Time-multiplexed photonically enabled radio-frequency arbitrary waveform generation with 100 ps transitions

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For the first time, to our knowledge, radio-frequency arbitrary waveforms are time-multiplexed within 100 ps by integrating wavelength switching, optical frequency comb generation, and spectral line-by-line shaping. The novel time-multiplexed scheme demonstrated here can be extended to wide user specifications and faster waveform transition time. © 2007 Optical Society of America

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Fourier-transform (FT) based optical pulse shaping is a frequently adopted technique that has facilitated numerous applications [1]. Conventionally, a liquid crystal modulator (LCM) is placed on the Fourier plane of the shaper to allow flexible amplitude and phase manipulation of the input source spectral components. The waveform update rate is limited by the response time of the LCM, typically tens of milliseconds. Recently, there have been several reported efforts to increase the waveform update rate, with results demonstrated up to 33 MHz [2–4]. However, due to limited spectral resolution, groups, rather than individual spectral lines, have been manipulated in these works.

Recently, by utilizing optical pulse shaping and gigahertz-period optical frequency combs together, quasi-static (~10 ms update time) spectral line-by-line pulse shaping examples have been demonstrated [5–7]. In line-by-line shaping, the amplitude and phase of discrete spectral comb lines are independently controlled. A LCM-based FT shaper has been reported to generate optical arbitrary waveforms using more than 100 spectral lines at 5 GHz comb spacing [6]. A hyperfine wavelength demultiplexer with subsequent electro-optical modulators has been reported with a waveform modulation rate ranging from tens to hundreds of megahertz, but only two spectral lines were controlled [8–10]. In a previous demonstration, our group reported switching between two optical waveforms at 10 GHz in the group-of-lines shaping regime; however, each waveform required a separate shaper [11]. Here we report a novel scheme where distinct waveforms can be generated at high update speed using a single pulse shaper.

Photonically assisted radio-frequency arbitrary waveform generation (RF-AWG) [12] is a promising application of pulse shaping that has been demonstrated previously at low pulse shaping resolution and with a low update rate [13,14]. In this Letter, we overcome the limitation of the LCM response time and report a simple structure that allows RF-AWG waveform updates in less than 100 ps (10 GHz), to our knowledge the fastest reported to date.

The schematic of our proposed novel time-multiplexed setup is shown in Fig. 1. Two CW lasers (λ_a, λ_b), with a $LiNbO_3$ intensity modulator (IM) after each laser, are used to provide rapid wavelength switching. IM1 (for λ_a) and IM2 (for λ_b) are driven by the programmable data port (Q) and inverted data port ($\bar{Q}$) of a bit-error-ratio test set (BERT) with bit duration of 100 ps (10 GHz signal), respectively. The wavelength-switched CW outputs are combined via an optical coupler [node (i)] and sent to an optical frequency comb generator comprising a lithium niobate phase modulator (PM) driven at a repetition frequency of $f_{rep} = 10$ GHz by the clock of the BERT [node (ii)]. These phase-modulated CW (PMCW) combs [6,15] are manipulated by a FT shaper, where distinct waveforms are generated for each different input center wavelengths [node (iii)], $I_a(t)$ and $I_b(t)$. Details of the pulse shaper configuration can be found within [6].

In order to enable high-speed waveform updates, the LCM pixels are logically divided into different regions, each of which may be programmed to generate different waveforms; each region may be selected by rapidly changing the input wavelength. An optical amplifier is used after the shaper, and the rapid-updated waveforms are detected by using a 50 GHz

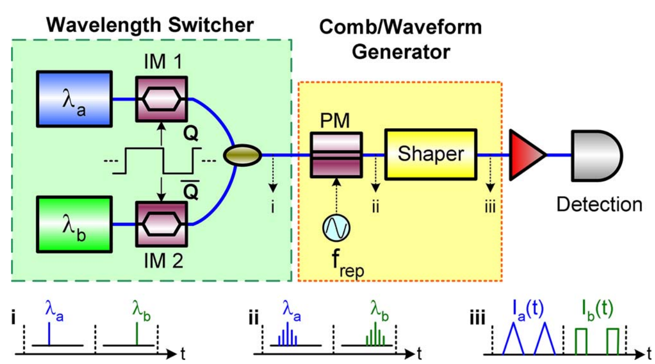

Fig. 1. (Color online) Schematic of the experimental setup. (λ_a, λ_b): two CW lasers; IM: intensity modulator; Q: data pattern; PM: phase modulator; f_{rep}: comb frequency spacing.

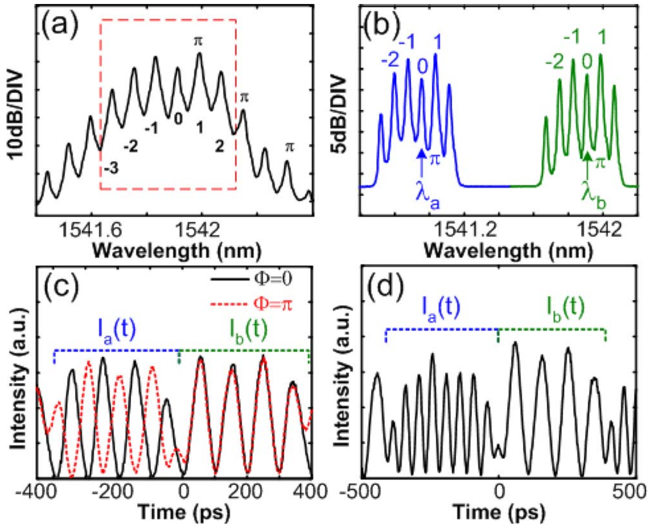

Fig. 2. (Color online) (a) PMCW spectrum. Six lines within the rectangle are used for waveform generation. (b) Six-line selected PMCW combs when both CW lasers are on. (c), (d) sampling scope traces of rapid RF-AWG updates with $Q = [1111\ 0000]$: (c) switching between waveform phase modulation using two spectral lines from each comb; (d) switching between waveform frequencies.

bandwidth sampling scope and/or photodiode. An optical spectrum analyzer (OSA) with 0.01 nm resolution is used to measure the comb spectra.

In order to more clearly explain the concept, first consider the use of only one CW laser. Figure 2(a) shows the λ_b PMCW comb (line {0} denotes the CW input). The spectral lines that have a π-phase difference are labeled within the figure. Note that without phase correction, the time-domain output intensity of the PMCW comb is still CW in nature. In our experiments, lines {−3–2} are selected by the line-by-line shaper to demonstrate shaped waveform updates so that the optical bandwidth does not exceed the electrical bandwidth of our sampling scope. Figure 2(b) shows the six-line PMCW combs when both CW lasers are turned on with $\lambda_a = 1540.95$ nm and $\lambda_b = 1541.91$ nm. As a first demonstration of shaped RF-AWG updates, Fig. 2(c) shows rapid waveform switching, in which a repetitive data pattern $Q = [1111\ 0000]$ is fed to IM1. Here, two cosine waveforms (spectral lines $\{a_{-1}, a_0\}$ and $\{b_{-1}, b_0\}$ selected while others are suppressed) are generated. The corresponding intensity waveforms $I_a(t)$ and $I_b(t)$ are labeled within the Fig. 2. The solid trace indicates the measured waveform when no optical phase control is applied, and I_a and I_b are identical cosine waveforms. Switching between I_a and I_b simply results in a continuous RF cosine signal shown in the figure (although transient effects are evident with a reduction in signal amplitude near the wavelength switching times). The dashed trace indicates the measured waveform when a π phase is applied to line $\{a_{-1}\}$ so that I_a is delayed by exactly half the period compared to I_b. This yields an RF waveform with abrupt π phase shifts inserted at times determined by the driving data. Figure 2(d) shows rapid switching of waveform frequencies. Here lines $\{a_{-1}, a_1\}$ are selected for the λ_a comb, resulting in a cosine waveform with a repetition rate of $2f_{\rm rep}$, while the λ_b comb is again filtered to yield a cosine waveform with a repetition rate of $f_{\rm rep}$. Rapid switching between the two waveforms is observed in direct correspondence to the data pattern. The update transition time is less than 100 ps, defined here by the data pattern frequency (10 GHz).

Figures 3(a) and 3(b) show examples of RF-AWG using line-by-line phase control on the six-line combs. Here, a longer data pattern (length of 40) is used so that regions of the RF signals located away from the transition regions may be examined to check the fidelity of waveforms under quasi-static generation conditions. With a π phase applied to λ_a comb line {1}, transform-limited pulses are generated and measured in the sampling scope trace (dots) of Fig. 3(a), which is in excellent agreement with the calculated result (line). Figure 3(b) demonstrates pulse doublet generation by applying a π phase to λ_b comb lines {−3, −2, −1, and 1}. The peak amplitude of the doublet pulse is faithfully lowered by a factor of two. In Figs. 3(c)–3(e), we discuss the effect of data pattern length on the RF-AWG update using these two waveforms. In Fig. 3(c), we apply a repetitive 16 bit data pattern $Q = [0000\ \ 111111111111]$ to IM1, defining the length of I_a. For I_a and I_b, slight amplitude variation is observed near the edges of the waveform transitions. We attribute this behavior to: (1) a nonideal rectangular data pattern from the BERT (bandwidth of 13.5 GHz) due to finite rise (~20 ps) and fall (~65 ps) time; (2) finite optical intensity extinction ratio of the IM (~15 dB). Intermixing of the two waveforms occurs during these intervals and may cause the observed amplitude modulation in the RF-AWG results. This issue could be improved by using a

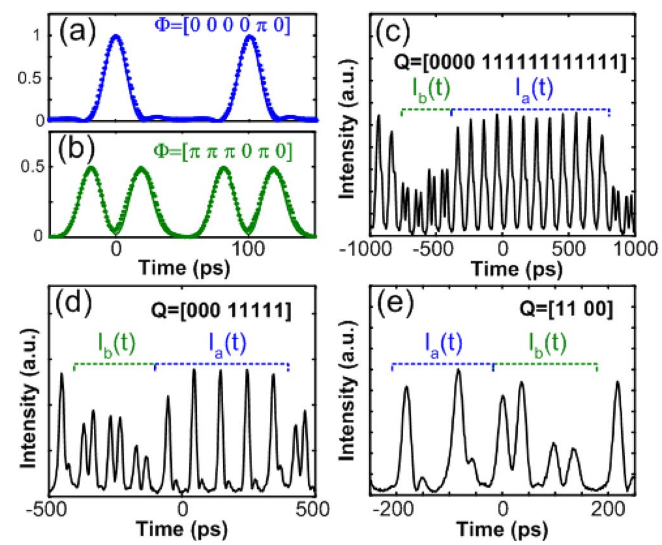

Fig. 3. (Color online) Sampling scope traces of RF-AWG using six comb lines: (a) π-phase applied to λ_a comb line {1} for transform-limited pulses; (b) π-phase applied to λ_b comb lines {−3 to −1 and 1}, resulting in optical odd-pulses. (c)–(e) RF-AWG update results: (c) $Q = [0000\ \ 111111111111]$; (d) $Q = [000\ \ 11111]$; and (e) $Q = [11\ \ 00]$.

data pattern generator with greater bandwidth, and IM with improved optical extinction ratio.

In one extreme, one could envision the capability of a bit-by-bit (waveform-by-waveform) update function enabled by our scheme. Figures 3(d) and 3(e) compare the effects of gradually shortening the duration of each waveform using repetitive data patterns of Q=[000 11111] and Q=[11 00] to drive IM1. Waveform updates are apparent down to 2 bits per waveform [Fig. 3(e)], but with larger amplitude variance within the waveforms due to the nonideality of the drives discussed previously. In Figs. 3(d) and 3(e), λ_a comb lines are gradually attenuated by using shaper amplitude control and lowering the bandwidth-limited pulse peaks of $I_a(t)$ as compared to Fig. 3(c), demonstrating another degree of freedom in waveform control.

Figure 4 demonstrates signals incorporating rapid triangular waveforms. These are obtained by applying a cubic spectral phase to a broader PMCW comb (using dual stage phase-modulation [6]) resulting in oscillatory tails, so that a triangular RF waveform is converted via the photodetector. The resulting PMCW spectra are shown in Fig. 4(a), where 28 spectral lines (280 GHz bandwidth) are selected from each comb. The spectral line phases are corrected by using an automated process, resulting in transform-limited pulses. On top of these phase corrections, a cubic spectral phase is applied to the λ_a comb, resulting in rapid updates between triangular and transform-limited pulses, as shown in Fig. 4(b). Figure 4(c) shows the waveforms when the λ_b comb has an applied cubic phase of opposite sign to that of the λ_a comb, providing triangular pulse updates with opposite {fast, slow} edges. The slight ripples observed on the trailing edge of $I_b(t)$ are due to the detector impulse response. In these two examples, Q =[1111 0000] is used. To demonstrate flexibility of data patterning, Fig. 4(d) shows waveform updates using a repetitive 20 bit length data pattern.

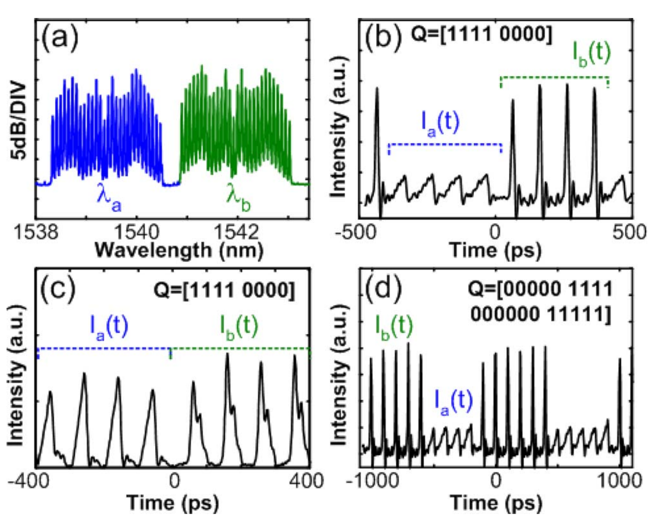

Fig. 4. (Color online) (a) 28-line PMCW combs used for triangular RF waveforms: (b) switching between triangular and transform-limited pulses; (c) switching between triangular waves with opposite (fast, slow) trailing edges; and (d) waveform switching using a more complicated data pattern.

Our scheme has the potential for significant scalability and extensibility. For example: (1) waveforms of different repetition rates and bandwidths may be obtained through slight modification of the comb generator setup; (2) the bulk wavelength switching in our current scheme can be replaced by a monolithically integrated wavelength converter [16]; (3) multiple waveforms can be controlled by switching among more CW wavelengths while incorporating a spatial light modulator with a larger pixel count, or in a two-dimensional geometry [17]; and (4) the waveform update rate can be increased by using a faster data pattern generator.

In summary, using a simple configuration, we demonstrate what is to our knowledge the fastest time-multiplexed RF arbitrary waveform generation ever reported. By combining 10 GHz wavelength switching, optical comb generation, and liquid crystal modulator based line-by-line pulse shaping, RF waveforms are updated within 100 ps.

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