

Integrated, Ultrahigh-Fidelity 17×40 GHz OAWG

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Abstract: We demonstrate ultrahigh-fidelity ($G' < 0.4\%$) optical arbitrary waveform generation using an integrated arrayed-waveguide-grating pair based 128-channel Fourier pulse shaper with computer-controlled-feedback, a 17-mode 40-GHz optical-frequency comb source, and cross-correlation frequency-resolved optical-gating measurements.

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Optical arbitrary waveform generation (OAWG), in which the intensity and phase of an optical source is precisely manipulated on a spectral line-by-line basis to create desired temporal waveforms, offers the ultimate control over light by controlling femtosecond features of the electric field. Such control facilitates generation of THz bandwidth communication signals, emulation of noise sources (ASE), or applications in LIDAR sources. A futuristic implementation of OAWG could consist of an OAWG transmitter and receiver (generator and measurement diagnostic), both of which manage the unrestricted electric field of optical waveforms. This paper investigates an OAWG transmitter and receiver capable of manipulating repetitive 40-GHz waveforms with bandwidths in excess of 5 THz (680 GHz is demonstrated below). Feedback from the OAWG receiver is applied to the OAWG transmitter until the fidelity of the measured waveform no longer improves and the best performance (instrument-limited) is achieved.

Fig. 1 shows the OAWG transmitter and receiver. The transmitter uses a line-by-line [1, 2] Fourier-based waveform shaper (WS) silica arrayed waveguide grating (AWG) pair with 128 channels at a 40 GHz channel spacing and an optical frequency comb generator (OFCG) with 40 GHz spacing and > 17 modes. The phase and amplitude of the light on each wavelength channel can be controlled with > 30 dB amplitude extinction and $> 2\pi$ phase modulation via resistive heater [3] based Mach-Zehnder switches (MZS) and phase modulators (PM). The OFCG generates the comb by strong amplitude and phase modulation of a narrow linewidth laser and subsequent linear compression in a short length (203 m) of single mode fiber. The OAWG receiver uses cross-correlation frequency resolved optical gating (XFROG) to unambiguously and fully characterize the waveform generated by the OAWG-transmitter using the OFCG as a reference (XFROG gate) waveform which is pre-characterized with SHG-FROG [4].

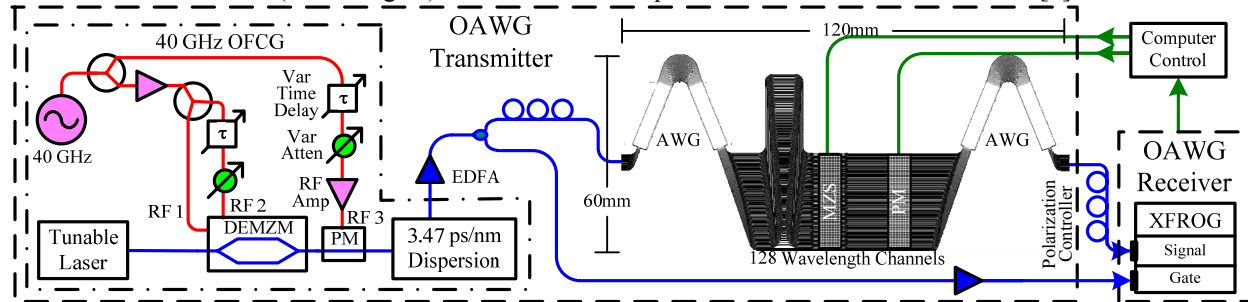


Fig. 1. Experimental setup with the OAWG transmitter and receiver. Electrical (red) and optical (blue) connections, feedback (green). DEMZM: dual-electrode Mach-Zehnder modular, PM: phase modulator, EDFA: erbium-doped fiber amplifier.

Calibrated computer controlled feedback from the OAWG receiver to the intensity and phase channels of the line-by-line WS enables generation of the highest fidelity waveforms reported to date. The fidelity of the system is characterized by an energy-normalized FROG error parameter G' [5] which captures differences in phase and amplitude in both spectral and time domains between a target and a measured waveform simultaneously. Waveform shaping errors are recorded after each iteration to track the computer feedback. The two shaping error indicators are the total spectral domain phase deviation from the target waveform and the total percent spectral intensity error. The experiment utilized two high-fidelity waveforms: a complex waveform spread across the entire temporal window (25 ps) and a transform-limited waveform (1.65 ps). For both waveforms the total phase deviation from the target across 17 modes is 0.2 rad, or < 0.015 rad per mode and approximately 2% spectral intensity error which is believed to be approaching the limits of the OAWG system, which includes the resolution and stability of the XFROG characterization and the computer control to the WS (control resolution is 1.5 mrad). In general, approximately eight iterations or corrections to the amplitude and phase of the WS are required for the G' value stabilize at its minimum

value. Multiple iterations are required due to crosstalk between adjacent channels in the WS, device heating, slight variations in each PM, and unwanted phase modulation from the MZS. Fig. 2(a,b) shows generation of a complex waveform consisting of two pulses positioned at the opposite edges of the time window with opposite cubic spectral phase. It fills the entire time window, and has significant mode-by-mode amplitude and phase variations. Fig. 2(e) shows a table of the G' evolution and waveform shaping errors (intensity and phase) after each iteration. The G' decreases with each iteration, whether the improvement was from lower error in the spectral intensity or phase. The G' for this waveform stabilized after about five iterations at 3.5% with ~ 0.2 rad total spectral phase shaping error and 2% spectral intensity shaping error. If the intensity shaping errors were removed, the G' would drop to less than 0.1%, indicating that this waveform is very sensitive to small intensity shaping errors. Fig. 2(f) shows the time domain intensity error (between the target and measurement) after applying both intensity correction and a calibrated phase correction (i.e., iteration 2), and the final shaped waveform (iteration 8). The differences between the two traces appear small but, the waveform after iteration 2 has a G' of $> 10\%$ and cannot be considered high-fidelity.

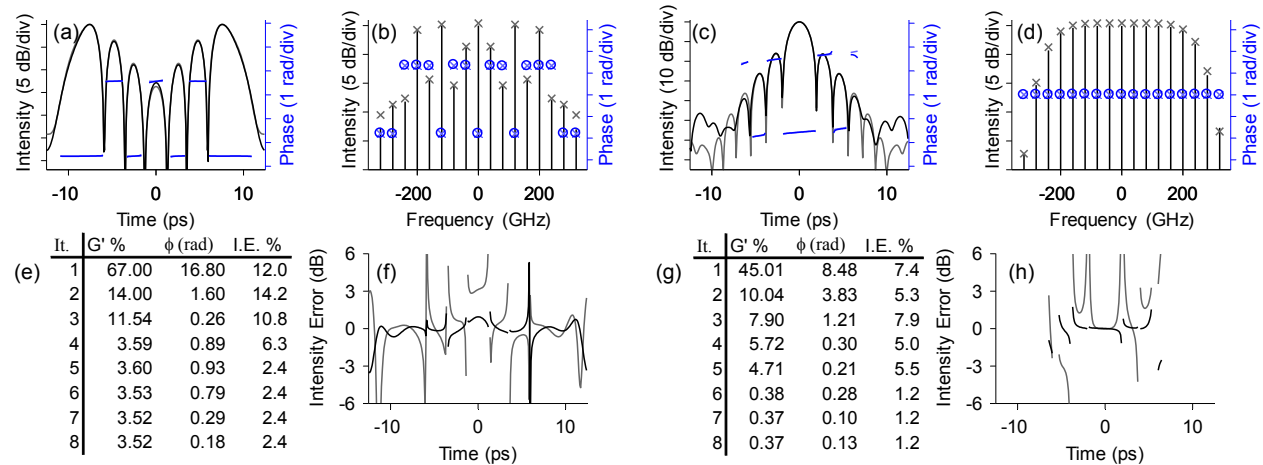


Fig. 2. Complex waveform in temporal (a) and spectral (b) domains. Transform-limited waveform in temporal (c) and spectral (d) domains, phase (blue) intensity (black). Target waveforms (gray). Waveform fidelity (G'), waveform spectral shaping phase error (ϕ) and percent spectral intensity shaping error (I.E.) after each iteration for complex pulse (e) and transform-limited pulse (g). Comparison of temporal intensity error between target and measured at iteration 2 (gray) and iteration 8 (black) for complex waveform (f) and transform limited waveform (h).

Fig. 2(c,d) shows a shaped transform-limited pulse. The temporal phase has a slight linear component due to the asymmetric spectrum. The $0-\pi$ phase jumps and ringing in the time domain, or time domain amplitude flipping from positive to negative are indicative of the sixth-order super-Gaussian spectral intensity envelope. Note, the time-domain intensity is a very close match until intensities are below -50 dB of the peak. Fig. 2(g) shows the trend of G' , phase and amplitude shaping errors after each iteration. After 7 iterations, the G' drops below 1%, and the total phase error is < 0.15 rad. Fig. 2(h) shows the shaped waveform after iteration 2 (just one amplitude and phase correction) and iteration 7 (lowest G'). G' will be larger for complex pulses [5] with similar shaping errors since energy is spread over the entire time window. Displaced energy due to random shaping errors also distributes across the entire time window increasing the overlap between the waveform and shaping error energy, impacting the complex waveform fidelity more than for the transform-limited waveform.

We demonstrated a high-fidelity OAWG system using calibrated computer controlled feedback, compact AWG WS, stable OFCG and XFROG characterization. The best fidelity is determined by iterating until the waveform shaping error no longer improves, and G' value of 0.37% has been achieved. This current OAWG system is capable of shaping the full 128 channels of the WS or 5.1 THz bandwidth, once the OFCG bandwidth is extended.

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