

Rapid updating of optical arbitrary waveforms via time-domain multiplexing

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We demonstrate high-fidelity optical arbitrary waveform generation with 5 GHz waveform switching via time-domain multiplexing. Compact, integrated waveform shapers based on silica arrayed-waveguide grating pairs with 10 GHz channel spacing are used to shape (line-by-line) two different waveforms from the output of a 10-mode \times 10 GHz optical frequency comb generator. Characterization of the time multiplexer's complex transfer function (amplitude and phase) by frequency-resolved optical gating permits compensation of its impact on the switched waveforms and matching of the measured and target waveforms to better than $G' = 5\%$. © 2008 Optical Society of America

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In recent years, optical arbitrary waveform generation (OAWG) technology [1] has advanced to the point where truly arbitrary optical waveforms of high fidelity are possible [2]. The most successful demonstrations of OAWG have been via a Fourier synthesis technique in which the amplitude and phase of individual optical modes of a repetitive optical source are manipulated in the spectral domain to achieve a particular temporal waveform (i.e., line-by-line pulse shaping) [1,3,4]. It is the ability to individually control every optical line that allows for true OAWG.

However, the implementations to date have been quasi-static in the sense that it is not possible to make adjustments to the amplitude and phase of the optical modes at a rate approaching the mode spacing (i.e., optical source repetition rate). Typical mode spacings for line-by-line shaping are in excess of 1 GHz, while the maximum modulation rates for the amplitude and phase modulators used in the waveform shapers are in the kilohertz range. Since nearly all line-by-line waveform shapers utilize liquid-crystal or thermo-optic based modulation, it is not likely that direct gigahertz modulation rates will be available in the near future from those technologies. However, it is possible to use less-direct techniques, such as time multiplexing, to quickly switch between multiple quasi-static waveforms. Although time multiplexing has been shown in photonic-enabled rf arbitrary waveform generation [5,6] and code switching in optical code division multiple access (O-CDMA) systems [7,8], its application to high-fidelity OAWG has not been previously investigated. In this Letter, we demonstrate how time multiplexing can be used to create high-fidelity alternating OAWG waveforms with 26 ps switching times. And, through the use of frequency-resolved optical gating (FROG), we explore the importance of characterizing the time multiplexer's complex transfer function and maximizing its extinction ratio (ER) to minimize its impact on the waveforms.

To realize a practical time-multiplexed OAWG it is necessary to have a quality optical frequency comb

generator (OFCG), multiple encoders, and a time multiplexer. Our approach, shown in Fig. 1, utilizes a high-speed 2×2 switch as the time multiplexer. The OFCG is based on strong modulation of a single-frequency tunable laser, which creates sidebands (optical modes) spaced at the modulation frequency (10 GHz in this case). Our implementation of the OFCG follows that of [9], where a single dual-electrode Mach-Zehnder modulator (DEMZM) is used to apply both amplitude modulation (AM) and phase modulation (PM) to the single-frequency tunable laser output, thereby producing a flattened output. In the time domain, the OFCG output is a 25 ps chirped pulse, and in the frequency domain it consists of ten optical modes spaced at 10 GHz. Further OFCG details can be found in [2].

A sample of the OFCG output is used for the cross-correlation FROG (XFROG) gate or reference pulse, and the gate pulse is characterized via second-harmonic-generation (SHG) FROG for a 200 ps win-

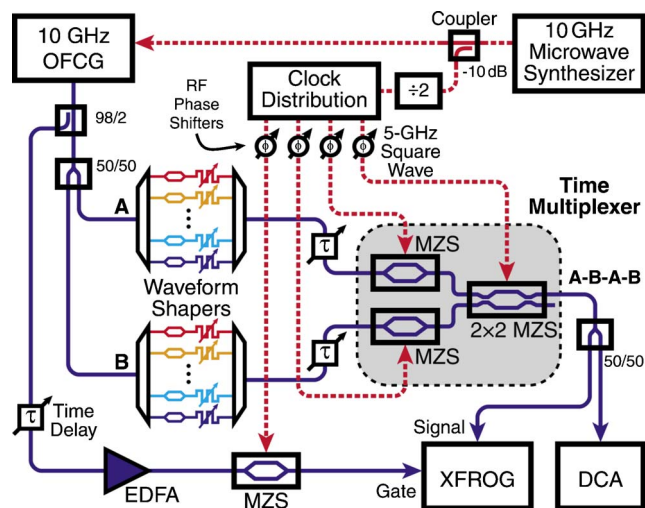


Fig. 1. (Color online) Diagram of the time-multiplexed OAWG system: OFCG, optical frequency comb generator; MZM, Mach-Zehnder switch; DCA, digital communications analyzer.

dow. The remaining signal is evenly split and sent into two separate waveform shapers (detailed below), one shapes the **A** waveform the other the **B** waveform. We chose the target **A** waveform to be a chirped pulse with purely quadratic spectral phase and a sixth-order super-Gaussian spectral envelope, while the **B** waveform is not actively shaped and acquires some random spectral phase errors from the waveform shaper (i.e., truly arbitrary). A 2×2 lithium-niobate Mach-Zehnder switch (MZS) is electrically driven by a 5 GHz square wave from a 12 Gbit/s pattern generator (HP 70843A) derived from the 10 GHz synthesizer. The 2×2 MZS is used to multiplex every other pulse from the waveform shapers onto its outputs. One of the 2×2 MZS outputs, which now consists of alternating **A** and **B** waveforms, is sent to either the XFROG or the sampling oscilloscope for analysis. Variable optical delay lines and rf phase shifters are used to adjust the timing of the optical and electrical signals so each waveform is temporally aligned with the transmission windows of the 2×2 MZS. An additional MZS is added to each encoder output to increase the total ER of the time multiplexer. The 2×2 MZS has a 30 GHz bandwidth and a dynamic ER of ~ 13 dB, while the additional MZSs have a bandwidth of 12 GHz and ~ 15 dB ER. The combined ER of the MZSs in series is >23 dB, large enough to minimize interference between the wanted waveform and the suppressed waveform in a particular 100 ps window. Without the two additional MZSs, the interference is significant and prevents accurate waveform retrievals from the measured XFROG traces.

The waveform shapers are based on a compact, fully integrated, silica arrayed-waveguide grating (AWG) pair with 10 GHz channel spacing and 64 channels. The first AWG demultiplexes the wavelengths at the input onto individual channels, each with its own amplitude and phase modulator. The second AWG then multiplexes all of the wavelength channels onto a single output. The amplitude modulators within each channel are realized using a Mach-Zehnder structure with a phase modulator in one arm. The phase modulators utilize the thermo-optic effect and resistive heaters above the silica waveguides to achieve 2π rad phase shift with 570 mW of electrical power. The waveform shaper operation is similar to the 20 GHz device detailed in [2], and the detailed design and performance characteristics of these particular 10 GHz devices will be described in an upcoming publication [10].

One of the keys to creating high-fidelity waveforms when using the time-multiplexing technique is complete characterization of the time multiplexer itself. It is inevitable that the time multiplexer will modify the temporal amplitude and phase of any waveform passing through it. Figure 2 shows the measured temporal transfer function of the input-output pair of the time multiplexer corresponding to the **A** waveform's transmission path. Figure 2(a) is a trace from a 65 GHz sampling oscilloscope (Agilent 86116 DCA module) showing the time-multiplexer output with a

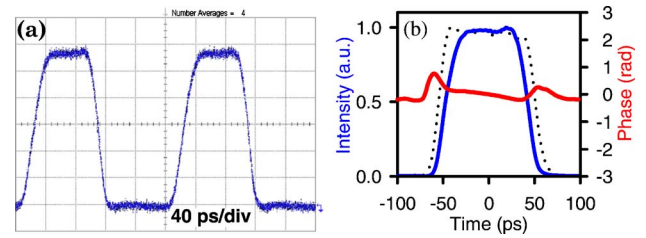


Fig. 2. (Color online) Time-multiplexer characteristics of one input port: (a) DCA measurement. (b) Complex transfer function retrieved from XFROG (dotted without MZS).

single-frequency laser input. The rise and fall times (10%–90%) are 26 ps. The intensity and phase of the multiplexer's transmission (difference between input and output) retrieved from an XFROG measurement are shown as solid curves in Fig. 2(b). The dotted curve represents the intensity transmission response without the additional 12 GHz MZS. Note that the finite rise and fall time of the gate function will apodize the temporal edges of the waveform and, while reasonably flat, the temporal phase is added to the waveform. Although seemingly minor effects, they can severely limit the fidelity of the output waveform.

Figure 3(a) presents a 65 GHz sampling oscilloscope trace of the multiplexed **A-B-A-B** waveform. Two different waveforms are in their respective 100 ps window, where the double-peaked waveform is the **A** waveform. Figure 3(b) shows the XFROG trace of the **A-B-A-B** waveform on a logarithmic intensity scale, and Fig. 3(c) displays the retrieved temporal waveform.

To measure the fidelity of a crafted waveform, we have previously proposed a figure of merit called G' (G -prime) [2]. It is a modified version of the FROG error value G that is commonly used to determine the accuracy of the retrieved field from the well-known SHG FROG trace [11]. However, instead of normalizing the error to the binned trace size (N^2), G' is normalized to the total FROG trace energy, which, in turn, is related to the total energy of the waveform. Thus, the rms difference between a target waveform and a measured waveform is given by

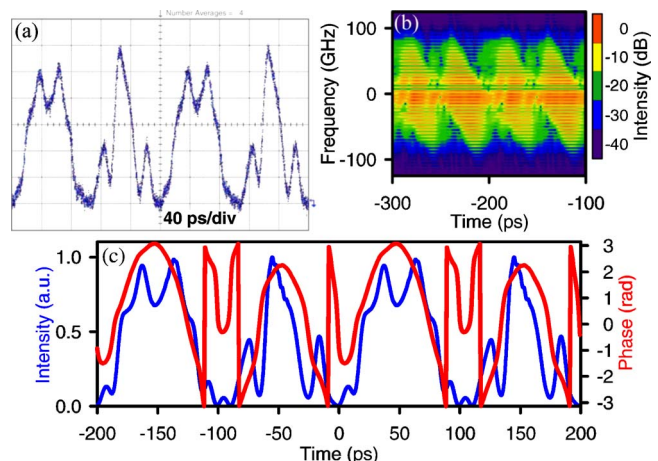


Fig. 3. (Color online) Switched waveform data (**A-B-A-B** waveform): (a) DCA trace, (b) XFROG trace, (c) retrieved temporal intensity and phase.

$$G' = \sqrt{\frac{\iint |I_{\text{FROG}}^{\text{Target}}(\omega, \tau) - \alpha I_{\text{FROG}}^{\text{Meas.}}(\omega, \tau)|^2 d\omega d\tau}{\iint [I_{\text{FROG}}^{\text{Target}}(\omega, \tau)]^2 d\omega d\tau}}, \quad (1)$$

where the SHG FROG traces $I_{\text{FROG}}(\omega, \tau)$ are calculated from the respective waveforms according to

$$I_{\text{FROG}}^{\text{SHG}}(\omega, \tau) \triangleq \left| \int E(t)E(t - \tau)\exp(-i\omega t)dt \right|^2, \quad (2)$$

where $E(t)$ is the optical waveform and τ is the relative delay between waveforms [11]. In practice, the FROG traces are not continuous functions but are discrete since they have been binned to a particular size and therefore the integrals in Eq. (1) become summations over the binned traces. Generally, G' values of less than 5% are considered to be high fidelity, where the measured waveform is a very close match to the target.

As stated earlier, in this OAWG time-multiplexing demonstration only the **A** waveform is shaped, while the **B** waveform is arbitrary. The retrieved **A** waveform is shown along with the target **A** waveform in Fig. 4. The measured waveform has a G' of 12.2% and not surprisingly, the mismatch between the measured and target waveforms is greatest near the edges of the temporal window. The bar plot representation of intensity data in Fig. 4(b) is for readability only, and the bars do not represent optical modes *per se*; the 10 GHz spectral resolution is determined by the 100 ps temporal region of interest.

Although the initial time-multiplexed **A** waveform (Fig. 4) has a high G' , the transfer function for the time multiplexer shown in Fig. 2(b) can be used to correct for its impact. Figure 5 shows the measured **A** waveform after the correction has been applied. The G' has decreased to a very respectable 3.96%. There is still a slight mismatch in the temporal intensity of the corrected and target waveforms, but the temporal phase match between the two is extremely close.

Current OAWG technology utilizes waveform shapers, which have limited modulation capability, typically in the kilohertz regime. Through the use of

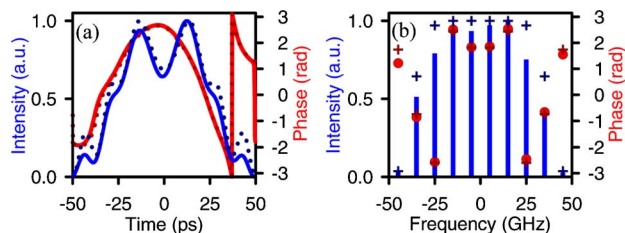


Fig. 4. (Color online) Retrieved **A** waveform without correction. (a) Time domain showing the target (dotted) and measured (solid) waveforms. (b) Spectral domain showing the target (crosses) and measured (bars and circles) waveforms. $G' = 12.2\%$.

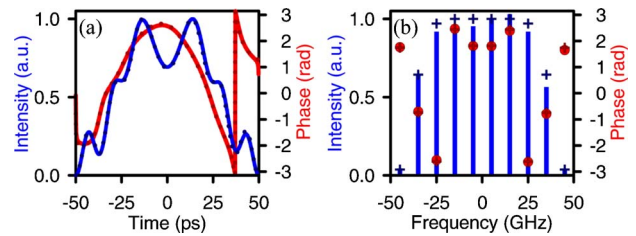


Fig. 5. (Color online) Retrieved **A** waveform after correction: (a) Time domain showing the target (dotted) and measured (solid) waveforms. (b) Spectral domain showing the target (crosses) and measured (bars and circles) waveforms. $G' = 3.96\%$.

time multiplexing, we have shown alternating high-fidelity 100 ps waveforms and that complete characterization of the time multiplexer's complex transfer function permits compensation of its impact to achieve a G' of 3.96%.

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