

# Complete Characterization of Precise Line-by-Line Optical Arbitrary Waveform Generation with XFROG

N. K. Fontaine<sup>(1)</sup>, R. P. Scott<sup>(2)</sup>, J. Cao<sup>(1)</sup>, K. Okamoto<sup>(1)</sup>, J. P. Heritage<sup>(1)</sup>, B. H. Kolner<sup>(2)</sup>, and S. J. B. Yoo<sup>(1)</sup>

1: Department of Electrical and Computer Engineering, 2: Department of Applied Science

University of California, Davis, One Shields Ave, Davis, California 95616, email: sbyoo@ucdavis.edu

**Abstract** This paper demonstrates *precise line-by-line optical pulse shaping using an arrayed-waveguide grating (AWG) pair and optical combs. Cross-correlation frequency-resolved-optical-gating characterized complex fields of arbitrary waveforms with phase errors less than  $\pm 0.02$  rad.*

## Introduction

Optical pulse shaping is an active research topic with application to many diverse fields including optical communications, spectroscopy, and electrical arbitrary waveform generation. The technology has progressed from manipulation of the amplitude or phase of large groups of spectral lines to full amplitude and phase control of each spectral line[1-4]. In particular, its capability to generate arbitrary waveforms at very high speeds can potentially enable a very new ultra-high capacity optical communication technique. However, the optical waveforms are not necessarily well characterized. Much of the literature contains only auto- or cross-correlations and corresponding power spectra as proof of a correctly shaped pulse. Yet, there are many waveforms which provide ambiguous autocorrelations or even ambiguous cross-correlations. To truly characterize an optical arbitrary waveform, it is necessary to utilize a diagnostic tool that provides the full complex electric field. Frequency-resolved optical gating (FROG) is one such technique[5]. This paper demonstrates line-by-line optical arbitrary waveform generation and characterization of these waveforms by cross-correlation FROG (XFROG). We also present example optical waveforms that are different even though their intensity cross-correlations are identical.

## Measurement Description

The experimental measurement setup (Fig. 1) consists of an optical frequency comb source, XFROG system, and a pulse shaper based on an AWG pair. The Sakamoto comb generator[6] employs a dual-electrode Mach-Zehnder modulator to produce nine spectral lines (-20 dBc) with 20-GHz spacing through a combination of amplitude and phase modulation of a single-frequency laser line (1551.08 nm). The comb source has an average power of +15 dBm after passing through the erbium doped fiber amplifier (EDFA). A portion of the 20.06-GHz microwave signal that drives the modulator is frequency divided by a factor of two. A harmonically mode-locked fiber laser is phase locked to the resulting 10.03-GHz signal. This laser produces a nearly transform-limited 2.5-ps pulse centered at 1540.5 nm that is used as the XFROG gate pulse. Through this arrangement, the gate pulse

repetition rate is phase locked to the optical comb source repetition rate. The pulse shaper is a silica-based 64-channel AWG pair with both amplitude and phase modulation on each channel. The free spectral range (FSR) is 10.23 nm and the channel spacing is 20.06 GHz. The two AWG's are aligned with each other for maximum throughput by temperature tuning of thermo-electric coolers (TEC) and individual channel amplitude and phase modulation is provided by temperature tuning of resistive heaters. The center frequency of the comb source is adjusted to pass through center of the FSR of the AWG pair. Phase and amplitude modulation is applied to eight channels while leaving one channel constant. Typically, phase tuning of  $\pi$  rad requires  $\sim 0.3$  W of electrical power for resistive heating.

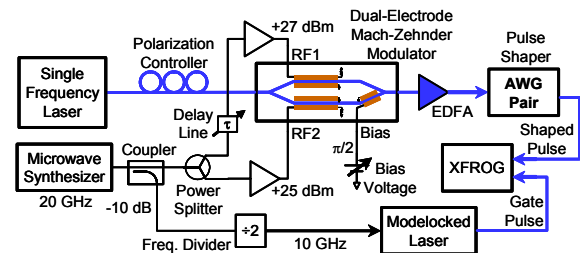


Fig. 1. Diagram of the measurement arrangement.

XFROG line-by-line characterization of an optical waveform forces constraints on data acquisition and processing beyond typical FROG treatments. The XFROG algorithm processes on an  $N \times N$  binned XFROG trace where its frequency step and time window are inversely related and  $N$  is a power of 2. For line-by-line characterization, the frequency step must be equal to the line spacing of the comb source. This constrains the temporal window to the inverse of the line spacing, or the waveform repetition rate. For inclusion of energy at the edges of temporal window, the XFROG algorithm must implement periodic boundary conditions. Further, the binned XFROG trace's center frequency must lie on a spectral line. Otherwise, the spectral lines are incorrectly retrieved which can be confirmed by independent spectral measurements. Since the XFROG traces distribute information about a measured pulse into the time and frequency domain, the XFROG spectrometer does not need to resolve individual lines. Yet, a higher

resolution spectrometer may aid in aligning the optical lines to the frequency bins of the binned XFROG trace. For the following measurements, the XFROG spectrometer had a spectral resolution of  $\sim 15$  GHz at 775 nm and used a low-noise, high efficiency, cooled ( $-10$  °C) CCD camera for detection.

## Results and Discussion

Starting from an amplitude-adjusted comb spectrum with arbitrary phase, we generate and measure four different target waveforms; chirped, constant spectral phase, and two unique  $0-\pi$  pulses. Figs. 2(a,b) show the amplitude adjusted AWG pair output waveform. Its spectral phase appears random and results from the superposition of the frequency chirp from the comb generator and the inherent phase errors of the AWG pair. Iteratively, the phase of the waveform is adjusted and measured until it matches the target waveform. Figs. 2(c,d) show the chirped pulse (quadratic spectral phase). Figs. 2(e,f) show the constant spectral phase pulse. For both waveforms, the spectral phase is within  $\pm 0.02$  rad of the target phase. Note the phase becomes undefined as the intensity approaches zero, as is apparent in the time domain.

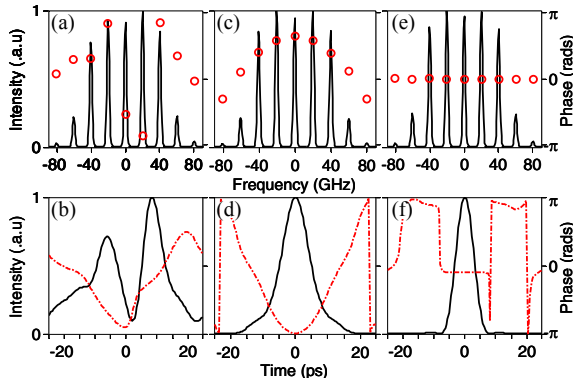


Fig. 2. Retrieved spectral (top) and temporal (bottom) intensity waveforms (solid traces) with corresponding phase (circles or dashed traces) for the AWG pair output with (a,b) uncorrected phase, (c,d) quadratic phase, and (e,f) constant phase.

Power spectra and correlation traces alone are not enough to characterize arbitrary waveforms. An example where identical temporal intensity waveforms result from different optical waveforms is a  $0-\pi$  pulse, one in which there is a zero-to- $\pi$  phase transition in the spectrum. Figs. 3(a-e) show two unique  $0-\pi$  pulses which have their phase transitions occurring at different frequencies (compare Figs. 3(a&d)). They both have identical power spectra, cross-correlations, and autocorrelations. The only difference is the spectral phase of the center frequency (0 GHz) which is apparent in the corresponding XFROG traces (Figs. 3(c&f)) and retrieved field phases. As a further example, Fig. 3(g) shows Fig. 3(a) with simulated random spectral phase errors. Although its cross-correlation (Fig. 3(h)) is different from Fig. 3(b), its

autocorrelation (Fig. 3(i), dashed trace) is not easily distinguished from Fig. 3(a)'s autocorrelation (Fig. 3(i), solid trace). In fact, many would consider the two correlation traces in Fig. 3(i) to be a good indication of a close waveform match.

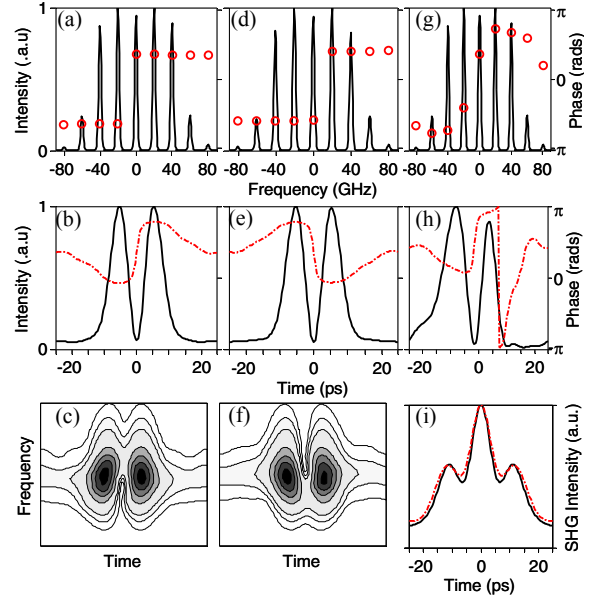


Fig. 3. Retrieved spectral (top) and temporal (middle) intensity waveforms (solid traces) with corresponding phase (circles or dashed traces) and XFROG traces (c,f) for  $0-\pi$  pulses. (g,h) shows random phase applied to (a,b). (i) autocorrelation of (a) as solid trace, (g) as dashed trace.

## Conclusion

We have demonstrated precise line-by-line optical pulse shaping using an optical comb generator and a silica AWG pair. Employing XFROG to characterize the complex electric field of the shaped waveforms allowed generation of shaped pulses with phase errors less than  $\pm 0.02$  rad from a target. Additionally, we show that only an optical waveform measurement technique that can retrieve the spectral and/or temporal phase will corroborate whether the target waveform has truly been achieved. The arbitrary waveform generation capability and the precise measurement technique can potentially help design a new ultrahigh capacity communication technique.

## References

- 1 Z. Jiang, et al., Opt. Exp., 13 (2005), p. 10431-9
- 2 D. Miyamoto, et al., IEEE Photon. Technol. Lett., 18 (2006), p. 721-3
- 3 W. Lee, et al., LEOS Summer Topical Meetings, (2005), p. 213-4
- 4 K. Mandai, et al., IEEE Photon. Technol. Lett., 18 (2006), p. 679-81
- 5 R. Trebino, *Frequency-resolved optical gating: the measurement of ultrashort laser pulses*, (2000)
- 6 T. Sakamoto, et al., ECOC, 3 (2005), p. 743-4

This work was supported in part by DARPA DSO OAWG contract HR0011-05-C-0155