noise on $\boldsymbol{S_g}$ is dominant. Fig. 2(c-f) show the intensity and phase fluctuations (indicated by ±1 standard of deviation $\boldsymbol{\sigma}$) of 200 SS-OAWM measurements (500 GHz × 200 ps) of a shaped cubic spectral phase waveform with energies of 10 fJ [Fig. 2(c,d)] and 150 aJ [Fig. 2(e,f)] compared to simulated QL waveform fluctuations calculated by adding QN to each field-quadrature in each spectral bin. At 10 fJ the SS-OAWM measurement shows shot-to-shot variations dominated by excess noise on $\boldsymbol{S_g}$. The time-domain intensity fluctuations are 4% compared to the QL fluctuations of 1%. At 150 aJ the waveform fluctuations from QN and $\boldsymbol{R_g}$ noise are dominant. However, the close comparison between measurement and the QL simulation indicate near-QL performance. Finally, the SS-OAWM does not require coherence between $\boldsymbol{R_g}$ and $\boldsymbol{S_g}$, allowing for study of waveforms with rapid shot-to-shot changes such as ASE noise waveforms and waveforms generated by propagation through large lengths of fiber.

References

[1] E. Ip, *et al.*, "Coherent detection in optical fiber systems," *Opt. Express,* **16**, 753-791 (2008).
[2] B. L. Schumaker, "Noise in homodyne detection," *Opt. Lett.,* **9**, 189-191 (1984).
[3] Z. Jiang, *et al.*, "Optical arbitrary waveform processing of more than 100 spectral comb lines," *Nature Photon.,* **1**, 463-467 (2007).
[4] R. P. Scott, *et al.*, "High-fidelity line-by-line optical waveform generation and complete characterization using FROG," *Opt. Express,* (2007).
[5] N. K. Fontaine, *et al.*, "Compact 10 GHz loopback arrayed-waveguide grating for high-fidelity optical arbitrary waveform generation," *Opt. Lett.,* **33**, 1714-1716 (2008).

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